Topics in Differential Geometry

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Differentialgeometrie und Lie Gruppen

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0. Introduction

In this lecture notes I try to give an introduction to the fundamentals of differential geometry (manifolds, flows, Lie groups, differential forms, bundles and connections) which stresses naturality and functoriality from the beginning and is as coordinate free as possible. The material presented in the beginning is standard - but some parts are not so easily found in text books: we treat initial submanifolds and the Frobenius theorem for distributions of non constant rank, and we give a quick proof in two pages of the Campbell - Baker - Hausdorff formula for Lie groups. We also prove that closed subgroups of Lie groups are Lie subgroups.

Then the deviation from the standard presentations becomes larger. In the section on vector bundles I treat the Lie derivative for natural vector bundles, i.e. functors which associate vector bundles to manifolds and vector bundle homomorphisms to local diffeomorphisms. I give a formula for the Lie derivative of the form of a commutator, but it involves the tangent bundle of the vector bundle involved. So I also give a careful treatment to this situation. It follows a standard presentation of differential forms and a thorough treatment of the Frölicher-Nijenhuis bracket via the study of all graded derivations of the algebra of differential forms. This bracket is a natural extension of the Lie bracket from vector fields to tangent bundle valued differential forms. I believe that this bracket is one of the basic structures of differential geometry, and later I will base nearly all treatment of curvature and the Bianchi identities on it. This allows me to present the concept of a connection first on general fiber bundles (without structure group), with curvature, parallel transport and Bianchi identity, and only then add G-equivariance as a further property for principal fiber bundles. I think, that in this way the underlying geometric ideas are more easily understood by the novice than in the traditional approach, where too much structure at the same time is rather confusing.

We begin our treatment of connections in the general setting of fiber bundles (without structure group). A connection on a fiber bundle is just a projection onto the vertical bundle. Curvature and the Bianchi identity is expressed with the help of the Frölicher-Nijenhuis bracket. The parallel transport for such a general connection is not defined along the whole of the curve in the base in general - if this is the case, the connection is called complete. We show that every fiber bundle admits complete connections. For complete connections we treat holonomy groups and the holonomy Lie algebra, a subalgebra of the Lie algebra of all vector fields on the standard fiber.

Then we present principal bundles and associated bundles in detail together with the most important examples. Finally we investigate principal connections by requiring equivariance under the structure group. It is remarkable how fast the usual structure equations can be derived from the basic properties of the Frölicher-Nijenhuis bracket. Induced connections are investigated thoroughly - we describe tools to recognize induced connections among general ones.

If the holonomy Lie algebra of a connection on a fiber bundle with compact standard fiber turns out to be finite dimensional, we are able to show, that in fact the fiber bundle is associated to a principal bundle and the connection is an induced one.

We think that the treatment of connections presented here offers some didactical advantages besides presenting new results: the geometric content of a connection is treated first, and the additional requirement of equivariance under a structure group is seen to be additional and can be dealt with later - so the student is not required to grasp all the structures at the same time. Besides that it gives new results and new insights. This treatment is taken from [Michor, 87].

CHAPTER I
Manifolds and Vector Fields

1. Differentiable Manifolds

1.1. Manifolds. A *topological manifold* is a separable metrizable space M which is locally homeomorphic to $\mathbb{R}^n$. So for any $x \in M$ there is some homeomorphism $u : U \to u(U) \subseteq \mathbb{R}^n$, where U is an open neighborhood of x in M and $u(U)$ is an open subset in $\mathbb{R}^n$. The pair (U, u) is called a *chart* on M.

From algebraic topology it follows that the number n is locally constant on M; if n is constant, M is sometimes called a *pure manifold*. We will only consider pure manifolds and consequently we will omit the prefix pure.

A family $(U_\alpha, u_\alpha)_{\alpha\in A}$ of charts on M such that the U_α form a cover of M is called an *atlas*. The mappings $u_{\alpha\beta} := u_\alpha \circ u_\beta^{-1} : u_\beta(U_{\alpha\beta}) \to u_\alpha(U_{\alpha\beta})$ are called the chart changings for the atlas (U_α), where $U_{\alpha\beta} := U_\alpha \cap U_\beta$.

An atlas $(U_\alpha, u_\alpha)_{\alpha\in A}$ for a manifold M is said to be a C^k*-atlas*, if all chart changings $u_{\alpha\beta} : u_\beta(U_{\alpha\beta}) \to u_\alpha(U_{\alpha\beta})$ are differentiable of class C^k. Two C^k-atlases are called C^k*-equivalent*, if their union is again a C^k-atlas for M. An equivalence class of C^k-atlases is called a C^k*-structure* on M. From differential topology we know that if M has a C^1-structure, then it also has a C^1-equivalent C^∞-structure and even a C^1-equivalent C^ω-structure, where C^ω is shorthand for real analytic, see [Hirsch, 1976]. By a C^k-manifold M we mean a topological manifold together with a C^k-structure and a chart on M will be a chart belonging to some atlas of the C^k-structure.

But there are topological manifolds which do not admit differentiable structures. For example, every 4-dimensional manifold is smooth off some point, but there are such which are not smooth, see [Quinn, 1982], [Freedman, 1982]. There are also topological manifolds which admit several inequivalent smooth structures. The spheres from dimension 7 on have finitely many, see [Milnor, 1956]. But the most surprising result is that on $\mathbb{R}^4$ there are uncountably many pairwise inequivalent (exotic) differentiable structures. This follows from the results of [Donaldson, 1983] and [Freedman, 1982], see [Gompf, 1983] for an overview.

Note that for a Hausdorff C^∞-manifold in a more general sense the following properties are equivalent:

(1) It is paracompact.

(2) It is metrizable.
(3) It admits a Riemannian metric.
(4) Each connected component is separable.

In this book a manifold will usually mean a C^∞-manifold, and smooth is used synonymously for C^∞, it will be Hausdorff, separable, finite dimensional, to state it precisely.

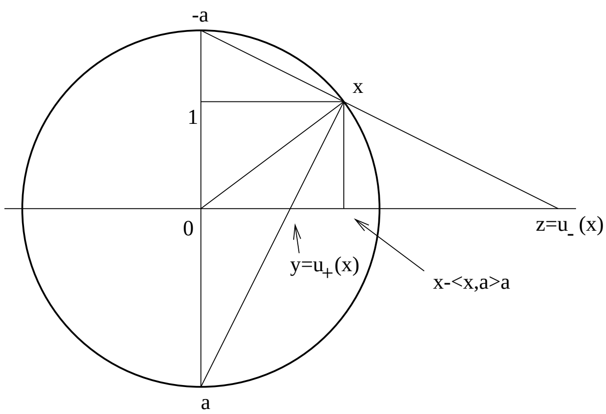
Note finally that any manifold M admits a finite atlas consisting of $\dim M + 1$ (not connected) charts. This is a consequence of topological dimension theory [Nagata, 1965], a proof for manifolds may be found in [Greub-Halperin-Vanstone, Vol. I].

1.2. Example: Spheres. We consider the space $\mathbb{R}^{n+1}$, equipped with the standard inner product $\langle x, y\rangle = \sum x^i y^i$. The *n-sphere* S^n is then the subset $\{x \in \mathbb{R}^{n+1} : \langle x, x\rangle = 1\}$. Since $f(x) = \langle x, x\rangle$, $f : \mathbb{R}^{n+1} \to \mathbb{R}$, satisfies $df(x)y = 2\langle x, y\rangle$, it is of rank 1 off 0 and by (1.12) the sphere S^n is a submanifold of $\mathbb{R}^{n+1}$.

In order to get some feeling for the sphere we will describe an explicit atlas for S^n, the *stereographic atlas*. Choose $a \in S^n$ ('south pole'). Let

$$U_+ := S^n \setminus \{a\}, \qquad u_+ : U_+ \to \{a\}^\perp, \qquad u_+(x) = \tfrac{x - \langle x,a\rangle a}{1 - \langle x,a\rangle},$$
$$U_- := S^n \setminus \{-a\}, \qquad u_- : U_- \to \{a\}^\perp, \qquad u_-(x) = \tfrac{x - \langle x,a\rangle a}{1 + \langle x,a\rangle}.$$

From an obvious drawing in the 2-plane through 0, x, and a it is easily seen that u_+ is the usual stereographic projection.



We also get

$$u_+^{-1}(y) = \tfrac{|y|^2 - 1}{|y|^2 + 1} a + \tfrac{2}{|y|^2 + 1} y \qquad \text{for } y \in \{a\}^\perp \setminus \{0\}$$

and $(u_- \circ u_+^{-1})(y) = \frac{y}{|y|^2}$. The latter equation can directly be seen from the drawing using 'Strahlensatz'.

1.3. Smooth mappings. A mapping $f : M \to N$ between manifolds is said to be C^k if for each $x \in M$ and one (equivalently: any) chart (V, v) on N with $f(x) \in V$ there is a chart (U, u) on M with $x \in U$, $f(U) \subseteq V$, and $v \circ f \circ u^{-1}$ is C^k. We will denote by $C^k(M, N)$ the space of all C^k-mappings from M to N.

A C^k-mapping $f : M \to N$ is called a C^k-*diffeomorphism* if $f^{-1} : N \to M$ exists and is also C^k. Two manifolds are called *diffeomorphic* if there exists a diffeomorphism between them. From differential topology (see [Hirsch, 1976]) we know that if there is a C^1-diffeomorphism between M and N, then there is also a C^∞-diffeomorphism.

There are manifolds which are homeomorphic but not diffeomorphic: on $\mathbb{R}^4$ there are uncountably many pairwise non-diffeomorphic differentiable structures; on every other $\mathbb{R}^n$ the differentiable structure is unique. There are finitely many different differentiable structures on the spheres S^n for $n \geq 7$.

A mapping $f : M \to N$ between manifolds of the same dimension is called a *local diffeomorphism*, if each $x \in M$ has an open neighborhood U such that $f|U : U \to f(U) \subset N$ is a diffeomorphism. Note that a local diffeomorphism need not be surjective.

1.4. Smooth functions. The set of smooth real valued functions on a manifold M will be denoted by $C^\infty(M)$, in order to distinguish it clearly from spaces of sections which will appear later. $C^\infty(M)$ is a real commutative algebra.

The *support* of a smooth function f is the closure of the set, where it does not vanish, $\operatorname{supp}(f) = \overline{\{x \in M : f(x) \neq 0\}}$. The *zero set* of f is the set where f vanishes, $Z(f) = \{x \in M : f(x) = 0\}$.

1.5. Theorem. *Any (separable, metrizable, smooth) manifold admits smooth partitions of unity: Let $(U_\alpha)_{\alpha\in A}$ be an open cover of M.*

Then there is a family $(\varphi_\alpha)_{\alpha\in A}$ of smooth functions on M, such that:

(1) $\varphi_\alpha(x) \geq 0$ *for all* $x \in M$ *and all* $\alpha \in A$.
(2) $\operatorname{supp}(\varphi_\alpha) \subset U_\alpha$ *for all* $\alpha \in A$.
(3) $(supp(\varphi_\alpha))_{\alpha\in A}$ *is a locally finite family (so each $x \in M$ has an open neighborhood which meets only finitely many* $\operatorname{supp}(\varphi_\alpha)$*).*
(4) $\sum_\alpha \varphi_\alpha = 1$ *(locally this is a finite sum).*

Proof. Any (separable metrizable) manifold is a *'Lindelöf space'*, i. e. each open cover admits a countable subcover. This can be seen as follows:

Let $\mathcal{U}$ be an open cover of M. Since M is separable there is a countable dense subset S in M. Choose a metric on M. For each $U \in \mathcal{U}$ and each $x \in U$ there is an $y \in S$ and $n \in \mathbb{N}$ such that the ball $B_{1/n}(y)$ with respect to that metric with center y and radius $\frac{1}{n}$ contains x and is contained in U. But there are only countably many of these balls; for each of them we choose an open set $U \in \mathcal{U}$ containing it. This is then a countable subcover of $\mathcal{U}$.

Now let $(U_\alpha)_{\alpha\in A}$ be the given cover. Let us fix first α and $x \in U_\alpha$. We choose a chart (U, u) centered at x (i. e. $u(x) = 0$) and $\varepsilon > 0$ such that $\varepsilon\mathbb{D}^n \subset u(U \cap U_\alpha)$, where $\mathbb{D}^n = \{y \in \mathbb{R}^n : |y| \leq 1\}$ is the closed unit ball. Let

$$h(t) := \begin{cases} e^{-1/t} & \text{for } t > 0, \\ 0 & \text{for } t \leq 0, \end{cases}$$

a smooth function on $\mathbb{R}$. Then

$$f_{\alpha,x}(z) := \begin{cases} h(\varepsilon^2 - |u(z)|^2) & \text{for } z \in U, \\ 0 & \text{for } z \notin U \end{cases}$$

is a non negative smooth function on M with support in U_α which is positive at x.

We choose such a function $f_{\alpha,x}$ for each α and $x \in U_\alpha$. The interiors of the supports of these smooth functions form an open cover of M which refines (U_α), so by the argument at the beginning of the proof there is a countable subcover with corresponding functions $f_1, f_2, \dots$. Let

$$W_n = \{x \in M : f_n(x) > 0 \text{ and } f_i(x) < \tfrac{1}{n} \text{ for } 1 \le i < n\},$$

and denote by $\overline{W}_n$ the closure. Then $(W_n)_n$ is an open cover. We claim that $(\overline{W}_n)_n$ is locally finite: Let $x \in M$. Then there is a smallest n such that $x \in W_n$. Let $V := \{y \in M : f_n(y) > \frac{1}{2} f_n(x)\}$. If $y \in V \cap \overline{W}_k$ then we have $f_n(y) > \frac{1}{2} f_n(x)$ and $f_i(y) \le \frac{1}{k}$ for $i < k$, which is possible for finitely many k only.

Consider the non negative smooth function $g_n(x) = h(f_n(x)) h(\frac{1}{n} - f_1(x)) \dots h(\frac{1}{n} - f_{n-1}(x))$ for each n. Then obviously $\operatorname{supp}(g_n) = \overline{W}_n$. So $g := \sum_n g_n$ is smooth, since it is locally only a finite sum, and everywhere positive, thus $(g_n/g)_{n\in\mathbb{N}}$ is a smooth partition of unity on M. Since $\operatorname{supp}(g_n) = \overline{W}_n$ is contained in some $U_{\alpha(n)}$ we may put $\varphi_\alpha = \sum_{\{n:\alpha(n)=\alpha\}} \frac{g_n}{g}$ to get the required partition of unity which is subordinated to $(U_\alpha)_{\alpha\in A}$. □

1.6. Germs. Let M and N be manifolds and $x \in M$. We consider all smooth mappings $f : U_f \to N$, where U_f is some open neighborhood of x in M, and we put $f \underset{x}{\sim} g$ if there is some open neighborhood V of x with $f|V = g|V$. This is an equivalence relation on the set of mappings considered. The equivalence class of a mapping f is called the *germ of f at x*, sometimes denoted by $\operatorname{germ}_x f$. The set of all these germs is denoted by $C^\infty_x(M, N)$.

Note that for a germs at x of a smooth mapping only the value at x is defined. We may also consider composition of germs: $\operatorname{germ}_{f(x)} g \circ \operatorname{germ}_x f := \operatorname{germ}_x(g \circ f)$.

If $N = \mathbb{R}$, we may add and multiply germs of smooth functions, so we get the real commutative algebra $C^\infty_x(M, \mathbb{R})$ of germs of smooth functions at x. This construction works also for other types of functions like real analytic or holomorphic ones, if M has a real analytic or complex structure.

Using smooth partitions of unity ((1.4)) it is easily seen that each germ of a smooth function has a representative which is defined on the whole of M. For germs of real analytic or holomorphic functions this is not true. So $C^\infty_x(M, \mathbb{R})$ is the quotient of the algebra $C^\infty(M)$ by the ideal of all smooth functions $f : M \to \mathbb{R}$ which vanish on some neighborhood (depending on f) of x.

1.7. The tangent space of $\mathbb{R}^n$. Let $a \in \mathbb{R}^n$. A *tangent vector* with foot point a is simply a pair (a, X) with $X \in \mathbb{R}^n$, also denoted by X_a. It induces a *derivation*

$X_a : C^\infty(\mathbb{R}^n) \to \mathbb{R}$ by $X_a(f) = df(a)(X_a)$. The value depends only on the germ of f at a and we have $X_a(f \cdot g) = X_a(f) \cdot g(a) + f(a) \cdot X_a(g)$ (the derivation property).

If conversely $D : C^\infty(\mathbb{R}^n) \to \mathbb{R}$ is linear and satisfies $D(f \cdot g) = D(f) \cdot g(a) + f(a) \cdot D(g)$ (a derivation at a), then D is given by the action of a tangent vector with foot point a. This can be seen as follows. For $f \in C^\infty(\mathbb{R}^n)$ we have

$$\begin{aligned}
f(x) &= f(a) + \int_0^1 \tfrac{d}{dt} f(a + t(x-a))dt \\
&= f(a) + \sum_{i=1}^n \int_0^1 \tfrac{\partial f}{\partial x^i}(a + t(x-a))dt\,(x^i - a^i) \\
&= f(a) + \sum_{i=1}^n h_i(x)(x^i - a^i). \\
D(1) &= D(1 \cdot 1) = 2D(1), \text{ so } D(\text{constant}) = 0. \text{ Thus} \\
D(f) &= D(f(a) + \sum_{i=1}^n h_i(x^i - a^i)) \\
&= 0 + \sum_{i=1}^n D(h_i)(a^i - a^i) + \sum_{i=1}^n h_i(a)(D(x^i) - 0) \\
&= \sum_{i=1}^n \tfrac{\partial f}{\partial x^i}(a) D(x^i),
\end{aligned}$$

where x^i is the i-th coordinate function on $\mathbb{R}^n$. So we have

$$D(f) = \sum_{i=1}^n D(x^i) \tfrac{\partial}{\partial x^i}|_a(f), \qquad D = \sum_{i=1}^n D(x^i) \tfrac{\partial}{\partial x^i}|_a.$$

Thus D is induced by the tangent vector $(a, \sum_{i=1}^n D(x^i) e_i)$, where (e_i) is the standard basis of $\mathbb{R}^n$.

1.8. The tangent space of a manifold. Let M be a manifold and let $x \in M$ and $\dim M = n$. Let $T_x M$ be the vector space of all derivations at x of $C_x^\infty(M, \mathbb{R})$, the algebra of germs of smooth functions on M at x. (Using (1.5) it may easily be seen that a derivation of $C^\infty(M)$ at x factors to a derivation of $C_x^\infty(M, \mathbb{R})$.)

So $T_x M$ consists of all linear mappings $X_x : C^\infty(M) \to \mathbb{R}$ with the property $X_x(f \cdot g) = X_x(f) \cdot g(x) + f(x) \cdot X_x(g)$. The space $T_x M$ is called the *tangent space of M at x*.

If (U, u) is a chart on M with $x \in U$, then $u^* : f \mapsto f \circ u$ induces an isomorphism of algebras $C_{u(x)}^\infty(\mathbb{R}^n, \mathbb{R}) \cong C_x^\infty(M, \mathbb{R})$, and thus also an isomorphism $T_x u : T_x M \to T_{u(x)}\mathbb{R}^n$, given by $(T_x u.X_x)(f) = X_x(f \circ u)$. So $T_x M$ is an n-dimensional vector space.

We will use the following notation: $u = (u^1, \dots, u^n)$, so u^i denotes the i-th coordinate function on U, and

$$\tfrac{\partial}{\partial u^i}|_x := (T_x u)^{-1}(\tfrac{\partial}{\partial x^i}|_{u(x)}) = (T_x u)^{-1}(u(x), e_i).$$

So $\frac{\partial}{\partial u^i}|_x \in T_xM$ is the derivation given by

$$\tfrac{\partial}{\partial u^i}|_x(f) = \frac{\partial(f\circ u^{-1})}{\partial x^i}(u(x)).$$

From (1.7) we have now

$$\begin{aligned}
T_xu.X_x &= \sum_{i=1}^n (T_xu.X_x)(x^i)\tfrac{\partial}{\partial x^i}|_{u(x)} = \sum_{i=1}^n X_x(x^i\circ u)\tfrac{\partial}{\partial x^i}|_{u(x)}\\
&= \sum_{i=1}^n X_x(u^i)\tfrac{\partial}{\partial x^i}|_{u(x)},\\
X_x &= (T_xu)^{-1}.T_xu.X_x = \sum_{i=1}^n X_x(u^i)\tfrac{\partial}{\partial u^i}|_x.
\end{aligned}$$

1.9. The tangent bundle. For a manifold M of dimension n we put $TM := \bigsqcup_{x\in M} T_xM$, the disjoint union of all tangent spaces. This is a family of vector spaces parameterized by M, with projection $\pi_M : TM \to M$ given by $\pi_M(T_xM) = x$.

For any chart (U_α, u_α) of M consider the chart $(\pi_M^{-1}(U_\alpha), Tu_\alpha)$ on TM, where $Tu_\alpha : \pi_M^{-1}(U_\alpha) \to u_\alpha(U_\alpha)\times\mathbb{R}^n$ is given by $Tu_\alpha.X = (u_\alpha(\pi_M(X)), T_{\pi_M(X)}u_\alpha.X)$. Then the chart changings look as follows:

$$\begin{aligned}
Tu_\beta\circ(Tu_\alpha)^{-1} &: Tu_\alpha(\pi_M^{-1}(U_{\alpha\beta})) = u_\alpha(U_{\alpha\beta})\times\mathbb{R}^n \to\\
&\qquad \to u_\beta(U_{\alpha\beta})\times\mathbb{R}^n = Tu_\beta(\pi_M^{-1}(U_{\alpha\beta})),\\
((Tu_\beta\circ(Tu_\alpha)^{-1})(y,Y))(f) &= ((Tu_\alpha)^{-1}(y,Y))(f\circ u_\beta)\\
&= (y,Y)(f\circ u_\beta\circ u_\alpha^{-1}) = d(f\circ u_\beta\circ u_\alpha^{-1})(y).Y\\
&= df(u_\beta\circ u_\alpha^{-1}(y)).d(u_\beta\circ u_\alpha^{-1})(y).Y\\
&= (u_\beta\circ u_\alpha^{-1}(y), d(u_\beta\circ u_\alpha^{-1})(y).Y)(f).
\end{aligned}$$

So the chart changings are smooth. We choose the topology on TM in such a way that all Tu_α become homeomorphisms. This is a Hausdorff topology, since X, $Y\in TM$ may be separated in M if $\pi(X)\neq\pi(Y)$, and in one chart if $\pi(X) = \pi(Y)$. So TM is again a smooth manifold in a canonical way; the triple (TM, π_M, M) is called the *tangent bundle* of M.

1.10. Kinematic definition of the tangent space. Let $C_0^\infty(\mathbb{R}, M)$ denote the space of germs at 0 of smooth curves $\mathbb{R}\to M$. We put the following equivalence relation on $C_0^\infty(\mathbb{R}, M)$: the germ of c is equivalent to the germ of e if and only if $c(0) = e(0)$ and in one (equivalently each) chart (U, u) with $c(0) = e(0)\in U$ we have $\frac{d}{dt}|_0(u\circ c)(t) = \frac{d}{dt}|_0(u\circ e)(t)$. The equivalence classes are also called velocity vectors of curves in M. We have the following mappings

$$\begin{array}{ccc}
C_0^\infty(\mathbb{R},M)/\sim & \longleftarrow & C_0^\infty(\mathbb{R},M)\\
{\scriptstyle\alpha}\big\downarrow & \overset{\beta}{\nearrow} & \big\downarrow{\scriptstyle \mathrm{ev}_0}\\
TM & \xrightarrow[\pi_M]{} & M,
\end{array}$$

where $\alpha(c)(\text{germ}_{c(0)} f) = \frac{d}{dt}|_0 f(c(t))$ and $\beta : TM \to C_0^\infty(\mathbb{R}, M)$ is given by: $\beta((Tu)^{-1}(y,Y))$ is the germ at 0 of $t \mapsto u^{-1}(y+tY)$. So TM is canonically identified with the set of all possible velocity vectors of curves in M.

1.11. Tangent mappings. Let $f : M \to N$ be a smooth mapping between manifolds. Then f induces a linear mapping $T_x f : T_x M \to T_{f(x)}N$ for each $x \in M$ by $(T_x f.X_x)(h) = X_x(h \circ f)$ for $h \in C^\infty_{f(x)}(N,\mathbb{R})$. This mapping is well defined and linear since $f^* : C^\infty_{f(x)}(N,\mathbb{R}) \to C^\infty_x(M,\mathbb{R})$, given by $h \mapsto h \circ f$, is linear and an algebra homomorphism, and $T_x f$ is its adjoint, restricted to the subspace of derivations.

If (U,u) is a chart around x and (V,v) is one around $f(x)$, then

$$\begin{aligned}(T_x f.\tfrac{\partial}{\partial u^i}|_x)(v^j) &= \tfrac{\partial}{\partial u^i}|_x(v^j \circ f) = \tfrac{\partial}{\partial x^i}(v^j \circ f \circ u^{-1})(u(x)),\\ T_x f.\tfrac{\partial}{\partial u^i}|_x &= \textstyle\sum_j (T_x f.\tfrac{\partial}{\partial u^i}|_x)(v^j)\tfrac{\partial}{\partial v^j}|_{f(x)} \qquad \text{by (1.8)}\\ &= \textstyle\sum_j \tfrac{\partial(v^j\circ f\circ u^{-1})}{\partial x^i}(u(x))\tfrac{\partial}{\partial v^j}|_{f(x)}.\end{aligned}$$

So the matrix of $T_x f : T_x M \to T_{f(x)}N$ in the bases $(\frac{\partial}{\partial u^i}|_x)$ and $(\frac{\partial}{\partial v^j}|_{f(x)})$ is just the Jacobi matrix $d(v \circ f \circ u^{-1})(u(x))$ of the mapping $v \circ f \circ u^{-1}$ at $u(x)$, so $T_{f(x)}v \circ T_x f \circ (T_x u)^{-1} = d(v \circ f \circ u^{-1})(u(x))$.

Let us denote by $Tf : TM \to TN$ the total mapping, given by $Tf|T_x M := T_x f$. Then the composition $Tv \circ Tf \circ (Tu)^{-1} : u(U) \times \mathbb{R}^m \to v(V) \times \mathbb{R}^n$ is given by $(y,Y) \mapsto ((v \circ f \circ u^{-1})(y), d(v \circ f \circ u^{-1})(y)Y)$, and thus $Tf : TM \to TN$ is again smooth.

If $f : M \to N$ and $g : N \to P$ are smooth mappings, then we have $T(g \circ f) = Tg \circ Tf$. This is a direct consequence of $(g \circ f)^* = f^* \circ g^*$, and it is the global version of the chain rule. Furthermore we have $T(Id_M) = Id_{TM}$.

If $f \in C^\infty(M)$, then $Tf : TM \to T\mathbb{R} = \mathbb{R} \times \mathbb{R}$. We then define the *differential* of f by $df := pr_2 \circ Tf : TM \to \mathbb{R}$. Let t denote the identity function on $\mathbb{R}$, then $(Tf.X_x)(t) = X_x(t \circ f) = X_x(f)$, so we have $df(X_x) = X_x(f)$.

1.12. Submanifolds. A subset N of a manifold M is called a *submanifold*, if for each $x \in N$ there is a chart (U,u) of M such that $u(U \cap N) = u(U) \cap (\mathbb{R}^k \times 0)$, where $\mathbb{R}^k \times 0 \hookrightarrow \mathbb{R}^k \times \mathbb{R}^{n-k} = \mathbb{R}^n$. Then clearly N is itself a manifold with $(U \cap N, u|(U \cap N))$ as charts, where (U,u) runs through all *submanifold charts* as above.

1.13. Let $f : \mathbb{R}^n \to \mathbb{R}^q$ be smooth. A point $x \in \mathbb{R}^q$ is called a *regular value* of f if the rank of f (more exactly: the rank of its derivative) is q at each point y of $f^{-1}(x)$. In this case, $f^{-1}(x)$ is a submanifold of $\mathbb{R}^n$ of dimension $n-q$ (or empty). This is an immediate consequence of the implicit function theorem, as follows: Let $x = 0 \in \mathbb{R}^q$. Permute the coordinates $(x^1,\dots,x^n)$ on $\mathbb{R}^n$ such that the Jacobi matrix

$$df(y) = \left(\left(\frac{\partial f^i}{\partial x^j}(y)\right)^{1\le i\le q}_{1\le j\le q} \middle| \left(\frac{\partial f^i}{\partial x^j}(y)\right)^{1\le i\le q}_{q+1\le j\le n} \right)$$

has the left hand part invertible. Then $u := (f, \text{pr}_{n-q}) : \mathbb{R}^n \to \mathbb{R}^q \times \mathbb{R}^{n-q}$ has invertible differential at y, so (U, u) is a chart at any $y \in f^{-1}(0)$, and we have $f \circ u^{-1}(z^1, \dots, z^n) = (z^1, \dots, z^q)$, so $u(f^{-1}(0)) = u(U) \cap (0 \times \mathbb{R}^{n-q})$ as required.

Constant rank theorem. [Dieudonné, I, 10.3.1] *Let $f : W \to \mathbb{R}^q$ be a smooth mapping, where W is an open subset of $\mathbb{R}^n$. If the derivative $df(x)$ has constant rank k for each $x \in W$, then for each $a \in W$ there are charts (U, u) of W centered at a and (V, v) of $\mathbb{R}^q$ centered at $f(a)$ such that $v \circ f \circ u^{-1} : u(U) \to v(V)$ has the following form:*

$$(x_1, \dots, x_n) \mapsto (x_1, \dots, x_k, 0, \dots, 0).$$

So $f^{-1}(b)$ is a submanifold of W of dimension $n - k$ for each $b \in f(W)$.

Proof. We will use the inverse function theorem several times. $df(a)$ has rank $k \le n, q$, without loss we may assume that the upper left $k \times k$ submatrix of $df(a)$ is invertible. Moreover, let $a = 0$ and $f(a) = 0$.

We consider $u : W \to \mathbb{R}^n$, $u(x^1, \dots, x^n) := (f^1(x), \dots, f^k(x), x^{k+1}, \dots, x^n)$. Then

$$du = \begin{pmatrix} (\frac{\partial f^i}{\partial z^j})^{1\le i\le k}_{1\le j\le k} & (\frac{\partial f^i}{\partial z^j})^{1\le i\le k}_{k+1\le j\le n} \\ 0 & \text{Id}_{\mathbb{R}^{n-k}} \end{pmatrix}$$

is invertible, so u is a diffeomorphism $U_1 \to U_2$ for suitable open neighborhoods of 0 in $\mathbb{R}^n$. Consider $g = f \circ u^{-1} : U_2 \to \mathbb{R}^q$. Then we have

$$\begin{aligned} g(z_1, \dots, z_n) &= (z_1, \dots, z_k, g_{k+1}(z), \dots, g_q(z)), \\ dg(z) &= \begin{pmatrix} \text{Id}_{\mathbb{R}^k} & 0 \\ * & (\frac{\partial g^i}{\partial z^j})^{k+1\le i\le q}_{k+1\le j\le n} \end{pmatrix}, \\ \text{rank}(dg(z)) &= \text{rank}(d(f \circ u^{-1})(z)) = \text{rank}(df(u^{-1}(z).du^{-1}(z)) \\ &= \text{rank}(df(z)) = k. \end{aligned}$$

Therefore,

$$\begin{aligned} \frac{\partial g^i}{\partial z^j}(z) = 0 \qquad &\text{for } k+1 \le i \le q \text{ and } k+1 \le j \le n; \\ g^i(z^1, \dots, z^n) = g^i(z^1, \dots, z^k, 0, \dots, 0) \qquad &\text{for } k+1 \le i \le q. \end{aligned}$$

Let $v : U_3 \to \mathbb{R}^q$, where $U_3 = \{y \in \mathbb{R}^q : (y^1, \dots, y^k, 0, \dots, 0) \in U_2 \subset \mathbb{R}^n\}$, be given by

$$v\begin{pmatrix} y^1 \\ \vdots \\ y^q \end{pmatrix} = \begin{pmatrix} y^1 \\ \vdots \\ y^k \\ y^{k+1} - g^{k+1}(y^1, \dots, y^k, 0, \dots, 0) \\ \vdots \\ y^q - g^q(y^1, \dots, y^k, 0, \dots, 0) \end{pmatrix} = \begin{pmatrix} y^1 \\ \vdots \\ y^k \\ y^{k+1} - g^{k+1}(\bar{y}) \\ \vdots \\ y^q - g^q(\bar{y}) \end{pmatrix},$$

where $\bar{y} = (y^1, \dots, y^q, 0, \dots, 0) \in \mathbb{R}^n$ if $q < n$, and $\bar{y} = (y^1, \dots, y^n)$ if $q \geq n$. We have $v(0) = 0$, and

$$dv = \begin{pmatrix} \mathrm{Id}_{\mathbb{R}^k} & 0 \\ * & \mathrm{Id}_{\mathbb{R}^{q-k}} \end{pmatrix}$$

is invertible, thus $v : V \to \mathbb{R}^q$ is a chart for a suitable neighborhood of 0. Now let $U := f^{-1}(V) \cup U_1$. Then $v \circ f \circ u^{-1} = v \circ g : \mathbb{R}^n \supseteq u(U) \to v(V) \subseteq \mathbb{R}^q$ looks as follows:

$$\begin{pmatrix} x^1 \\ \vdots \\ x^n \end{pmatrix} \xrightarrow{g} \begin{pmatrix} x^1 \\ \vdots \\ x^k \\ g^{k+1}(x) \\ \vdots \\ g^q(x) \end{pmatrix} \xrightarrow{v} \begin{pmatrix} x^1 \\ \vdots \\ x^k \\ g^{k+1}(x) - g^{k+1}(x) \\ \vdots \\ g^q(x) - g^q(x) \end{pmatrix} = \begin{pmatrix} x^1 \\ \vdots \\ x^k \\ 0 \\ \vdots \\ 0 \end{pmatrix} \qquad \square$$

Corollary. *Let $f : M \to N$ be C^∞ with $T_x f$ of constant rank k for all $x \in M$. Then for each $b \in f(M)$ the set $f^{-1}(b) \subset M$ is a submanifold of M of dimension* $\dim M - k$. $\square$

1.14. Products. Let M and N be smooth manifolds described by smooth atlases $(U_\alpha, u_\alpha)_{\alpha \in A}$ and $(V_\beta, v_\beta)_{\beta \in B}$, respectively. Then the family $(U_\alpha \times V_\beta, u_\alpha \times v_\beta : U_\alpha \times V_\beta \to \mathbb{R}^m \times \mathbb{R}^n)_{(\alpha,\beta) \in A \times B}$ is a smooth atlas for the cartesian product $M \times N$. Clearly the projections

$$M \xleftarrow{pr_1} M \times N \xrightarrow{pr_2} N$$

are also smooth. The *product* $(M \times N, pr_1, pr_2)$ has the following universal property:

For any smooth manifold P and smooth mappings $f : P \to M$ and $g : P \to N$ the mapping $(f, g) : P \to M \times N$, $(f, g)(x) = (f(x), g(x))$, is the unique smooth mapping with $pr_1 \circ (f, g) = f$, $pr_2 \circ (f, g) = g$.

From the construction of the tangent bundle in (1.9) it is immediately clear that

$$TM \xleftarrow{T(pr_1)} T(M \times N) \xrightarrow{T(pr_2)} TN$$

is again a product, so that $T(M \times N) = TM \times TN$ in a canonical way.

Clearly we can form products of finitely many manifolds.

1.15. Theorem. *Let M be a connected manifold and suppose that $f : M \to M$ is smooth with $f \circ f = f$. Then the image $f(M)$ of f is a submanifold of M.*

This result can also be expressed as: 'smooth retracts' of manifolds are manifolds. If we do not suppose that M is connected, then $f(M)$ will not be a pure manifold in general, it will have different dimension in different connected components.

Proof. We claim that there is an open neighborhood U of $f(M)$ in M such that the rank of $T_y f$ is constant for $y \in U$. Then by theorem (1.13) the result follows.

For $x \in f(M)$ we have $T_x f \circ T_x f = T_x f$, thus $\operatorname{im} T_x f = \ker(Id - T_x f)$ and $\operatorname{rank} T_x f + \operatorname{rank}(Id - T_x f) = \dim M$. Since $\operatorname{rank} T_x f$ and $\operatorname{rank}(Id - T_x f)$ cannot fall locally, $\operatorname{rank} T_x f$ is locally constant for $x \in f(M)$, and since $f(M)$ is connected, $\operatorname{rank} T_x f = r$ for all $x \in f(M)$.

But then for each $x \in f(M)$ there is an open neighborhood U_x in M with $\operatorname{rank} T_y f \geq r$ for all $y \in U_x$. On the other hand $\operatorname{rank} T_y f = \operatorname{rank} T_y(f \circ f) = \operatorname{rank} T_{f(y)} f \circ T_y f \leq \operatorname{rank} T_{f(y)} f = r$ since $f(y) \in f(M)$. So the neighborhood we need is given by $U = \bigcup_{x \in f(M)} U_x$. $\square$

1.16. Corollary. *1. The (separable) connected smooth manifolds are exactly the smooth retracts of connected open subsets of $\mathbb{R}^n$'s.*

2. $f : M \to N$ is an embedding of a submanifold if and only if there is an open neighborhood U of $f(M)$ in N and a smooth mapping $r : U \to M$ with $r \circ f = Id_M$.

Proof. Any manifold M may be embedded into some $\mathbb{R}^n$, see (1.17) below. Then there exists a tubular neighborhood of M in R^n (see later or [Hirsch, 1976, pp. 109–118]), and M is clearly a retract of such a tubular neighborhood. The converse follows from (1.15).

For the second assertion repeat the argument for N instead of $\mathbb{R}^n$. $\square$

1.16a. Sets of Lebesque measure 0 in manifolds. An *m-cube of width $w > 0$ in $\mathbb{R}^m$* is a set of the form $C = [x_1, x_1 + w] \times \ldots \times [x_m, x_m + w]$. The measure $\mu(C)$ is then $\mu(C) = w^n$. A subset $S \subset \mathbb{R}^m$ is called a *set of (Lebesque) measure 0* if for each $\varepsilon > 0$ these are at most countably many m-cubes C_i with $S \subset \bigcup_{i=0}^\infty C_i$ and $\sum_{i=0}^\infty \mu(C_i) < \varepsilon$. Obviously, a countable union of sets of Lebesque measure 0 is again of measure 0.

Lemma. *Let $U \subset \mathbb{R}^m$ be open and let $f : U \to \mathbb{R}^m$ be C^1. If $S \subset U$ is of measure 0 then also $f(S) \subset \mathbb{R}^m$ is of measure 0.*

Proof. Every point of S belongs to an open ball $B \subset U$ such that the operator norm $\|df(x)\| \leq K_B$ for all $x \in B$. Then $|f(x) - f(y)| \leq K_B|x - y|$ for all $x, y \in B$. So if $C \subset B$ is an m-cube of width w then $f(C)$ is contained in an m-cube C' of width $\sqrt{m} K_B w$ and measure $\mu(C') \leq m^{m/2} K_B^m \mu(C)$. Now let $S = \bigcup_{j=1}^\infty S_j$ where each S_j is a compact subset of a ball B_j as above. It suffices to show that each $f(S_j)$ is of measure 0.

For each $\varepsilon > 0$ there are m-cubes C_i in B_j with $S_j \subset \bigcup_i C_i$ and $\sum_i \mu(C_i) < \varepsilon$. As we saw above then $f(X_j) \subset \bigcup_i C'_i$ with $\sum_i \mu(C'_i) < m^{m/2} K_{B_j}^m \varepsilon$. $\square$

Let M be a smooth (separable) manifold. A subset $S \subset M$ is is called a *set of (Lebesque) measure 0* if for each chart (U, u) of M the set $u(S \cap U)$ is of measure 0 in $\mathbb{R}^m$. By the lemma it suffices that there is some atlas whose charts have this property. Obviously, a countable union of sets of measure 0 in a manifold is again of measure 0.

A m-cube is not of measure 0. Thus a subset of $\mathbb{R}^m$ of measure 0 does not contain any m-cube; hence its interior is empty. Thus a closed set of measure 0 in a manifold is nowhere dense. More generally, let S be a subset of a manifold which is of measure 0 and σ-compact, i.e., a countable union of compact subsets. Then each of the latter is nowhere dense, so S is nowhere dense by the Baire category theorem. The complement of S is *residual*, i.e., it contains the intersection of a countable family of open dense subsets. The Baire theorem says that a residual subset of a complete metric space is dense.

10.12. Regular values. Let $f : M \to N$ be a smooth mapping between manifolds.

(1) $x \in M$ is called a *singular point* of f if $T_x f$ is not surjective, and is called a *regular point* of f if $T_x f$ is surjective.
(2) $y \in N$ is called a *regular value* of f if $T_x f$ is surjective for all $x \in f^{-1}(y)$. If not y is called a *singular value*. Note that any $y \in N \setminus f(M)$ is a regular value.

Theorem. [Morse, 1939], [Sard, 1942] *The set of all singular values of a C^k mapping $f : M \to N$ is of Lebesgue measure 0 in N, if $k > \max\{0, \dim(M) - \dim(N)\}$.*

So any smooth mapping has regular values.

Proof. We proof this only for smooth mappings. It is sufficient to prove this locally. Thus we consider a smooth mapping $f : U \to \mathbb{R}^n$ where $U \subset \mathbb{R}^m$ is open. If $n > m$ then the result follows from lemma (1.16a) above (consider the set $U \times 0 \subset \mathbb{R}^m \times \mathbb{R}^{n-m}$ of measure 0). Thus let $m \ge n$.

Let $\Sigma(f) \subset U$ denote the set of singular points of f. Let $f = (f^1, \dots, f^n)$, and let $\Sigma(f) = \Sigma_1 \cup \Sigma_2 \cup \Sigma_3$ where:

Σ_1 is the set of singular points x such that $Pf(x) = 0$ for all linear differential operators P of order $\le \frac{m}{n}$.
Σ_2 is the set of singular points x such that $Pf(x) \ne 0$ for some differential operator P of order ≥ 2.
Σ_3 is the set of singular points x such that $\frac{\partial f^i}{x^j}(x) = 0$ for some i, j.

We first show that $f(\Sigma_1)$ has measure 0. Let $\nu = \lceil \frac{m}{n} + 1 \rceil$ be the smallest integer $> m/n$. Then each point of Σ_1 has an open neigborhood $W \subset U$ such that $|f(x) - f(y) \le K|x - y|^\nu$ for all $x \in \Sigma_1 \cap W$ and $y \in W$ and for some $K > 0$, by Taylor expansion. We take W to be a cube, of width w. It suffices to prove that $f(\Sigma_1 \cap W)$ has measure 0. We divide W in p^m cubes of width $\frac{w}{p}$; those which meet Si_1 will be denoted by $C_1, \dots, C_q$ for $q \le p^m$. Each C_k is contained in a ball of radius $\frac{w}{p}\sqrt{m}$ centered at a point of $\Sigma_1 \cap W$. The set $f(C_k)$ is contained in a cube $C'_k \subset \mathbb{R}^n$ of width $2K(\frac{w}{p}\sqrt{m})^\nu$. Then

$$\sum_k \mu^n(C'_k) \le p^m (2K)^n (\frac{w}{p}\sqrt{m})^{\nu n} = p^{m-\nu n}(2K)^n w^{\nu n} \to 0 \text{ for } p \to \infty,$$

since $m - \nu n < 0$.

Note that $\Sigma(f) = \Sigma_1$ if $n = m = 1$. So the theorem is proved in this case. We proceed by induction on m. So let $m > 1$ and assume that the theorem is true for each smooth map $P \to Q$ where $\dim(P) < m$.

We prove that $f(\Sigma_2 \setminus \Sigma_3)$ has measure 0. For each $x \in \Sigma_2 \setminus \Sigma_3$ there is a linear differential operator P such that $Pf(x) = 0$ and $\frac{\partial f^i}{\partial x^j}(x) \neq 0$ for some i, j. Let W be the set of all such points, for fixed P, i, j. It suffices to show that $f(W)$ has measure 0. By assumption, $0 \in \mathbb{R}$ is a regular value for the function $Pf^i : W \to \mathbb{R}$. Therefore W is a smooth submanifold of dimension $m-1$ in $\mathbb{R}^m$. Clearly, $\Sigma(f) \cap W$ is contained in the set of all singular points of $f|W : W \to \mathbb{R}^n$, and by induction we get that $f((\Sigma_2 \setminus \Sigma_3) \cap W) \subset f(\Sigma(f) \cap W) \subset f(\Sigma(f|W))$ has measure 0.

It remains to prove that $f(\Sigma_3)$ has measure 0. Every point of Σ_3 has an open neighborhood $W \subset U$ on which $\frac{\partial f^i}{\partial x^j} \neq 0$ for some i, j. By shrinking W if necessary and applying diffeomorphisms we may assume that

$$\mathbb{R}^{m-1} \times \mathbb{R} \supseteq W_1 \times W_2 = W \xrightarrow{f} \mathbb{R}^{n-1} \times \mathbb{R}, \qquad (y,t) \mapsto (g(y,t),t).$$

Clearly, (y,t) is a critical point for f iff y is a critical point for $g(\quad,t)$. Thus $\Sigma(f) \cap W = \bigcup_{t \in W_2} (\Sigma(g(\quad,t)) \times \{t\})$. Since $\dim(W_1) = m-1$, by induction we get that $\mu^{n-1}(g(\Sigma(g(\quad,t),t))) = 0$, where μ^{n-1} is the Lebesque measure in $\mathbb{R}^{n-1}$. By Fubini's theorem we get

$$\mu^n(\bigcup_{t \in W_2} (\Sigma(g(\quad,t)) \times \{t\})) = \int_{W_2} \mu^{n-1}(g(\Sigma(g(\quad,t),t)))\,dt = \int_{W_2} 0\,dt = 0. \quad \square$$

1.17. Embeddings into $\mathbb{R}^n$'s. Let M be a smooth manifold of dimension m. Then M can be embedded into $\mathbb{R}^n$, if

(1) $n = 2m+1$ (this is due to [Whitney, 1944], see also [Hirsch, 1976, p 55] or [Bröcker-Jänich, 1973, p 73]).
(2) $n = 2m$ (see [Whitney, 1944]).
(3) Conjecture (still unproved): The minimal n is $n = 2m - \alpha(m) + 1$, where $\alpha(m)$ is the number of 1's in the dyadic expansion of m.

There exists an immersion (see section 2) $M \to \mathbb{R}^n$, if

(4) $n = 2m$ (see [Hirsch, 1976]),
(5) $n = 2m - 1$ (see [Whitney, 1944]).
(6) Conjecture: The minimal n is $n = 2m - \alpha(m)$. [Cohen, 1982]) claims to have proven this, but there are doubts.

Examples and Exercises

1.18. Discuss the following submanifolds of $\mathbb{R}^n$, in particular make drawings of them:

The unit sphere $S^{n-1} = \{x \in \mathbb{R}^n :< x, x >= 1\} \subset \mathbb{R}^n$.

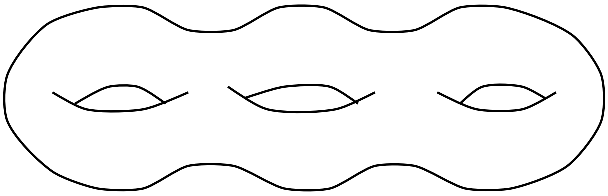
The *ellipsoid* $\{x \in \mathbb{R}^n : f(x) := \sum_{i=1}^n \frac{x_i^2}{a_i^2} = 1\}$, $a_i \neq 0$ with principal axis $a_1, \dots, a_n$.

The *hyperboloid* $\{x \in \mathbb{R}^n : f(x) := \sum_{i=1}^n \varepsilon_i \frac{x_i^2}{a_i^2} = 1\}$, $\varepsilon_i = \pm 1$, $a_i \neq 0$ with principal axis a_i and index $= \sum \varepsilon_i$.

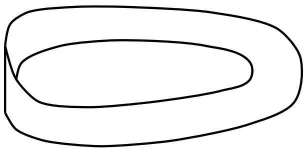
The *saddle* $\{x \in \mathbb{R}^3 : x_3 = x_1 x_2\}$.

The *torus*: the rotation surface generated by rotation of $(y-R)^2 + z^2 = r^2$, $0 < r < R$ with center the z–axis, i.e. $\{(x,y,z) : (\sqrt{x^2+y^2} - R)^2 + z^2 = r^2\}$.

1.19. A compact surface of genus g. Let $f(x) := x(x-1)^2(x-2)^2 \dots (x-(g-1))^2(x-g)$. For small $r > 0$ the set $\{(x,y,z) : (y^2 + f(x))^2 + z^2 = r^2\}$ describes a surface of genus g (topologically a sphere with g handles) in $\mathbb{R}^3$. Visualize this.



1.20. The Moebius strip.



It is not the set of zeros of a regular function on an open neighborhood of $\mathbb{R}^n$. Why not? But it may be represented by the following parametrization:

$$f(r,\varphi) := \begin{pmatrix} \cos\varphi(R + r\cos(\varphi/2)) \\ \sin\varphi(R + r\cos(\varphi/2)) \\ r\sin(\varphi/2) \end{pmatrix}, \qquad (r,\varphi) \in (-1,1) \times [0, 2\pi),$$

where R is quite big.

1.21. Describe an atlas for the real projective plane which consists of three charts (homogeneous coordinates) and compute the chart changings.

Then describe an atlas for the n-dimensional real projective space $P^n(\mathbb{R})$ and compute the chart changes.

1.22. Let $f : L(\mathbb{R}^n, \mathbb{R}^n) \to L(\mathbb{R}^n, \mathbb{R}^n)$ be given by $f(A) := A^t A$. Where is f of constant rank? What is $f^{-1}(\mathrm{Id})$?

1.23. Let $f : L(\mathbb{R}^n, \mathbb{R}^m) \to L(\mathbb{R}^n, \mathbb{R}^n)$, $n < m$ be given by $f(A) := A^t A$. Where is f of constant rank? What is $f^{-1}(Id_{\mathbb{R}^n})$?

1.24. Let S be a symmetric matrix, i.e., $S(x,y) := x^t S y$ is a symmetric bilinear form on $\mathbb{R}^n$. Let $f : L(\mathbb{R}^n, \mathbb{R}^n) \to L(\mathbb{R}^n, \mathbb{R}^n)$ be given by $f(A) := A^t S A$. Where is f of constant rank? What is $f^{-1}(S)$?

1.25. Describe $TS^2 \subset \mathbb{R}^6$.

2. Submersions and Immersions

2.1. Definition. A mapping $f : M \to N$ between manifolds is called a *submersion* at $x \in M$, if the rank of $T_x f : T_x M \to T_{f(x)} N$ equals $\dim N$. Since the rank cannot fall locally (the determinant of a submatrix of the Jacobi matrix is not 0), f is then a submersion in a whole neighborhood of x. The mapping f is said to be a *submersion*, if it is a submersion at each $x \in M$.

2.2. Lemma. *If $f : M \to N$ is a submersion at $x \in M$, then for any chart (V, v) centered at $f(x)$ on N there is chart (U, u) centered at x on M such that $v \circ f \circ u^{-1}$ looks as follows:*

$$(y^1, \dots, y^n, y^{n+1}, \dots, y^m) \mapsto (y^1, \dots, y^n)$$

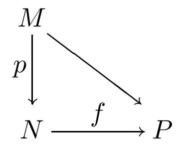
Proof. Use the inverse function theorem once: Apply the argument from the beginning of (1.13) to $v \circ f \circ u_1^{-1}$ for some chart (U_1, u_1) centered at x. $\square$

2.3. Corollary. *Any submersion $f : M \to N$ is open: for each open $U \subset M$ the set $f(U)$ is open in N.* $\square$

2.4. Definition. A triple (M, p, N), where $p : M \to N$ is a surjective submersion, is called a *fibered manifold*. M is called the *total space*, N is called the *base*.

A fibered manifold admits local sections: For each $x \in M$ there is an open neighborhood U of $p(x)$ in N and a smooth mapping $s : U \to M$ with $p \circ s = Id_U$ and $s(p(x)) = x$.

The existence of local sections in turn implies the following universal property:



If (M, p, N) is a fibered manifold and $f : N \to P$ is a mapping into some further manifold, such that $f \circ p : M \to P$ is smooth, then f is smooth.

2.5. Definition. A smooth mapping $f : M \to N$ is called an *immersion at* $x \in M$ if the rank of $T_x f : T_x M \to T_{f(x)} N$ equals $\dim M$. Since the rank is maximal at x and cannot fall locally, f is an immersion on a whole neighborhood of x. f is called an immersion if it is so at every $x \in M$.

2.6. Lemma. *If $f : M \to N$ is an immersion, then for any chart (U, u) centered at $x \in M$ there is a chart (V, v) centered at $f(x)$ on N such that $v \circ f \circ u^{-1}$ has the form:*

$$(y^1, \dots, y^m) \mapsto (y^1, \dots, y^m, 0, \dots, 0)$$

Proof. Use the inverse function theorem. $\square$

2.7. Corollary. *If $f : M \to N$ is an immersion, then for any $x \in M$ there is an open neighborhood U of $x \in M$ such that $f(U)$ is a submanifold of N and $f|U : U \to f(U)$ is a diffeomorphism.* $\square$

2.8. Corollary. *If an injective immersion $i : M \to N$ is a homeomorphism onto its image, then $i(M)$ is a submanifold of N.*

Proof. Use (2.7). $\square$

2.9. Definition. If $i : M \to N$ is an injective immersion, then (M, i) is called an *immersed submanifold* of N.

A submanifold is an immersed submanifold, but the converse is wrong in general. The structure of an immersed submanifold (M, i) is in general not determined by the subset $i(M) \subset N$. All this is illustrated by the following example. Consider the curve $\gamma(t) = (\sin^3 t, \sin t. \cos t)$ in $\mathbb{R}^2$. Then $((-\pi, \pi), \gamma|(-\pi, \pi))$ and $((0, 2\pi), \gamma|(0, 2\pi))$ are two different immersed submanifolds, but the image of the embedding is in both cases just the figure eight.

2.10. Let M be a submanifold of N. Then the embedding $i : M \to N$ is an injective immersion with the following property:

(1) *For any manifold Z a mapping $f : Z \to M$ is smooth if and only if $i \circ f : Z \to N$ is smooth.*

The example in (2.9) shows that there are injective immersions without property (1).

We want to determine all injective immersions $i : M \to N$ with property (1). To require that i is a homeomorphism onto its image is too strong as (2.11) below shows. To look for all smooth mappings $i : M \to N$ with property (2.10.1) (initial mappings in categorical terms) is too difficult as remark (2.12) below shows.

2.11. Example. We consider the 2-dimensional torus $\mathbb{T}^2 = \mathbb{R}^2/\mathbb{Z}^2$. Then the quotient mapping $\pi : \mathbb{R}^2 \to \mathbb{T}^2$ is a covering map, so locally a diffeomorphism. Let us also consider the mapping $f : \mathbb{R} \to \mathbb{R}^2$, $f(t) = (t, \alpha.t)$, where α is irrational. Then $\pi \circ f : \mathbb{R} \to \mathbb{T}^2$ is an injective immersion with dense image, and it is obviously not a homeomorphism onto its image. But $\pi \circ f$ has property (2.10.1), which follows from the fact that π is a covering map.

2.12. Remark. If $f : \mathbb{R} \to \mathbb{R}$ is a function such that f^p and f^q are smooth for some p, q which are relatively prime in $\mathbb{N}$, then f itself turns out to be smooth, see [Joris, 1982]. So the mapping $i : t \mapsto \binom{t^p}{t^q}$, $\mathbb{R} \to \mathbb{R}^2$, has property (2.10.1), but i is not an immersion at 0.

In [Joris, Preissmann, 1987] all germs of mappings at 0 with property (2.10.1) are characterized as follows: Let $g : (\mathbb{R}, 0) \to (\mathbb{R}^n, 0)$ be a germ of a C^∞-curve, $g(t) = (g_1(t), ..., g_n(t))$. Without loss we may suppose that g is not infinitely flat at 0, so that $g_1(t) = t^r$ for $r \in \mathbb{N}$ after a suitable change of coordinates. Then g *has property* (2.10.1) *near 0 if and only if the Taylor series of g is not contained in any $\mathbb{R}^n[[t^s]]$ for $s \geq 2$.*

2.13. Definition. For an arbitrary subset A of a manifold N and $x_0 \in A$ let $C_{x_0}(A)$ denote the set of all $x \in A$ which can be joined to x_0 by a smooth curve in M lying in A.

A subset M in a manifold N is called *initial submanifold* of dimension m, if the following property is true:

(1) *For each $x \in M$ there exists a chart (U, u) centered at x on N such that* $u(C_x(U \cap M)) = u(U) \cap (\mathbb{R}^m \times 0)$.

The following three lemmas explain the name initial submanifold.

2.14. Lemma. *Let $f : M \to N$ be an injective immersion between manifolds with the universal property* (2.10.1). *Then $f(M)$ is an initial submanifold of N.*

Proof. Let $x \in M$. By (2.6) we may choose a chart (V, v) centered at $f(x)$ on N and another chart (W, w) centered at x on M such that $(v \circ f \circ w^{-1})(y^1, \dots, y^m) = (y^1, \dots, y^m, 0, \dots, 0)$. Let $r > 0$ be so small that $\{y \in \mathbb{R}^m : |y| < 2r\} \subset w(W)$ and $\{z \in \mathbb{R}^n : |z| < 2r\} \subset v(V)$. Put

$$\begin{aligned} U &:= v^{-1}(\{z \in \mathbb{R}^n : |z| < r\}) \subset N, \\ W_1 &:= w^{-1}(\{y \in \mathbb{R}^m : |y| < r\}) \subset M. \end{aligned}$$

We claim that $(U, u = v|U)$ satisfies the condition of 2.14.1.

$$\begin{aligned} u^{-1}(u(U) \cap (\mathbb{R}^m \times 0)) &= u^{-1}(\{(y^1, \dots, y^m, 0 \dots, 0) : |y| < r\}) = \\ &= f \circ w^{-1} \circ (u \circ f \circ w^{-1})^{-1}(\{(y^1, \dots, y^m, 0 \dots, 0) : |y| < r\}) = \\ &= f \circ w^{-1}(\{y \in \mathbb{R}^m : |y| < r\}) = f(W_1) \subseteq C_{f(x)}(U \cap f(M)), \end{aligned}$$

since $f(W_1) \subseteq U \cap f(M)$ and $f(W_1)$ is C^∞-contractible.

Now let conversely $z \in C_{f(x)}(U \cap f(M))$. Then by definition there is a smooth curve $c : [0, 1] \to N$ with $c(0) = f(x)$, $c(1) = z$, and $c([0, 1]) \subseteq U \cap f(M)$. By property 2.9.1 the unique curve $\bar{c} : [0, 1] \to M$ with $f \circ \bar{c} = c$, is smooth.

We claim that $\bar{c}([0, 1]) \subseteq W_1$. If not then there is some $t \in [0, 1]$ with $\bar{c}(t) \in w^{-1}(\{y \in \mathbb{R}^m : r \leq |y| < 2r\})$ since $\bar{c}$ is smooth and thus continuous. But then we have

$$\begin{aligned} (v \circ f)(\bar{c}(t)) &\in (v \circ f \circ w^{-1})(\{y \in \mathbb{R}^m : r \leq |y| < 2r\}) = \\ &= \{(y, 0) \in \mathbb{R}^m \times 0 : r \leq |y| < 2r\} \subseteq \{z \in \mathbb{R}^n : r \leq |z| < 2r\}. \end{aligned}$$

This means $(v \circ f \circ \bar{c})(t) = (v \circ c)(t) \in \{z \in \mathbb{R}^n : r \leq |z| < 2r\}$, so $c(t) \notin U$, a contradiction.

So $\bar{c}([0, 1]) \subseteq W_1$, thus $\bar{c}(1) = f^{-1}(z) \in W_1$ and $z \in f(W_1)$. Consequently we have $C_{f(x)}(U \cap f(M)) = f(W_1)$ and finally $f(W_1) = u^{-1}(u(U) \cap (\mathbb{R}^m \times 0))$ by the first part of the proof. □

2.15. Lemma. *Let M be an initial submanifold of a manifold N. Then there is a unique C^∞-manifold structure on M such that the injection $i : M \to N$ is an injective immersion with property* (2.10.1)*:*

(1) *For any manifold Z a mapping $f : Z \to M$ is smooth if and only if $i \circ f : Z \to N$ is smooth.*

The connected components of M are separable (but there may be uncountably many of them).

Proof. We use the sets $C_x(U_x \cap M)$ as charts for M, where $x \in M$ and (U_x, u_x) is a chart for N centered at x with the property required in (2.13.1). Then the chart changings are smooth since they are just restrictions of the chart changings on N. But the sets $C_x(U_x \cap M)$ are not open in the induced topology on M in general. So the identification topology with respect to the charts $(C_x(U_x \cap M), u_x)_{x\in M}$ yields a topology on M which is finer than the induced topology, so it is Hausdorff. Clearly $i : M \to N$ is then an injective immersion. Uniqueness of the smooth structure follows from the universal property (1) which we prove now: For $z \in Z$ we choose a chart (U, u) on N, centered at $f(z)$, such that $u(C_{f(z)}(U \cap M)) = u(U) \cap (\mathbb{R}^m \times 0)$. Then $f^{-1}(U)$ is open in Z and contains a chart (V, v) centered at z on Z with $v(V)$ a ball. Then $f(V)$ is C^∞-contractible in $U \cap M$, so $f(V) \subseteq C_{f(z)}(U \cap M)$, and $(u|C_{f(z)}(U \cap M)) \circ f \circ v^{-1} = u \circ f \circ v^{-1}$ is smooth.

Finally note that N admits a Riemannian metric (see (13.1)) which can be induced on M, so each connected component of M is separable, by (1.1.4). □

2.16. Transversal mappings. Let M_1, M_2, and N be manifolds and let $f_i : M_i \to N$ be smooth mappings for $i = 1, 2$. We say that f_1 and f_2 are *transversal* at $y \in N$, if

$$\operatorname{im} T_{x_1} f_1 + \operatorname{im} T_{x_2} f_2 = T_y N \quad \text{whenever} \quad f_1(x_1) = f_2(x_2) = y.$$

Note that they are transversal at any y which is not in $f_1(M_1)$ or not in $f_2(M_2)$. The mappings f_1 and f_2 are simply said to be *transversal*, if they are transversal at every $y \in N$.

If P is an initial submanifold of N with embedding $i : P \to N$, then $f : M \to N$ is said to be transversal to P, if i and f are transversal.

Lemma. *In this case $f^{-1}(P)$ is an initial submanifold of M with the same codimension in M as P has in N, or the empty set. If P is a submanifold, then also $f^{-1}(P)$ is a submanifold.*

Proof. Let $x \in f^{-1}(P)$ and let (U, u) be an initial submanifold chart for P centered at $f(x)$ on N, i.e. $u(C_{f(x)}(U \cap P)) = u(U) \cap (\mathbb{R}^p \times 0)$. Then the mapping

$$M \supseteq f^{-1}(U) \xrightarrow{f} U \xrightarrow{u} u(U) \subseteq \mathbb{R}^p \times \mathbb{R}^{n-p} \xrightarrow{pr_2} \mathbb{R}^{n-p}$$

is a submersion at x since f is transversal to P. So by lemma (2.2) there is a chart (V, v) on M centered at x such that we have

$$(pr_2 \circ u \circ f \circ v^{-1})(y^1, \dots, y^{n-p}, \dots, y^m) = (y^1, \dots, y^{n-p}).$$

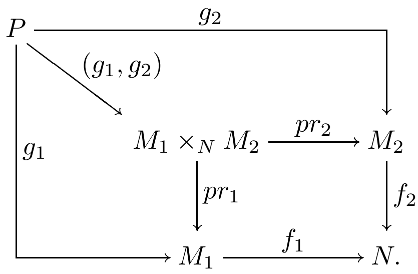
But then $z \in C_x(f^{-1}(P) \cap V)$ if and only if $v(z) \in v(V) \cap (0 \times \mathbb{R}^{m-n+p})$, so $v(C_x(f^{-1}(P) \cap V)) = v(V) \cap (0 \times \mathbb{R}^{m-n+p})$. □

2.17. Corollary. *If $f_1 : M_1 \to N$ and $f_2 : M_2 \to N$ are smooth and transversal, then the topological pullback*

$$M_1 \underset{(f_1,N,f_2)}{\times} M_2 = M_1 \times_N M_2 := \{(x_1, x_2) \in M_1 \times M_2 : f_1(x_1) = f_2(x_2)\}$$

is a submanifold of $M_1 \times M_2$, and it has the following universal property:

> *For any smooth mappings $g_1 : P \to M_1$ and $g_2 : P \to M_2$ with $f_1 \circ g_1 = f_2 \circ g_2$ there is a unique smooth mapping $(g_1, g_2) : P \to M_1 \times_N M_2$ with $pr_1 \circ (g_1, g_2) = g_1$ and $pr_2 \circ (g_1, g_2) = g_2$.*



This is also called the pullback property in the category $\mathcal{M}f$ of smooth manifolds and smooth mappings. So one may say, that transversal pullbacks exist in the category $\mathcal{M}f$. But there also exist pullbacks which are not transversal.

Proof. $M_1 \times_N M_2 = (f_1 \times f_2)^{-1}(\Delta)$, where $f_1 \times f_2 : M_1 \times M_2 \to N \times N$ and where Δ is the diagonal of $N \times N$, and $f_1 \times f_2$ is transversal to Δ if and only if f_1 and f_2 are transversal. □

C. Covering spaces and fundamental groups

In this section we present the rudiments of covering space theory and fundamental groups which is most relevant for the following. By a *space* we shall mean a Hausdorff topological space in this section, and all mappings will be continuous. The reader may well visualize only manifolds and smooth mapping, if he wishes. We will comment on the changes for for smooth mappings.

C.1. Covering spaces. Consider a mapping $p : X \to Y$ between path-connected spaces. We say that X is a *covering space* of Y, that p is a *covering mapping*, or simply a *covering*, if the following holds:

> p is surjective and for each $y \in Y$ there exist an open neighborhood U of y in Y such that $p^{-1}(U)$ is a disjoint union $p^{-1}(U) = \bigsqcup_i U_i$ of open sets U_i in X such that $p|U_i : U_i \to U$ is a homeomorphism for each i.

Note that then $p^{-1}(U)$ is homeomorphic to $U \times S$ for a discrete space S such that p corresponds to $\mathrm{pr}_1 : U \times S \to U$. Such a neighborhood U is called a *trivializing set for the covering* and each U_i is called a *branch* over U.

Note that each open subset of U is again trivializing.

C.2. Lemma. *Let $p : X \to M$ be a covering where M is a smooth manifold. Then there exists a unique smooth manifold structure on X such that p becomes a surjective local diffeomorphism.*

Proof. We choose a smooth atlas $(U_\alpha, u_\alpha)_{\alpha\in A}$ for the manifold M where the charts U_α are so small that they are all trivializing for the convering p. Then by (C.1) we have disjoint unions $p^{-1}(U_\alpha) = \bigsqcup_i U_\alpha^i$ where each $p : U_\alpha^i \to U_\alpha$ is a homeomorphism. Consider the charts $(U_\alpha^i, u_\alpha^i = u_\alpha \circ p|U_\alpha^i)$ of X. The chart changes look as follows: If $U_\alpha^i \cap U_\beta^j \neq \emptyset$ then $U_\alpha \cap U_\beta \neq \emptyset$ and

$$u_\alpha \circ (p|U_\alpha^i) \circ (p|U_\beta^j)^{-1} \circ u_\beta^{-1} = u_\alpha \circ u_\beta^{-1} : u_\beta(U_\alpha \cap U_\beta) \to u_\alpha(U_\alpha \cap U_\beta).$$

These are smooth. We shall see later that X is then also separable. □

C.3 Homotopy. Let X, Y be spaces and $f, g : X \to Y$.

A *homotopy* between and f and g is a mapping $h : [0,1] \times X \to Y$ with $h(0, \quad) = f$ and $h(1, \quad) = g$. Then f and g are called are called *homotopic*, in symbols $f \sim g$. This is an equivalence relation. If we consider smooth homotopies we may reparameterize each homotopy in such a way that that is is constantly f or g near the ends $\{0\} \times X$ or $\{1\} \times X$; then we can piece it together smoothly to see that we have again an equivalence relation.

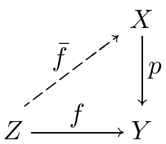
Suppose that $f|A = g|A$ for a subset $A \subset X$. We say that f and g are *homotopic relative* A if there exists a homotopy $h : [0,1]\times X \to Y$ between them with $h(t,x) = f(x) = g(x)$ for all $x \in A$.

Two spaces X and Y are called *homotopy equivalent* if there exists mappings $f : X \to Y$ and $g : Y \to X$ such that $g \circ f \sim \mathrm{Id}_X$ and $f \circ g \sim \mathrm{Id}_Y$.

A space X is called *contractible* if it is homotopy equivalent to a point.

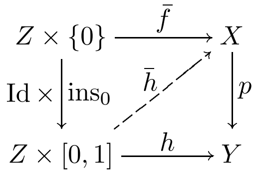
C.4. Lifting. Let $p : X \to Y$ be a covering.

(1)



Let Z be a path connected space and $f : Z \to Y$. A mapping $\tilde f : Z \to X$ is called a *lift* of f if $p \circ \bar f = f$.

A lift, if it exists, is uniquely determined by its value $\bar f(z_0)$ at a single $z_0 \in Z$: Suppose that $\bar f$ and $\tilde f$ are two lifts with $\bar f(z_0) = \tilde f(z_0)$. Then the set $A = \{z \in Z : \bar f(z) = \tilde f(z)\}$ is nonempty, closed, and also open since p is a local homeomorphism. Thus $A = Z$ since Z is connected.

(2) 

Suppose that $h : [0,1] \times Z \to Y$ is a homotopy between $f, g : Z \to Y$ and that f admits a lift $\bar f$. Then there exists a unique lift $\bar h$ of the homotopy h.

Namely, for each $z \in Z$ there exists an open neighborhood V_z of z in Z and $0 = t_0^z < t_1^z < \cdots < t_{k_z}^z = 1$ such that $h([t_i^z, t_{i+1}^z] \times V_z) \subset U_{z,i}$ for an open trivializing set $U_{z,i} \subset Y$. Let $U_{z,0}^{j_0}$ be the branch over $U_{z,i}$ with $\bar f(z) \in U_{z,0}^{j_0}$. Then $\bar h|([0,t_1^z] \times V_z) = (p|U_{z,0}^{j_0})^{-1} \circ h|([0,t_1^z] \times V_z)$ is a local lift. Let then $U_{z,1}^{j_1}$ be the branch over $U_{z,1}$ with $\bar h(t_1^z, z) \in U_{z,1}^{j_1}$ and consider the continuation lift $\bar h|([t_1^z, t_2^z] \times V_z) = (p|U_{z,1}^{j_1})^{-1} \circ h|([t_1^z, t_2^z] \times V_z)$, and so on. These lifts coincide on the overlaps of their domains of definition and furnish a global lift $\bar h$ of the homotopy.

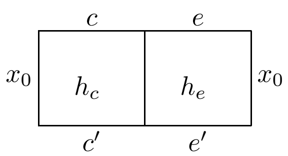
(3) *Let $c : [0,1] \to Y$ be a curve. Then for each $x_0 \in p^{-1}(c(0))$ there exists a unique lift* $\mathrm{lift}_{x_0}(c) : [0,1] \to X$ *with* $\mathrm{lift}_{x_0}(c)(0) = x_0$ *and* $p \circ \mathrm{lift}_{x_0}(c) = c$. This is the special case of (2) where Z is a point.

C.5. Theorem and Definition. *Let X be a space with fixed base point $x_0 \in X$. Let us denote by $\pi_1(X, x_0)$ the set of all homotopy classes $[c]$ relative $\{0,1\}$ of curves $c : [0,1] \to X$ with $c(0) = c(1) = x_0$. We define a multiplication in $\pi_1(X, x_0)$ by piecing together curves. This makes $\pi_1(X, x_0)$ into a group which is called the fundamental group of X centered at x_0.*

The multiplication is given by $[c].[e] = [ce]$, where
$$ce(t) = \begin{cases} c(2t) & \text{for } 0 \le t \le \frac12 \\ e(2t-1) & \text{for } \frac12 \le t \le 1 \end{cases}$$

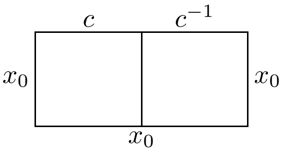
Proof. The multiplication is well defined in $\pi_1(X, x_0)$:

$$c \sim_{h_c} c' \text{ rel } \{0,1\}, \quad e \sim_{h_e} e' \text{ rel } \{0,1\} \implies ce \sim_h c'e' \text{ rel } \{0,1\}$$



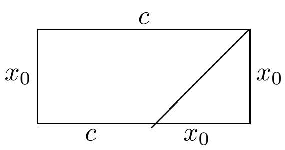
$$h(s,t) = \begin{cases} h_c(s,2t) & \text{for } 0 \le t \le \frac12 \\ h_e(s,2t-1) & \text{for } \frac12 \le t \le 1 \end{cases}$$

$[c]^{-1} = [c^{-1}]$ where $c^{-1}(t) = c(1-t)$ for $t \in [0,1]$ since cc^{-1} is homotopic to x_0 relative $\{0,1\}$:



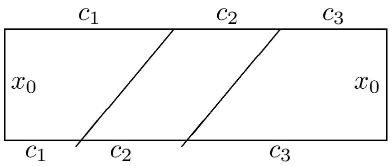
$$h(s,t) = \begin{cases} c(2st) & \text{for } 0 \le 2t \le \frac12 \\ c^{-1}(\frac{2-s}{2}(1 - \frac{2-s}{2})(2t-1)) & \text{for } \frac12 \le t \le 1 \end{cases}$$

$[c].[x_0] = [c]$ where the identity in $\pi_1(X, x_0)$ is given by the constant path x_0:



$$h(s,t) = \begin{cases} c(\frac{2}{1+s}t) & \text{for } 0 \le t \le \frac12 + \frac{s}{2} \\ x_0 & \text{for } \frac12 + \frac{s}{2} \le t \le 1 \end{cases}$$

Associativity: $([c_1].[c_2]).[c_3] = [c_1].([c_2].[c_3])$ by using the homotopy



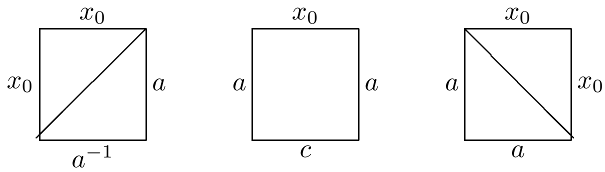
$$h(s,t) = \begin{cases} c(\frac{4}{1+s}t), & 0 \le t \le \frac{1+s}{4} \\ c(4(t - \frac{1+s}{4})), & \frac{1+s}{4} \le t \le \frac{2+s}{4} \\ c(\frac{4}{2-s}(t - \frac{2+s}{4})), & \frac{2+s}{4} \le t \le 1 \end{cases}$$

This suffices to see that $\pi_1(X, x_0)$ is a group. $\square$

C.6. Properties of the fundamental group.

If e is a path from x_0 to x_1 on X then $[c] = [ece^{-1}]$ is an isomorphism $\pi_1(X, x_0) \to \pi_1(X, x_1)$. Thus for pathconnected X the isomorphism class of $\pi_1(X, x_0)$ does not depend on x_0; we write sometimes $\pi_1(X)$.

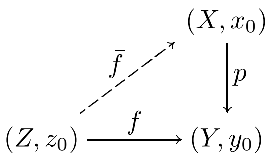
A space X is called *simply connected* if X is pathwise connected with trivial fundamental group: $\pi_1(X) = \{1\}$. *A contractible space is simply connected*, by the following argument: A closed curve c through x_0 in X is homotopic to x_0, but not necessarily relative $\{0, 1\}$. But this can be remedied by composing the following homotopies:



So $[a^{-1}].[c].[a] = [x_0]$ and thus $[c] = [x_0]$ in $\pi_1(X, x_0)$.

Any mapping $f : X \to Y$ induces a group homomorphism $f_* : \pi_1(X, x_0) \to \pi_1(Y, f(x_0))$ via $f_*([c]) = [f \circ c]$; f_* depends only on the homotopy class relative $\{x_0\}$ of f. We consider thus the category of spaces $(X, *)$ with base points and base point preserving homotopy classes of mappings. Then π_1 is a functor from this category into the category of groups and their homomorphisms.

C.7. Lifting II. *Let $p : (X, x_0) \to (Y, y_0)$ be a covering where X is connected and locally path connected.*



Let $f : (Z, z_0) \to (Y, y_0)$ where Z is path connected. Then we have: A lift $\tilde f : (Z, z_0) \to (X, x_0)$ of f exists if and only if $f_*\pi_1(Z, z_0) \subseteq p_*\pi_1(X, x_0)$.

Proof. If a lift $\tilde f$ exists then $f_*\pi_1(Z, z_0) = p_*\tilde f_*\pi_1(Z, z_0) \subseteq p_*\pi_1(X, x_0)$.

Conversely, for $z \in Z$ choose a path c from z_0 to z. Then $f \circ c$ is a path from y_0 to $f(z)$. We put $\tilde f(z) = \text{lift}_{x_0}(f \circ c)(1)$. Then $p(\tilde f(z)) = p(\text{lift}_{x_0}(f \circ c)(1)) = f(c(1)) = f(z)$. We claim that $\tilde f(z)$ does not depend on the the choice of of c. So let e be another path from z_0 to z. Then ce^{-1} is a closed path through z_0 so $[ce^{-1}] \in \pi_1(Z, z_0)$ and $f_*[ce^{-1}] = [f \circ (ce^{-1})] = [(f \circ c)(f \circ e)^{-1}] \in p_*\pi(X, x_0)$ which means that $\text{lift}_{x_0}((f \circ c)(f \circ e)^{-1})$ is a closed path, or $\text{lift}_{x_0}(f \circ c)(1) = \text{lift}_{x_0}(f \circ e)(1)$. To see that $\tilde f$ is continuous ...??? $\square$

3. Vector Fields and Flows

3.1. Definition. A *vector field* X on a manifold M is a smooth section of the tangent bundle; so $X : M \to TM$ is smooth and $\pi_M \circ X = Id_M$. A *local vector field* is a smooth section, which is defined on an open subset only. We denote the set of all vector fields by $\mathfrak{X}(M)$. With point wise addition and scalar multiplication $\mathfrak{X}(M)$ becomes a vector space.

Example. Let (U,u) be a chart on M. Then the $\frac{\partial}{\partial u^i} : U \to TM|U$, $x \mapsto \frac{\partial}{\partial u^i}|_x$, described in (1.8), are local vector fields defined on U.

Lemma. *If X is a vector field on M and (U,u) is a chart on M and $x \in U$, then we have $X(x) = \sum_{i=1}^m X(x)(u^i)\frac{\partial}{\partial u^i}|_x$. We write $X|U = \sum_{i=1}^m X(u^i)\frac{\partial}{\partial u^i}$.* $\square$

3.2. The vector fields $(\frac{\partial}{\partial u^i})_{i=1}^m$ on U, where (U,u) is a chart on M, form a *holonomic frame field*. By a *frame field* on some open set $V \subset M$ we mean $m = \dim M$ vector fields $s_i \in \mathfrak{X}(U)$ such that $s_1(x), \dots, s_m(x)$ is a linear basis of T_xM for each $x \in V$. A frame field is said to be *holonomic*, if $s_i = \frac{\partial}{\partial v^i}$ for some chart (V,v). If no such chart may be found locally, the frame field is called *anholonomic*.

With the help of partitions of unity and holonomic frame fields one may construct 'many' vector fields on M. In particular the values of a vector field can be arbitrarily preassigned on a discrete set $\{x_i\} \subset M$.

3.3. Lemma. *The space $\mathfrak{X}(M)$ of vector fields on M coincides canonically with the space of all derivations of the algebra $C^\infty(M)$ of smooth functions, i.e. those $\mathbb{R}$-linear operators $D : C^\infty(M) \to C^\infty(M)$ with $D(fg) = D(f)g + fD(g)$.*

Proof. Clearly each vector field $X \in \mathfrak{X}(M)$ defines a derivation (again called X, later sometimes called $\mathcal{L}_X$) of the algebra $C^\infty(M)$ by the prescription $X(f)(x) := X(x)(f) = df(X(x))$.

If conversely a derivation D of $C^\infty(M)$ is given, for any $x \in M$ we consider $D_x : C^\infty(M) \to \mathbb{R}$, $D_x(f) = D(f)(x)$. Then D_x is a derivation at x of $C^\infty(M)$ in the sense of (1.7), so $D_x = X_x$ for some $X_x \in T_xM$. In this way we get a section $X : M \to TM$. If (U,u) is a chart on M, we have $D_x = \sum_{i=1}^m X(x)(u^i)\frac{\partial}{\partial u^i}|_x$ by (1.7). Choose V open in M, $V \subset \overline{V} \subset U$, and $\varphi \in C^\infty(M,\mathbb{R})$ such that $\operatorname{supp}(\varphi) \subset U$ and $\varphi|V = 1$. Then $\varphi\cdot u^i \in C^\infty(M)$ and $(\varphi u^i)|V = u^i|V$. So $D(\varphi u^i)(x) = X(x)(\varphi u^i) = X(x)(u^i)$ and $X|V = \sum_{i=1}^m D(\varphi u^i)|V \cdot \frac{\partial}{\partial u^i}|V$ is smooth. $\square$

3.4. The Lie bracket. By lemma (3.3) we can identify $\mathfrak{X}(M)$ with the vector space of all derivations of the algebra $C^\infty(M)$, which we will do without any notational change in the following.

If X, Y are two vector fields on M, then the mapping $f \mapsto X(Y(f)) - Y(X(f))$ is again a derivation of $C^\infty(M)$, as a simple computation shows. Thus there is a unique vector field $[X,Y] \in \mathfrak{X}(M)$ such that $[X,Y](f) = X(Y(f)) - Y(X(f))$ holds for all $f \in C^\infty(M)$.

In a local chart (U,u) on M one immediately verifies that for $X|U = \sum X^i \frac{\partial}{\partial u^i}$ and $Y|U = \sum Y^i \frac{\partial}{\partial u^i}$ we have

$$\Big[\sum_i X^i \tfrac{\partial}{\partial u^i}, \sum_j Y^j \tfrac{\partial}{\partial u^j}\Big] = \sum_{i,j} \big(X^i(\tfrac{\partial}{\partial u^i}Y^j) - Y^i(\tfrac{\partial}{\partial u^i}X^j)\big)\tfrac{\partial}{\partial u^j},$$

since second partial derivatives commute. The $\mathbb{R}$-bilinear mapping

$$[\quad,\quad] : \mathfrak{X}(M) \times \mathfrak{X}(M) \to \mathfrak{X}(M)$$

is called the *Lie bracket*. Note also that $\mathfrak{X}(M)$ is a module over the algebra $C^\infty(M)$ by pointwise multiplication $(f,X) \mapsto fX$.

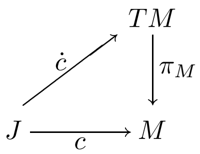
Theorem. *The Lie bracket* $[\quad,\quad] : \mathfrak{X}(M) \times \mathfrak{X}(M) \to \mathfrak{X}(M)$ *has the following properties:*

$$\begin{aligned}
&[X,Y] = -[Y,X],\\
&[X,[Y,Z]] = [[X,Y],Z] + [Y,[X,Z]], \quad \textit{the Jacobi identity,}\\
&[fX,Y] = f[X,Y] - (Yf)X,\\
&[X,fY] = f[X,Y] + (Xf)Y.
\end{aligned}$$

The form of the Jacobi identity we have chosen says that $ad(X) = [X,\quad]$ is a derivation for the Lie algebra $(\mathfrak{X}(M),[\quad,\quad])$. The pair $(\mathfrak{X}(M),[\quad,\quad])$ is the prototype of a *Lie algebra*. The concept of a Lie algebra is one of the most important notions of modern mathematics.

Proof. All these properties are checked easily for the commutator $[X,Y] = X \circ Y - Y \circ X$ in the space of derivations of the algebra $C^\infty(M)$. $\square$

3.5. Integral curves. Let $c : J \to M$ be a smooth curve in a manifold M defined on an interval J. We will use the following notations: $c'(t) = \dot c(t) = \frac{d}{dt}c(t) := T_t c.1$. Clearly $c' : J \to TM$ is smooth. We call c' a vector field along c since we have $\pi_M \circ c' = c$.



A smooth curve $c : J \to M$ will be called an *integral curve* or *flow line* of a vector field $X \in \mathfrak{X}(M)$ if $c'(t) = X(c(t))$ holds for all $t \in J$.

3.6. Lemma. *Let X be a vector field on M. Then for any $x \in M$ there is an open interval J_x containing 0 and an integral curve $c_x : J_x \to M$ for X (i.e. $c_x' = X \circ c_x$) with $c_x(0) = x$. If J_x is maximal, then c_x is unique.*

Proof. In a chart (U,u) on M with $x \in U$ the equation $c'(t) = X(c(t))$ is a system ordinary differential equations with initial condition $c(0) = x$. Since X is smooth there is a unique local solution which even depends smoothly on the initial values, by the theorem of Picard-Lindelöf, [Dieudonné I, 1969, 10.7.4]. So on M there are always local integral curves. If $J_x = (a,b)$ and $\lim_{t\to b-} c_x(t) =: c_x(b)$ exists in M, there is a unique local solution c_1 defined in an open interval containing b with $c_1(b) = c_x(b)$. By uniqueness of the solution on the intersection of the two intervals, c_1 prolongs c_x to a larger interval. This may be repeated (also on the left hand side of J_x) as long as the limit exists. So if we suppose J_x to be maximal, J_x either equals $\mathbb{R}$ or the integral curve leaves the manifold in finite (parameter-) time in the past or future or both. □

3.7. The flow of a vector field. Let $X \in \mathfrak{X}(M)$ be a vector field. Let us write $\mathrm{Fl}^X_t(x) = \mathrm{Fl}^X(t,x) := c_x(t)$, where $c_x : J_x \to M$ is the maximally defined integral curve of X with $c_x(0) = x$, constructed in lemma (3.6).

Theorem. *For each vector field X on M, the mapping $\mathrm{Fl}^X : \mathcal{D}(X) \to M$ is smooth, where $\mathcal{D}(X) = \bigcup_{x\in M} J_x \times \{x\}$ is an open neighborhood of $0\times M$ in $\mathbb{R}\times M$. We have*

$$\mathrm{Fl}^X(t+s,x) = \mathrm{Fl}^X(t,\mathrm{Fl}^X(s,x))$$

in the following sense. If the right hand side exists, then the left hand side exists and we have equality. If both t, $s \geq 0$ or both are ≤ 0, and if the left hand side exists, then also the right hand side exists and we have equality.

Proof. As mentioned in the proof of (3.6), $\mathrm{Fl}^X(t,x)$ is smooth in (t,x) for small t, and if it is defined for (t,x), then it is also defined for (s,y) nearby. These are local properties which follow from the theory of ordinary differential equations.

Now let us treat the equation $\mathrm{Fl}^X(t+s,x) = \mathrm{Fl}^X(t,\mathrm{Fl}^X(s,x))$. If the right hand side exists, then we consider the equation

$$\begin{cases} \frac{d}{dt}\mathrm{Fl}^X(t+s,x) = \frac{d}{du}\mathrm{Fl}^X(u,x)|_{u=t+s} = X(\mathrm{Fl}^X(t+s,x)), \\ \mathrm{Fl}^X(t+s,x)|_{t=0} = \mathrm{Fl}^X(s,x). \end{cases}$$

But the unique solution of this is $\mathrm{Fl}^X(t,\mathrm{Fl}^X(s,x))$. So the left hand side exists and equals the right hand side.

If the left hand side exists, let us suppose that $t, s \geq 0$. We put

$$\begin{aligned} c_x(u) &= \begin{cases} \mathrm{Fl}^X(u,x) & \text{if } u \leq s \\ \mathrm{Fl}^X(u-s,\mathrm{Fl}^X(s,x)) & \text{if } u \geq s. \end{cases} \\ \tfrac{d}{du}c_x(u) &= \left.\begin{cases} \frac{d}{du}\mathrm{Fl}^X(u,x) = X(\mathrm{Fl}^X(u,x)) & \text{for } u \leq s \\ \frac{d}{du}\mathrm{Fl}^X(u-s,\mathrm{Fl}^X(s,x)) = X(\mathrm{Fl}^X(u-s,\mathrm{Fl}^X(s,x))) \end{cases}\right\} = \\ &= X(c_x(u)) \quad \text{for } 0 \leq u \leq t+s. \end{aligned}$$

Also $c_x(0) = x$ and on the overlap both definitions coincide by the first part of the proof, thus we conclude that $c_x(u) = \mathrm{Fl}^X(u,x)$ for $0 \leq u \leq t+s$ and we have $\mathrm{Fl}^X(t,\mathrm{Fl}^X(s,x)) = c_x(t+s) = \mathrm{Fl}^X(t+s,x)$.

Now we show that $\mathcal{D}(X)$ is open and Fl^X is smooth on $\mathcal{D}(X)$. We know already that $\mathcal{D}(X)$ is a neighborhood of $0 \times M$ in $\mathbb{R} \times M$ and that Fl^X is smooth near $0 \times M$.

For $x \in M$ let J'_x be the set of all $t \in \mathbb{R}$ such that Fl^X is defined and smooth on an open neighborhood of $[0, t] \times \{x\}$ (respectively on $[t, 0] \times \{x\}$ for $t < 0$) in $\mathbb{R} \times M$. We claim that $J'_x = J_x$, which finishes the proof. It suffices to show that J'_x is not empty, open and closed in J_x. It is open by construction, and not empty, since $0 \in J'_x$. If J'_x is not closed in J_x, let $t_0 \in J_x \cap (\overline{J'_x} \setminus J'_x)$ and suppose that $t_0 > 0$, say. By the local existence and smoothness Fl^X exists and is smooth near $[-\varepsilon, \varepsilon] \times \{y := \mathrm{Fl}^X(t_0, x)\}$ in $\mathbb{R} \times M$ for some $\varepsilon > 0$, and by construction Fl^X exists and is smooth near $[0, t_0-\varepsilon] \times \{x\}$. Since $\mathrm{Fl}^X(-\varepsilon, y) = \mathrm{Fl}^X(t_0-\varepsilon, x)$ we conclude for t near $[0, t_0-\varepsilon]$, x' near x, and t' near $[-\varepsilon, \varepsilon]$, that $\mathrm{Fl}^X(t+t', x') = \mathrm{Fl}^X(t', \mathrm{Fl}^X(t, x'))$ exists and is smooth. So $t_0 \in J'_x$, a contradiction. □

3.8. Let $X \in \mathfrak{X}(M)$ be a vector field. Its flow Fl^X is called *global* or *complete*, if its domain of definition $\mathcal{D}(X)$ equals $\mathbb{R} \times M$. Then the vector field X itself will be called a *"complete vector field"*. In this case Fl^X_t is also sometimes called $\exp tX$; it is a diffeomorphism of M.

The *support* $\operatorname{supp}(X)$ of a vector field X is the closure of the set $\{x \in M : X(x) \neq 0\}$.

Lemma. *A vector field with compact support on M is complete.*

Proof. Let $K = \operatorname{supp}(X)$ be compact. Then the compact set $0 \times K$ has positive distance to the disjoint closed set $(\mathbb{R} \times M) \setminus \mathcal{D}(X)$ (if it is not empty), so $[-\varepsilon, \varepsilon] \times K \subset \mathcal{D}(X)$ for some $\varepsilon > 0$. If $x \notin K$ then $X(x) = 0$, so $\mathrm{Fl}^X(t, x) = x$ for all t and $\mathbb{R} \times \{x\} \subset \mathcal{D}(X)$. So we have $[-\varepsilon, \varepsilon] \times M \subset \mathcal{D}(X)$. Since $\mathrm{Fl}^X(t + \varepsilon, x) = \mathrm{Fl}^X(t, \mathrm{Fl}^X(\varepsilon, x))$ exists for $|t| \leq \varepsilon$ by theorem (3.7), we have $[-2\varepsilon, 2\varepsilon] \times M \subset \mathcal{D}(X)$ and by repeating this argument we get $\mathbb{R} \times M = \mathcal{D}(X)$. □

So on a compact manifold M each vector field is complete. If M is not compact and of dimension ≥ 2, then in general the set of complete vector fields on M is neither a vector space nor is it closed under the Lie bracket, as the following example on $\mathbb{R}^2$ shows: $X = y\frac{\partial}{\partial x}$ and $Y = \frac{x^2}{2}\frac{\partial}{\partial y}$ are complete, but neither $X + Y$ nor $[X, Y]$ is complete. In general one may embed $\mathbb{R}^2$ as a closed submanifold into M and extend the vector fields X and Y.

3.9. f-related vector fields. If $f : M \to M$ is a diffeomorphism, then for any vector field $X \in \mathfrak{X}(M)$ the mapping $Tf^{-1} \circ X \circ f$ is also a vector field, which we will denote by f^*X. Analogously we put $f_*X := Tf \circ X \circ f^{-1} = (f^{-1})^*X$.

But if $f : M \to N$ is a smooth mapping and $Y \in \mathfrak{X}(N)$ is a vector field there may or may not exist a vector field $X \in \mathfrak{X}(M)$ such that the following diagram commutes:

(1)
$$\begin{array}{ccc} TM & \xrightarrow{Tf} & TN \\ X\uparrow & & \uparrow Y \\ M & \xrightarrow{f} & N. \end{array}$$

Definition. Let $f : M \to N$ be a smooth mapping. Two vector fields $X \in \mathfrak{X}(M)$ and $Y \in \mathfrak{X}(N)$ are called *f-related*, if $Tf \circ X = Y \circ f$ holds, i.e. if diagram (1) commutes.

Example. If $X \in \mathfrak{X}(M)$ and $Y \in \mathfrak{X}(N)$ and $X \times Y \in \mathfrak{X}(M \times N)$ is given $(X \times Y)(x, y) = (X(x), Y(y))$, then we have:

(2) $X \times Y$ and X are pr_1-related.
(3) $X \times Y$ and Y are pr_2-related.
(4) X and $X \times Y$ are $ins(y)$-related if and only if $Y(y) = 0$, where the mapping $ins(y) : M \to M \times N$ is given by $ins(y)(x) = (x, y)$.

3.10. Lemma. *Consider vector fields $X_i \in \mathfrak{X}(M)$ and $Y_i \in \mathfrak{X}(N)$ for $i = 1, 2$, and a smooth mapping $f : M \to N$. If X_i and Y_i are f-related for $i = 1, 2$, then also $\lambda_1 X_1 + \lambda_2 X_2$ and $\lambda_1 Y_1 + \lambda_2 Y_2$ are f-related, and also $[X_1, X_2]$ and $[Y_1, Y_2]$ are f-related.*

Proof. The first assertion is immediate. To prove the second we choose $h \in C^\infty(N)$. Then by assumption we have $Tf \circ X_i = Y_i \circ f$, thus:

$$\begin{aligned}(X_i(h \circ f))(x) &= X_i(x)(h \circ f) = (T_x f.X_i(x))(h) = \\ &= (Tf \circ X_i)(x)(h) = (Y_i \circ f)(x)(h) = Y_i(f(x))(h) = (Y_i(h))(f(x)),\end{aligned}$$

so $X_i(h \circ f) = (Y_i(h)) \circ f$, and we may continue:

$$\begin{aligned}[X_1, X_2](h \circ f) &= X_1(X_2(h \circ f)) - X_2(X_1(h \circ f)) = \\ &= X_1(Y_2(h) \circ f) - X_2(Y_1(h) \circ f) = \\ &= Y_1(Y_2(h)) \circ f - Y_2(Y_1(h)) \circ f = [Y_1, Y_2](h) \circ f.\end{aligned}$$

But this means $Tf \circ [X_1, X_2] = [Y_1, Y_2] \circ f$. □

3.11. Corollary. *If $f : M \to N$ is a local diffeomorphism (so $(T_x f)^{-1}$ makes sense for each $x \in M$), then for $Y \in \mathfrak{X}(N)$ a vector field $f^*Y \in \mathfrak{X}(M)$ is defined by $(f^*Y)(x) = (T_x f)^{-1}.Y(f(x))$. The linear mapping $f^* : \mathfrak{X}(N) \to \mathfrak{X}(M)$ is then a Lie algebra homomorphism, i.e. $f^*[Y_1, Y_2] = [f^*Y_1, f^*Y_2]$.*

3.12. The Lie derivative of functions. For a vector field $X \in \mathfrak{X}(M)$ and $f \in C^\infty(M)$ we define $\mathcal{L}_X f \in C^\infty(M)$ by

$$\begin{aligned}\mathcal{L}_X f(x) &:= \tfrac{d}{dt}|_0 f(\operatorname{Fl}^X(t, x)) \quad \text{or} \\ \mathcal{L}_X f &:= \tfrac{d}{dt}|_0 (\operatorname{Fl}^X_t)^* f = \tfrac{d}{dt}|_0 (f \circ \operatorname{Fl}^X_t).\end{aligned}$$

Since $\operatorname{Fl}^X(t, x)$ is defined for small t, for any $x \in M$, the expressions above make sense.

Lemma. *$\frac{d}{dt}(\operatorname{Fl}^X_t)^* f = (\operatorname{Fl}^X_t)^* X(f) = X((\operatorname{Fl}^X_t)^* f)$, in particular for $t = 0$ we have $\mathcal{L}_X f = X(f) = df(X)$.*

Proof. We have

$$\tfrac{d}{dt}(\mathrm{Fl}^X_t)^* f(x) = df(\tfrac{d}{dt}\,\mathrm{Fl}^X(t,x)) = df(X(\mathrm{Fl}^X(t,x))) = (\mathrm{Fl}^X_t)^*(Xf)(x).$$

From this we get $\mathcal{L}_X f = X(f) = df(X)$ and then in turn

$$\tfrac{d}{dt}(\mathrm{Fl}^X_t)^* f = \tfrac{d}{ds}|_0(\mathrm{Fl}^X_t \circ \mathrm{Fl}^X_s)^* f = \tfrac{d}{ds}|_0(\mathrm{Fl}^X_s)^*(\mathrm{Fl}^X_t)^* f = X((\mathrm{Fl}^X_t)^* f). \quad \square$$

3.13. The Lie derivative for vector fields. For $X, Y \in \mathfrak{X}(M)$ we define $\mathcal{L}_X Y \in \mathfrak{X}(M)$ by

$$\mathcal{L}_X Y := \tfrac{d}{dt}|_0(\mathrm{Fl}^X_t)^* Y = \tfrac{d}{dt}|_0(T(\mathrm{Fl}^X_{-t}) \circ Y \circ \mathrm{Fl}^X_t),$$

and call it the *Lie derivative* of Y along X.

Lemma. *We have*

$$\begin{aligned}
&\mathcal{L}_X Y = [X,Y],\\
&\tfrac{d}{dt}(\mathrm{Fl}^X_t)^* Y = (\mathrm{Fl}^X_t)^*\mathcal{L}_X Y = (\mathrm{Fl}^X_t)^*[X,Y] = \mathcal{L}_X(\mathrm{Fl}^X_t)^* Y = [X, (\mathrm{Fl}^X_t)^* Y].
\end{aligned}$$

Proof. Let $f \in C^\infty(M)$ and consider the mapping $\alpha(t,s) := Y(\mathrm{Fl}^X(t,x))(f \circ \mathrm{Fl}^X_s)$, which is locally defined near 0. It satisfies

$$\begin{aligned}
\alpha(t,0) &= Y(\mathrm{Fl}^X(t,x))(f),\\
\alpha(0,s) &= Y(x)(f \circ \mathrm{Fl}^X_s),\\
\tfrac{\partial}{\partial t}\alpha(0,0) &= \tfrac{\partial}{\partial t}\big|_0 Y(\mathrm{Fl}^X(t,x))(f) = \tfrac{\partial}{\partial t}\big|_0 (Yf)(\mathrm{Fl}^X(t,x)) = X(x)(Yf),\\
\tfrac{\partial}{\partial s}\alpha(0,0) &= \tfrac{\partial}{\partial s}|_0 Y(x)(f \circ \mathrm{Fl}^X_s) = Y(x)\tfrac{\partial}{\partial s}|_0(f \circ \mathrm{Fl}^X_s) = Y(x)(Xf).
\end{aligned}$$

But on the other hand we have

$$\begin{aligned}
\tfrac{\partial}{\partial u}|_0\alpha(u,-u) &= \tfrac{\partial}{\partial u}|_0 Y(\mathrm{Fl}^X(u,x))(f \circ \mathrm{Fl}^X_{-u})\\
&= \tfrac{\partial}{\partial u}|_0 \Big(T(\mathrm{Fl}^X_{-u}) \circ Y \circ \mathrm{Fl}^X_u\Big)_x (f) = (\mathcal{L}_X Y)_x(f),
\end{aligned}$$

so the first assertion follows. For the second claim we compute as follows:

$$\begin{aligned}
\tfrac{\partial}{\partial t}(\mathrm{Fl}^X_t)^* Y &= \tfrac{\partial}{\partial s}|_0 \Big(T(\mathrm{Fl}^X_{-t}) \circ T(\mathrm{Fl}^X_{-s}) \circ Y \circ \mathrm{Fl}^X_s \circ \mathrm{Fl}^X_t\Big)\\
&= T(\mathrm{Fl}^X_{-t}) \circ \tfrac{\partial}{\partial s}|_0 \Big(T(\mathrm{Fl}^X_{-s}) \circ Y \circ \mathrm{Fl}^X_s\Big) \circ \mathrm{Fl}^X_t\\
&= T(\mathrm{Fl}^X_{-t}) \circ [X,Y] \circ \mathrm{Fl}^X_t = (\mathrm{Fl}^X_t)^*[X,Y].\\
\tfrac{\partial}{\partial t}(\mathrm{Fl}^X_t)^* Y &= \tfrac{\partial}{\partial s}|_0(\mathrm{Fl}^X_s)^*(\mathrm{Fl}^X_t)^* Y = \mathcal{L}_X(\mathrm{Fl}^X_t)^* Y. \quad \square
\end{aligned}$$

3.14. Lemma. *Let $X \in \mathfrak{X}(M)$ and $Y \in \mathfrak{X}(N)$ be f-related vector fields for a smooth mapping $f : M \to N$. Then we have $f \circ \mathrm{Fl}^X_t = \mathrm{Fl}^Y_t \circ f$, whenever both sides are defined. In particular, if f is a diffeomorphism, we have $\mathrm{Fl}^{f^*Y}_t = f^{-1} \circ \mathrm{Fl}^Y_t \circ f$.*

Proof. We have $\frac{d}{dt}(f \circ \mathrm{Fl}^X_t) = Tf \circ \frac{d}{dt}\mathrm{Fl}^X_t = Tf \circ X \circ \mathrm{Fl}^X_t = Y \circ f \circ Fl^X_t$ and $f(\mathrm{Fl}^X(0,x)) = f(x)$. So $t \mapsto f(\mathrm{Fl}^X(t,x))$ is an integral curve of the vector field Y on N with initial value $f(x)$, so we have $f(\mathrm{Fl}^X(t,x)) = \mathrm{Fl}^Y(t, f(x))$ or $f \circ \mathrm{Fl}^X_t = \mathrm{Fl}^Y_t \circ f$. □

3.15. Corollary. *Let $X, Y \in \mathfrak{X}(M)$. Then the following assertions are equivalent*

(1) $\mathcal{L}_X Y = [X, Y] = 0$.
(2) $(\mathrm{Fl}^X_t)^* Y = Y$, *wherever defined.*
(3) $\mathrm{Fl}^X_t \circ \mathrm{Fl}^Y_s = \mathrm{Fl}^Y_s \circ \mathrm{Fl}^X_t$, *wherever defined.*

Proof. (1) ⇔ (2) is immediate from lemma (3.13). To see (2) ⇔ (3) we note that $\mathrm{Fl}^X_t \circ \mathrm{Fl}^Y_s = \mathrm{Fl}^Y_s \circ \mathrm{Fl}^X_t$ if and only if $\mathrm{Fl}^Y_s = \mathrm{Fl}^X_{-t} \circ \mathrm{Fl}^Y_s \circ \mathrm{Fl}^X_t = \mathrm{Fl}^{(\mathrm{Fl}^X_t)^*Y}_s$ by lemma (3.14); and this in turn is equivalent to $Y = (\mathrm{Fl}^X_t)^* Y$. □

3.16. Theorem. *Let M be a manifold, let $\varphi^i : \mathbb{R} \times M \supset U_{\varphi^i} \to M$ be smooth mappings for $i = 1, \dots, k$ where each U_{φ^i} is an open neighborhood of $\{0\} \times M$ in $\mathbb{R} \times M$, such that each φ^i_t is a diffeomorphism on its domain, $\varphi^i_0 = Id_M$, and $\frac{\partial}{\partial t}\big|_0 \varphi^i_t = X_i \in \mathfrak{X}(M)$. We put $[\varphi^i, \varphi^j]_t = [\varphi^i_t, \varphi^j_t] := (\varphi^j_t)^{-1} \circ (\varphi^i_t)^{-1} \circ \varphi^j_t \circ \varphi^i_t$. Then for each formal bracket expression P of length k we have*

$$0 = \tfrac{\partial^\ell}{\partial t^\ell}|_0 P(\varphi^1_t, \dots, \varphi^k_t) \quad \text{for } 1 \le \ell < k,$$
$$P(X_1, \dots, X_k) = \tfrac{1}{k!}\tfrac{\partial^k}{\partial t^k}|_0 P(\varphi^1_t, \dots, \varphi^k_t) \in \mathfrak{X}(M)$$

in the sense explained in step 2 of the proof. In particular we have for vector fields $X, Y \in \mathfrak{X}(M)$

$$0 = \tfrac{\partial}{\partial t}\big|_0 (\mathrm{Fl}^Y_{-t} \circ \mathrm{Fl}^X_{-t} \circ \mathrm{Fl}^Y_t \circ \mathrm{Fl}^X_t),$$
$$[X, Y] = \tfrac{1}{2}\tfrac{\partial^2}{\partial t^2}|_0 (\mathrm{Fl}^Y_{-t} \circ \mathrm{Fl}^X_{-t} \circ \mathrm{Fl}^Y_t \circ \mathrm{Fl}^X_t).$$

Proof. *Step 1.* Let $c : \mathbb{R} \to M$ be a smooth curve. If $c(0) = x \in M$, $c'(0) = 0, \dots, c^{(k-1)}(0) = 0$, then $c^{(k)}(0)$ is a well defined tangent vector in $T_x M$ which is given by the derivation $f \mapsto (f \circ c)^{(k)}(0)$ at x.

For we have

$$((f.g) \circ c)^{(k)}(0) = ((f \circ c).(g \circ c))^{(k)}(0) = \sum_{j=0}^{k} \binom{k}{j} (f \circ c)^{(j)}(0)(g \circ c)^{(k-j)}(0)$$
$$= (f \circ c)^{(k)}(0) g(x) + f(x)(g \circ c)^{(k)}(0),$$

since all other summands vanish: $(f \circ c)^{(j)}(0) = 0$ for $1 \le j < k$.

Step 2. Let $\varphi : \mathbb{R} \times M \supset U_\varphi \to M$ be a smooth mapping where U_φ is an open neighborhood of $\{0\} \times M$ in $\mathbb{R} \times M$, such that each φ_t is a diffeomorphism on its domain and $\varphi_0 = Id_M$. We say that φ_t is a *curve of local diffeomorphisms* though Id_M.

From step 1 we see that if $\frac{\partial^j}{\partial t^j}|_0 \varphi_t = 0$ for all $1 \leq j < k$, then $X := \frac{1}{k!}\frac{\partial^k}{\partial t^k}|_0 \varphi_t$ is a well defined vector field on M. We say that X is the *first non-vanishing derivative* at 0 of the curve φ_t of local diffeomorphisms. We may paraphrase this as $(\partial_t^k|_0 \varphi_t^*)f = k!\mathcal{L}_X f$.

Claim 3. Let φ_t, ψ_t be curves of local diffeomorphisms through Id_M and let $f \in C^\infty(M)$. Then we have

$$\partial_t^k|_0(\varphi_t \circ \psi_t)^* f = \partial_t^k|_0(\psi_t^* \circ \varphi_t^*)f = \sum_{j=0}^k \binom{k}{j} (\partial_t^j|_0 \psi_t^*)(\partial_t^{k-j}|_0 \varphi_t^*)f.$$

Also the multinomial version of this formula holds:

$$\partial_t^k|_0(\varphi_t^1 \circ \ldots \circ \varphi_t^\ell)^* f = \sum_{j_1+\dots+j_\ell=k} \frac{k!}{j_1! \ldots j_\ell!} (\partial_t^{j_\ell}|_0(\varphi_t^\ell)^*) \ldots (\partial_t^{j_1}|_0(\varphi_t^1)^*)f.$$

We only show the binomial version. For a function $h(t,s)$ of two variables we have

$$\partial_t^k h(t,t) = \sum_{j=0}^k \binom{k}{j} \partial_t^j \partial_s^{k-j} h(t,s)|_{s=t},$$

since for $h(t,s) = f(t)g(s)$ this is just a consequence of the Leibnitz rule, and linear combinations of such decomposable tensors are dense in the space of all functions of two variables in the compact C^∞-topology, so that by continuity the formula holds for all functions. In the following form it implies the claim:

$$\partial_t^k|_0 f(\varphi(t, \psi(t,x))) = \sum_{j=0}^k \binom{k}{j} \partial_t^j \partial_s^{k-j} f(\varphi(t, \psi(s,x)))|_{t=s=0}.$$

Claim 4. Let φ_t be a curve of local diffeomorphisms through Id_M with first non-vanishing derivative $k!X = \partial_t^k|_0 \varphi_t$. Then the inverse curve of local diffeomorphisms φ_t^{-1} has first non-vanishing derivative $-k!X = \partial_t^k|_0 \varphi_t^{-1}$.

For we have $\varphi_t^{-1} \circ \varphi_t = Id$, so by claim 3 we get for $1 \leq j \leq k$

$$0 = \partial_t^j|_0(\varphi_t^{-1} \circ \varphi_t)^* f = \sum_{i=0}^j \binom{j}{i} (\partial_t^i|_0 \varphi_t^*)(\partial_t^{j-i}(\varphi_t^{-1})^*)f =$$
$$= \partial_t^j|_0 \varphi_t^* (\varphi_0^{-1})^* f + \varphi_0^* \partial_t^j|_0 (\varphi_t^{-1})^* f,$$

i.e. $\partial_t^j|_0 \varphi_t^* f = -\partial_t^j|_0 (\varphi_t^{-1})^* f$ as required.

Claim 5. Let φ_t be a curve of local diffeomorphisms through Id_M with first non-vanishing derivative $m!X = \partial_t^m|_0\varphi_t$, and let ψ_t be a curve of local diffeomorphisms through Id_M with first non-vanishing derivative $n!Y = \partial_t^n|_0\psi_t$.

Then the curve of local diffeomorphisms $[\varphi_t, \psi_t] = \psi_t^{-1} \circ \varphi_t^{-1} \circ \psi_t \circ \varphi_t$ has first non-vanishing derivative

$$(m+n)![X,Y] = \partial_t^{m+n}|_0[\varphi_t, \psi_t].$$

From this claim the theorem follows.

By the multinomial version of claim 3 we have

$$\begin{aligned}A_N f :&= \partial_t^N|_0(\psi_t^{-1} \circ \varphi_t^{-1} \circ \psi_t \circ \varphi_t)^* f\\ &= \sum_{i+j+k+\ell=N} \frac{N!}{i!j!k!\ell!}(\partial_t^i|_0\varphi_t^*)(\partial_t^j|_0\psi_t^*)(\partial_t^k|_0(\varphi_t^{-1})^*)(\partial_t^\ell|_0(\psi_t^{-1})^*)f.\end{aligned}$$

Let us suppose that $1 \le n \le m$, the case $m \le n$ is similar. If $N < n$ all summands are 0. If $N = n$ we have by claim 4

$$A_N f = (\partial_t^n|_0\varphi_t^*)f + (\partial_t^n|_0\psi_t^*)f + (\partial_t^n|_0(\varphi_t^{-1})^*)f + (\partial_t^n|_0(\psi_t^{-1})^*)f = 0.$$

If $n < N \le m$ we have, using again claim 4:

$$\begin{aligned}A_N f &= \sum_{j+\ell=N} \frac{N!}{j!\ell!}(\partial_t^j|_0\psi_t^*)(\partial_t^\ell|_0(\psi_t^{-1})^*)f + \delta_N^m\left((\partial_t^m|_0\varphi_t^*)f + (\partial_t^m|_0(\varphi_t^{-1})^*)f\right)\\ &= (\partial_t^N|_0(\psi_t^{-1} \circ \psi_t)^*)f + 0 = 0.\end{aligned}$$

Now we come to the difficult case $m, n < N \le m+n$.

$$\begin{aligned}A_N f &= \partial_t^N|_0(\psi_t^{-1} \circ \varphi_t^{-1} \circ \psi_t)^* f + \tbinom{N}{m}(\partial_t^m|_0\varphi_t^*)(\partial_t^{N-m}|_0(\psi_t^{-1} \circ \varphi_t^{-1} \circ \psi_t)^*)f\\ &\quad + (\partial_t^N|_0\varphi_t^*)f,\end{aligned} \tag{1}$$

by claim 3, since all other terms vanish, see (3) below. By claim 3 again we get:

$$\begin{aligned}\partial_t^N|_0(\psi_t^{-1} \circ \varphi_t^{-1} \circ \psi_t)^* f &= \sum_{j+k+\ell=N} \frac{N!}{j!k!\ell!}(\partial_t^j|_0\psi_t^*)(\partial_t^k|_0(\varphi_t^{-1})^*)(\partial_t^\ell|_0(\psi_t^{-1})^*)f\\ &= \sum_{j+\ell=N} \tbinom{N}{j}(\partial_t^j|_0\psi_t^*)(\partial_t^\ell|_0(\psi_t^{-1})^*)f + \tbinom{N}{m}(\partial_t^{N-m}|_0\psi_t^*)(\partial_t^m|_0(\varphi_t^{-1})^*)f\\ &\quad + \tbinom{N}{m}(\partial_t^m|_0(\varphi_t^{-1})^*)(\partial_t^{N-m}|_0(\psi_t^{-1})^*)f + \partial_t^N|_0(\varphi_t^{-1})^* f\\ &= 0 + \tbinom{N}{m}(\partial_t^{N-m}|_0\psi_t^*)m!\mathcal{L}_{-X}f + \tbinom{N}{m}m!\mathcal{L}_{-X}(\partial_t^{N-m}|_0(\psi_t^{-1})^*)f\\ &\quad + \partial_t^N|_0(\varphi_t^{-1})^* f\\ &= \delta_{m+n}^N(m+n)!(\mathcal{L}_X\mathcal{L}_Y - \mathcal{L}_Y\mathcal{L}_X)f + \partial_t^N|_0(\varphi_t^{-1})^* f\\ &= \delta_{m+n}^N(m+n)!\mathcal{L}_{[X,Y]}f + \partial_t^N|_0(\varphi_t^{-1})^* f\end{aligned} \tag{2}$$

From the second expression in (2) one can also read off that

$$\partial_t^{N-m}|_0(\psi_t^{-1}\circ\varphi_t^{-1}\circ\psi_t)^*f = \partial_t^{N-m}|_0(\varphi_t^{-1})^*f. \tag{3}$$

If we put (2) and (3) into (1) we get, using claims 3 and 4 again, the final result which proves claim 3 and the theorem:

$$\begin{aligned} A_N f &= \delta^N_{m+n}(m+n)!\mathcal{L}_{[X,Y]}f + \partial_t^N|_0(\varphi_t^{-1})^*f \\ &\quad + \tbinom{N}{m}(\partial_t^m|_0\varphi_t^*)(\partial_t^{N-m}|_0(\varphi_t^{-1})^*)f + (\partial_t^N|_0\varphi_t^*)f \\ &= \delta^N_{m+n}(m+n)!\mathcal{L}_{[X,Y]}f + \partial_t^N|_0(\varphi_t^{-1}\circ\varphi_t)^*f \\ &= \delta^N_{m+n}(m+n)!\mathcal{L}_{[X,Y]}f + 0. \quad \square \end{aligned}$$

3.17. Theorem. *Let $X_1,\dots,X_m$ be vector fields on M defined in a neighborhood of a point $x\in M$ such that $X_1(x),\dots,X_m(x)$ are a basis for T_xM and $[X_i,X_j]=0$ for all i,j.*

Then there is a chart (U,u) of M centered at x such that $X_i|U = \frac{\partial}{\partial u^i}$.

Proof. For small $t=(t^1,\dots,t^m)\in\mathbb{R}^m$ we put

$$f(t^1,\dots,t^m) = (\mathrm{Fl}^{X_1}_{t^1}\circ\dots\circ\mathrm{Fl}^{X_m}_{t^m})(x).$$

By (3.15) we may interchange the order of the flows arbitrarily. Therefore

$$\tfrac{\partial}{\partial t^i}f(t^1,\dots,t^m) = \tfrac{\partial}{\partial t^i}(\mathrm{Fl}^{X_i}_{t^i}\circ\mathrm{Fl}^{X_1}_{t^1}\circ\cdots)(x) = X_i((\mathrm{Fl}^{x_1}_{t^1}\circ\cdots)(x)).$$

So T_0f is invertible, f is a local diffeomorphism, and its inverse gives a chart with the desired properties. $\square$

3.18. The theorem of Frobenius. The next three subsections will be devoted to the theorem of Frobenius for distributions of constant rank. We will give a powerfull generalization for distributions of nonconstant rank below ((3.21) — (3.28)).

Let M be a manifold. By a *vector subbundle* E of TM of fiber dimension k we mean a subset $E\subset TM$ such that each $E_x := E\cap T_xM$ is a linear subspace of dimension k, and such that for each $x \operatorname{im} M$ there are k vector fields defined on an open neighborhood of M with values in E and spanning E, called a *local frame* for E. Such an E is also called a smooth *distribution* of constant rank k. See section (6) for a thorough discussion of the notion of vector bundles. The space of all vector fields with values in E will be called $\Gamma(E)$.

The vector subbundle E of TM is called *integrable* or *involutive*, if for all $X,Y\in\Gamma(E)$ we have $[X,Y]\in\Gamma(E)$.

Local version of Frobenius' theorem. *Let $E \subset TM$ be an integrable vector subbundle of fiber dimension k of TM.*

Then for each $x \in M$ there exists a chart (U, u) of M centered at x with $u(U) = V \times W \subset \mathbb{R}^k \times \mathbb{R}^{m-k}$, such that $T(u^{-1}(V \times \{y\})) = E|(u^{-1}(V \times \{y\}))$ for each $y \in W$.

Proof. Let $x \in M$. We choose a chart (U, u) of M centered at x such that there exist k vector fields $X_1, \dots, X_k \in \Gamma(E)$ which form a frame of $E|U$. Then we have $X_i = \sum_{j=1}^m f_i^j \frac{\partial}{\partial u^j}$ for $f_i^j \in C^\infty(U)$. Then $f = (f_i^j)$ is a $(k \times m)$-matrix valued smooth function on U which has rank k on U. So some $(k \times k)$-submatrix, say the top one, is invertible at x and thus we may take U so small that this top $(k \times k)$-submatrix is invertible everywhere on U. Let $g = (g_i^j)$ be the inverse of this submatrix, so that $f.g = \binom{\mathrm{Id}}{*}$. We put

$$(1) \qquad Y_i := \sum_{j=1}^k g_i^j X_j = \sum_{j=1}^k \sum_{l=1}^m g_i^j f_j^l \frac{\partial}{\partial u^l} = \frac{\partial}{\partial u^i} + \sum_{p \geq k+1} h_i^p \frac{\partial}{\partial u^p}.$$

We claim that $[Y_i, Y_j] = 0$ for all $1 \leq i, j \leq k$. Since E is integrable we have $[Y_i, Y_j] = \sum_{l=1}^k c_{ij}^l Y_l$. But from (1) we conclude (using the coordinate formula in (3.4)) that $[Y_i, Y_j] = \sum_{p \geq k+1} a^p \frac{\partial}{\partial u^p}$. Again by (1) this implies that $c_{ij}^l = 0$ for all l, and the claim follows.

Now we consider an $(m-k)$-dimensional linear subspace W_1 in $\mathbb{R}^m$ which is transversal to the k vectors $T_x u.Y_i(x) \in T_0\mathbb{R}^m$ spanning $\mathbb{R}^k$, and we define $f : V \times W \to U$ by

$$f(t^1, \dots, t^k, y) := \left(\mathrm{Fl}^{Y_1}_{t^1} \circ \mathrm{Fl}^{Y_2}_{t^2} \circ \dots \circ \mathrm{Fl}^{Y_k}_{t^k}\right)(u^{-1}(y)),$$

where $t = (t^1, \dots, t^k) \in V$, a small neighborhood of 0 in $\mathbb{R}^k$, and where $y \in W$, a small neighborhood of 0 in W_1. By (3.15) we may interchange the order of the flows in the definition of f arbitrarily. Thus

$$\frac{\partial}{\partial t^i} f(t, y) = \frac{\partial}{\partial t^i} \left(\mathrm{Fl}^{Y_i}_{t^i} \circ \mathrm{Fl}^{Y_1}_{t^1} \circ \dots\right)(u^{-1}(y)) = Y_i(f(t, y)),$$
$$\frac{\partial}{\partial y^k} f(0, y) = \frac{\partial}{\partial y^k}(u^{-1})(y),$$

and so $T_0 f$ is invertible and the inverse of f on a suitable neighborhood of x gives us the required chart. □

3.19. Remark. Any charts $(U, u : U \to V \times W \subset \mathbb{R}^k \times \mathbb{R}^{m-k})$ as constructed in theorem (3.18) with V and W open balls is called a *distinguished chart* for E. The submanifolds $u^{-1}(V \times \{y\})$ are called *plaques*. Two plaques of different distinguished charts intersect in open subsets in both plaques or not at all: this follows immediately by flowing a point in the intersection into both plaques with the same construction as in in the proof of (3.18). Thus an atlas of distinguished charts on M has chart change mappings which respect the submersion $\mathbb{R}^k \times \mathbb{R}^{m-k} \to \mathbb{R}^{m-k}$ (the plaque structure on M). Such an atlas (or the equivalence class of such atlases) is called the *foliation corresponding to the integrable vector subbundle $E \subset TM$.*

3.20. Global Version of Frobenius' theorem. *Let $E \subsetneq TM$ be an integrable vector subbundle of TM. Then, using the restrictions of distinguished charts to plaques as charts we get a new structure of a smooth manifold on M, which we denote by M_E. If $E \neq TM$ the topology of M_E is finer than that of M, M_E has uncountably many connected components called the leaves of the foliation, and the identity induces a bijective immersion $M_E \to M$. Each leaf L is a second countable initial submanifold of M, and it is a maximal integrable submanifold of M for E in the sense that $T_xL = E_x$ for each $x \in L$.*

Proof. Let $(U_\alpha, u_\alpha : U_\alpha \to V_\alpha \times W_\alpha \subseteq \mathbb{R}^k \times \mathbb{R}^{m-k})$ be an atlas of distuished charts corresponding to the integrable vector subbundle $E \subset TM$, as given by theorem (3.18). Let us now use for each plaque the homeomorphisms $\mathrm{pr}_1 \circ u_\alpha|(u_\alpha^{-1}(V_\alpha \times \{y\})) : u_\alpha^{-1}(V_\alpha \times \{y\}) \to V_\alpha \subset \mathbb{R}^{m-k}$ as charts, then we describe on M a new smooth manifold structure M_E with finer topology which however has uncountably many connected components, and the identity on M induces a bijective immersion $M_E \to M$. The connected components of M_E are called the *leaves of the foliation*.

In order to check the rest of the assertions made in the theorem let us construct the unique leaf L through an arbitrary point $x \in M$: choose a plaque containing x and take the union with any plaque meeting the first one, and keep going. Now choose $y \in L$ and a curve $c : [0,1] \to L$ with $c(0) = x$ and $c(1) = y$. Then there are finitely many distinguished charts $(U_1, u_1), \dots, (U_n, u_n)$ and $a_1, \dots, a_n \in \mathbb{R}^{m-k}$ such that $x \in u_1^{-1}(V_1 \times \{a_1\})$, $y \in u_n^{-1}(V_n \times \{a_n\})$ and such that for each i

$$u_i^{-1}(V_i \times \{a_i\}) \cap u_{i+1}^{-1}(V_{i+1} \times \{a_{i+1}\}) \neq \emptyset. \tag{1}$$

Given u_i, u_{i+1} and a_i there are only countably many points a_{i+1} such that (1) holds: if not then we get a cover of the the separable submanifold $u_i^{-1}(V_i \times \{a_i\}) \cap U_{i+1}$ by uncountably many pairwise disjoint open sets of the form given in (1), which contradicts separability.

Finally, since (each component of) M is a Lindelöf space, any distinguished atlas contains a countable subatlas. So each leaf is the union of at most countably many plaques. The rest is clear. □

3.21. Singular distributions. Let M be a manifold. Suppose that for each $x \in M$ we are given a sub vector space E_x of T_xM. The disjoint union $E = \bigsqcup_{x \in M} E_x$ is called a *(singular) distribution* on M. We do not suppose, that the dimension of E_x is locally constant in x.

Let $\mathfrak{X}_{loc}(M)$ denote the set of all locally defined smooth vector fields on M, i.e. $\mathfrak{X}_{loc}(M) = \bigcup \mathfrak{X}(U)$, where U runs through all open sets in M. Furthermore let $\mathfrak{X}_E$ denote the set of all local vector fields $X \in \mathfrak{X}_{loc}(M)$ with $X(x) \in E_x$ whenever defined. We say that a subset $\mathcal{V} \subset \mathfrak{X}_E$ *spans* E, if for each $x \in M$ the vector space E_x is the linear hull of the set $\{X(x) : X \in \mathcal{V}\}$. We say that E is a *smooth distribution* if $\mathfrak{X}_E$ spans E. Note that every subset $\mathcal{W} \subset \mathfrak{X}_{loc}(M)$ spans a distribution denoted by $E(\mathcal{W})$, which is obviously smooth (the linear span of the empty set is the vector space 0). From now on we will consider only smooth distributions.

An *integral manifold* of a smooth distribution E is a connected immersed submanifold (N, i) (see (2.9)) such that $T_x i(T_x N) = E_{i(x)}$ for all $x \in N$. We will see in theorem (3.25) below that any integral manifold is in fact an initial submanifold of M (see (2.13)), so that we need not specify the injective immersion i. An integral manifold of E is called *maximal*, if it is not contained in any strictly larger integral manifold of E.

3.22. Lemma. *Let E be a smooth distribution on M. Then we have:*

(1) *If (N, i) is an integral manifold of E and $X \in \mathfrak{X}_E$, then i^*X makes sense and is an element of $\mathfrak{X}_{loc}(N)$, which is $i|i^{-1}(U_X)$-related to X, where $U_X \subset M$ is the open domain of X.*

(2) *If (N_j, i_j) are integral manifolds of E for $j = 1, 2$, then $i_1^{-1}(i_1(N_1) \cap i_2(N_2))$ and $i_2^{-1}(i_1(N_1) \cap i_2(N_2))$ are open subsets in N_1 and N_2, respectively; furthermore $i_2^{-1} \circ i_1$ is a diffeomorphism between them.*

(3) *If $x \in M$ is contained in some integral submanifold of E, then it is contained in a unique maximal one.*

Proof. (1) Let U_X be the open domain of $X \in \mathfrak{X}_E$. If $i(x) \in U_X$ for $x \in N$, we have $X(i(x)) \in E_{i(x)} = T_x i(T_x N)$, so $i^*X(x) := ((T_x i)^{-1} \circ X \circ i)(x)$ makes sense. It is clearly defined on an open subset of N and is smooth in x.

(2) Let $X \in \mathfrak{X}_E$. Then $i_j^*X \in \mathfrak{X}_{loc}(N_j)$ and is i_j-related to X. So by lemma (3.14) for $j = 1, 2$ we have

$$i_j \circ \operatorname{Fl}_t^{i_j^*X} = Fl_t^X \circ i_j.$$

Now choose $x_j \in N_j$ such that $i_1(x_1) = i_2(x_2) = x_0 \in M$ and choose vector fields $X_1, \dots, X_n \in \mathfrak{X}_E$ such that $(X_1(x_0), \dots, X_n(x_0))$ is a basis of E_{x_0}. Then

$$f_j(t^1, \dots, t^n) := (\operatorname{Fl}_{t^1}^{i_j^*X_1} \circ \dots \circ \operatorname{Fl}_{t^n}^{i_j^*X_n})(x_j)$$

is a smooth mapping defined near zero $\mathbb{R}^n \to N_j$. Since obviously $\frac{\partial}{\partial t^k}|_0 f_j = i_j^*X_k(x_j)$ for $j = 1, 2$, we see that f_j is a diffeomorphism near 0. Finally we have

$$\begin{aligned}
(i_2^{-1} \circ i_1 \circ f_1)(t^1, \dots, t^n) &= (i_2^{-1} \circ i_1 \circ \operatorname{Fl}_{t^1}^{i_1^*X_1} \circ \dots \circ \operatorname{Fl}_{t^n}^{i_1^*X_n})(x_1) \\
&= (i_2^{-1} \circ \operatorname{Fl}_{t^1}^{X_1} \circ \dots \circ \operatorname{Fl}_{t^n}^{X_n} \circ i_1)(x_1) \\
&= (\operatorname{Fl}_{t^1}^{i_2^*X_1} \circ \dots \circ \operatorname{Fl}_{t^n}^{i_2^*X_n} \circ i_2^{-1} \circ i_1)(x_1) \\
&= f_2(t^1, \dots, t^n).
\end{aligned}$$

So $i_2^{-1} \circ i_1$ is a diffeomorphism, as required.

(3) Let N be the union of all integral manifolds containing x. Choose the union of all the atlases of these integral manifolds as atlas for N, which is a smooth atlas for N by 2. Note that a connected immersed submanifold of a separable manifold is automatically separable (since it carries a Riemannian metric). □

3.23. Integrable singular distributions and singular foliations. A smooth (singular) distribution E on a manifold M is called *integrable*, if each point of M is contained in some integral manifold of E. By (3.22.3) each point is then contained in a unique maximal integral manifold, so the maximal integral manifolds form a partition of M. This partition is called the *(singular) foliation* of M induced by the integrable (singular) distribution E, and each maximal integral manifold is called a *leaf* of this foliation. If $X \in \mathfrak{X}_E$ then by (3.22.1) the integral curve $t \mapsto \operatorname{Fl}^X(t,x)$ of X through $x \in M$ stays in the leaf through x.

Let us now consider an arbitrary subset $\mathcal{V} \subset \mathfrak{X}_{loc}(M)$. We say that $\mathcal{V}$ is *stable* if for all $X, Y \in \mathcal{V}$ and for all t for which it is defined the local vector field $(\operatorname{Fl}^X_t)^*Y$ is again an element of $\mathcal{V}$.

If $\mathcal{W} \subset \mathfrak{X}_{loc}(M)$ is an arbitrary subset, we call $\mathcal{S}(\mathcal{W})$ the set of all local vector fields of the form $(\operatorname{Fl}^{X_1}_{t_1} \circ \dots \circ \operatorname{Fl}^{X_k}_{t_k})^*Y$ for $X_i, Y \in \mathcal{W}$. By lemma (3.14) the flow of this vector field is

$$\operatorname{Fl}((\operatorname{Fl}^{X_1}_{t_1} \circ \dots \circ \operatorname{Fl}^{X_k}_{t_k})^*Y, t) = \operatorname{Fl}^{X_k}_{-t_k} \circ \dots \circ \operatorname{Fl}^{X_1}_{-t_1} \circ \operatorname{Fl}^Y_t \circ \operatorname{Fl}^{X_1}_{t_1} \circ \dots \circ \operatorname{Fl}^{X_k}_{t_k},$$

so $\mathcal{S}(\mathcal{W})$ is the minimal stable set of local vector fields which contains $\mathcal{W}$.

Now let F be an arbitrary distribution. A local vector field $X \in \mathfrak{X}_{loc}(M)$ is called an *infinitesimal automorphism* of F, if $T_x(\operatorname{Fl}^X_t)(F_x) \subset F_{\operatorname{Fl}^X(t,x)}$ whenever defined. We denote by $aut(F)$ the set of all infinitesimal automorphisms of F. By arguments given just above, $aut(F)$ is stable.

3.24. Lemma. *Let E be a smooth distribution on a manifold M. Then the following conditions are equivalent:*

(1) *E is integrable.*
(2) *$\mathfrak{X}_E$ is stable.*
(3) *There exists a subset $\mathcal{W} \subset \mathfrak{X}_{loc}(M)$ such that $\mathcal{S}(\mathcal{W})$ spans E.*
(4) *$aut(E) \cap \mathfrak{X}_E$ spans E.*

Proof. (1) $\Longrightarrow$ (2). Let $X \in \mathfrak{X}_E$ and let L be the leaf through $x \in M$, with $i : L \to M$ the inclusion. Then $\operatorname{Fl}^X_{-t} \circ i = i \circ \operatorname{Fl}^{i^*X}_{-t}$ by lemma (3.14), so we have

$$\begin{aligned} T_x(\operatorname{Fl}^X_{-t})(E_x) &= T(\operatorname{Fl}^X_{-t}).T_x i.T_x L = T(\operatorname{Fl}^X_{-t} \circ i).T_x L \\ &= Ti.T_x(\operatorname{Fl}^{i^*X}_{-t}).T_x L \\ &= Ti.T_{Fl^{i^*X}(-t,x)} L = E_{Fl^X(-t,x)}. \end{aligned}$$

This implies that $(\operatorname{Fl}^X_t)^*Y \in \mathfrak{X}_E$ for any $Y \in \mathfrak{X}_E$.

(2) $\Longrightarrow$ (4). In fact (2) says that $\mathfrak{X}_E \subset aut(E)$.

(4) $\Longrightarrow$ (3). We can choose $\mathcal{W} = aut(E) \cap \mathfrak{X}_E$: for $X, Y \in \mathcal{W}$ we have $(\operatorname{Fl}^X_t)^*Y \in \mathfrak{X}_E$; so $\mathcal{W} \subset \mathcal{S}(\mathcal{W}) \subset \mathfrak{X}_E$ and E is spanned by $\mathcal{W}$.

(3) $\Longrightarrow$ (1). We have to show that each point $x \in M$ is contained in some integral submanifold for the distribution E. Since $\mathcal{S}(\mathcal{W})$ spans E and is stable we have

$$T(\operatorname{Fl}^X_t).E_x = E_{\operatorname{Fl}^X(t,x)} \tag{5}$$

for each $X \in \mathcal{S}(\mathcal{W})$. Let $\dim E_x = n$. There are $X_1, \dots, X_n \in \mathcal{S}(\mathcal{W})$ such that $X_1(x), \dots, X_n(x)$ is a basis of E_x, since E is smooth. As in the proof of (3.22.2) we consider the mapping

$$f(t^1, \dots, t^n) := (\mathrm{Fl}^{X_1}_{t^1} \circ \dots \circ \mathrm{Fl}^{X_n}_{t^n})(x),$$

defined and smooth near 0 in $\mathbb{R}^n$. Since the rank of f at 0 is n, the image under f of a small open neighborhood of 0 is a submanifold N of M. We claim that N is an integral manifold of E. The tangent space $T_{f(t^1,\dots,t^n)}N$ is linearly generated by

$$\begin{aligned}\tfrac{\partial}{\partial t^k}(\mathrm{Fl}^{X_1}_{t^1} \circ \dots \circ \mathrm{Fl}^{X_n}_{t^n})(x) &= T(\mathrm{Fl}^{X_1}_{t^1} \circ \dots \circ \mathrm{Fl}^{X_{k-1}}_{t^{k-1}})X_k((\mathrm{Fl}^{X_k}_{t^k} \circ \dots \circ \mathrm{Fl}^{X_n}_{t^n})(x)) \\ &= ((\mathrm{Fl}^{X_1}_{-t^1})^* \cdots (\mathrm{Fl}^{X_{k-1}}_{-t^{k-1}})^* X_k)(f(t^1, \dots, t^n)).\end{aligned}$$

Since $\mathcal{S}(\mathcal{W})$ is stable, these vectors lie in $E_{f(t)}$. From the form of f and from (5) we see that $\dim E_{f(t)} = \dim E_x$, so these vectors even span $E_{f(t)}$ and we have $T_{f(t)}N = E_{f(t)}$ as required. $\square$

3.25. Theorem (local structure of singular foliations). *Let E be an integrable (singular) distribution of a manifold M. Then for each $x \in M$ there exists a chart (U, u) with $u(U) = \{y \in \mathbb{R}^m : |y^i| < \varepsilon$ for all $i\}$ for some $\varepsilon > 0$, and a countable subset $A \subset \mathbb{R}^{m-n}$, such that for the leaf L through x we have*

$$u(U \cap L) = \{y \in u(U) : (y^{n+1}, \dots, y^m) \in A\}.$$

Each leaf is an initial submanifold.

If furthermore the distribution E has locally constant rank, this property holds for each leaf meeting U with the same n.

This chart (U, u) is called a *distinguished chart* for the (singular) distribution or the (singular) foliation. A connected component of $U \cap L$ is called a *plaque*.

Proof. Let L be the leaf through x, $\dim L = n$. Let $X_1, \dots, X_n \in \mathfrak{X}_E$ be local vector fields such that $X_1(x), \dots, X_n(x)$ is a basis of E_x. We choose a chart (V, v) centered at x on M such that the vectors

$$X_1(x), \dots, X_n(x), \tfrac{\partial}{\partial v^{n+1}}|_x, \dots, \tfrac{\partial}{\partial v^m}|_x$$

form a basis of T_xM. Then

$$f(t^1, \dots, t^m) = (\mathrm{Fl}^{X_1}_{t^1} \circ \dots \circ \mathrm{Fl}^{X_n}_{t^n})(v^{-1}(0, \dots, 0, t^{n+1}, \dots, t^m))$$

is a diffeomorphism from a neighborhood of 0 in $\mathbb{R}^m$ onto a neighborhood of x in M. Let (U, u) be the chart given by f^{-1}, suitably restricted. We have

$$y \in L \iff (\mathrm{Fl}^{X_1}_{t^1} \circ \dots \circ \mathrm{Fl}^{X_n}_{t^n})(y) \in L$$

for all y and all $t^1, \dots, t^n$ for which both expressions make sense. So we have

$$f(t^1, \dots, t^m) \in L \iff f(0, \dots, 0, t^{n+1}, \dots, t^m) \in L,$$

and consequently $L\cap U$ is the disjoint union of connected sets of the form $\{y\in U : (u^{n+1}(y),\dots,u^m(y)) = \text{ constant}\}$. Since L is a connected immersive submanifold of M, it is second countable and only a countable set of constants can appear in the description of $u(L\cap U)$ given above. From this description it is clear that L is an initial submanifold ((2.13)) since $u(C_x(L\cap U)) = u(U)\cap(\mathbb{R}^n\times 0)$.

The argument given above is valid for any leaf of dimension n meeting U, so also the assertion for an integrable distribution of constant rank follows. □

3.26. Involutive singular distributions. A subset $\mathcal{V}\subset\mathfrak{X}_{loc}(M)$ is called *involutive* if $[X,Y]\in\mathcal{V}$ for all $X,Y\in\mathcal{V}$. Here $[X,Y]$ is defined on the intersection of the domains of X and Y.

A smooth distribution E on M is called *involutive* if there exists an involutive subset $\mathcal{V}\subset\mathfrak{X}_{loc}(M)$ spanning E.

For an arbitrary subset $\mathcal{W}\subset\mathfrak{X}_{loc}(M)$ let $\mathcal{L}(\mathcal{W})$ be the set consisting of all local vector fields on M which can be written as finite expressions using Lie brackets and starting from elements of $\mathcal{W}$. Clearly $\mathcal{L}(\mathcal{W})$ is the smallest involutive subset of $\mathfrak{X}_{loc}(M)$ which contains $\mathcal{W}$.

3.27. Lemma. *For each subset $\mathcal{W}\subset\mathfrak{X}_{loc}(M)$ we have*

$$E(\mathcal{W})\subset E(\mathcal{L}(\mathcal{W}))\subset E(\mathcal{S}(\mathcal{W})).$$

In particular we have $E(\mathcal{S}(\mathcal{W})) = E(\mathcal{L}(\mathcal{S}(\mathcal{W})))$.

Proof. We will show that for $X,Y\in\mathcal{W}$ we have $[X,Y]\in\mathfrak{X}_{E(\mathcal{S}(\mathcal{W}))}$, for then by induction we get $\mathcal{L}(\mathcal{W})\subset\mathfrak{X}_{E(\mathcal{S}(\mathcal{W}))}$ and $E(\mathcal{L}(\mathcal{W}))\subset E(\mathcal{S}(\mathcal{W}))$.

Let $x\in M$; since by (3.24) $E(\mathcal{S}(\mathcal{W}))$ is integrable, we can choose the leaf L through x, with the inclusion i. Then i^*X is i-related to X, i^*Y is i-related to Y, thus by (3.10) the local vector field $[i^*X,i^*Y]\in\mathfrak{X}_{loc}(L)$ is i-related to $[X,Y]$, and $[X,Y](x)\in E(\mathcal{S}(\mathcal{W}))_x$, as required. □

3.28. Theorem. *Let $\mathcal{V}\subset\mathfrak{X}_{loc}(M)$ be an involutive subset. Then the distribution $E(\mathcal{V})$ spanned by $\mathcal{V}$ is integrable under each of the following conditions.*

(1) *M is real analytic and $\mathcal{V}$ consists of real analytic vector fields.*
(2) *The dimension of $E(\mathcal{V})$ is constant along all flow lines of vector fields in $\mathcal{V}$.*

Proof. (1). For $X,Y\in\mathcal{V}$ we have $\frac{d}{dt}(\mathrm{Fl}^X_t)^*Y = (\mathrm{Fl}^X_t)^*\mathcal{L}_XY$, consequently $\frac{d^k}{dt^k}(\mathrm{Fl}^X_t)^*Y = (\mathrm{Fl}^X_t)^*(\mathcal{L}_X)^kY$, and since everything is real analytic we get for $x\in M$ and small t

$$(\mathrm{Fl}^X_t)^*Y(x) = \sum_{k\ge 0}\frac{t^k}{k!}\frac{d^k}{dt^k}|_0(\mathrm{Fl}^X_t)^*Y(x) = \sum_{k\ge 0}\frac{t^k}{k!}(\mathcal{L}_X)^kY(x).$$

Since $\mathcal{V}$ is involutive, all $(\mathcal{L}_X)^kY\in\mathcal{V}$. Therefore we get $(\mathrm{Fl}^X_t)^*Y(x)\in E(\mathcal{V})_x$ for small t. By the flow property of Fl^X the set of all t satisfying $(\mathrm{Fl}^X_t)^*Y(x)\in E(\mathcal{V})_x$ is open and closed, so it follows that (3.24.2) is satisfied and thus $E(\mathcal{V})$ is integrable.

(2). We choose $X_1,\dots,X_n\in\mathcal{V}$ such that $X_1(x),\dots,X_n(x)$ is a basis of $E(\mathcal{V})_x$. For any $X\in\mathcal{V}$, by hypothesis, $E(\mathcal{V})_{\operatorname{Fl}^X(t,x)}$ has also dimension n and admits the vectors $X_1(\operatorname{Fl}^X(t,x)),\dots,X_n(\operatorname{Fl}^X(t,x))$ as basis, for small t. So there are smooth functions $f_{ij}(t)$ such that

$$[X,X_i](\operatorname{Fl}^X(t,x))=\sum_{j=1}^n f_{ij}(t)X_j(\operatorname{Fl}^X(t,x)).$$

$$\begin{aligned}\tfrac{d}{dt}T(\operatorname{Fl}^X_{-t}).X_i(\operatorname{Fl}^X(t,x))&=T(\operatorname{Fl}^X_{-t}).[X,X_i](\operatorname{Fl}^X(t,x))=\\&=\sum_{j=1}^n f_{ij}(t)T(\operatorname{Fl}^X_{-t}).X_j(\operatorname{Fl}^X(t,x)).\end{aligned}$$

So the T_xM-valued functions $g_i(t)=T(\operatorname{Fl}^X_{-t}).X_i(\operatorname{Fl}^X(t,x))$ satisfy the linear ordinary differential equation $\frac{d}{dt}g_i(t)=\sum_{j=1}^n f_{ij}(t)g_j(t)$ and have initial values in the linear subspace $E(\mathcal{V})_x$, so they have values in it for all small t. Therefore $T(\operatorname{Fl}^X_{-t})E(\mathcal{V})_{\operatorname{Fl}^X(t,x)}\subset E(\mathcal{V})_x$ for small t. Using compact time intervals and the flow property one sees that condition (3.24.2) is satisfied and $E(\mathcal{V})$ is integrable. □

3.29. Examples. (1) The singular distribution spanned by $\mathcal{W}\subset\mathfrak{X}_{loc}(\mathbb{R}^2)$ is involutive, but not integrable, where $\mathcal{W}$ consists of all global vector fields with support in $\mathbb{R}^2\setminus\{0\}$ and the field $\frac{\partial}{\partial x^1}$; the leaf through 0 should have dimension 1 at 0 and dimension 2 elsewhere.

(2) The singular distribution on $\mathbb{R}^2$ spanned by the vector fields $X(x^1,x^2)=\frac{\partial}{\partial x^1}$ and $Y(x^1,x^2)=f(x^1)\frac{\partial}{\partial x^2}$ where $f:\mathbb{R}\to\mathbb{R}$ is a smooth function with $f(x^1)=0$ for $x^1\le 0$ and $f(x^1)>0$ for $x^1>0$, is involutive, but not integrable. Any leaf should pass $(0,x^2)$ tangentially to $\frac{\partial}{\partial x^1}$, should have dimension 1 for $x^1\le 0$ and should have dimension 2 for $x^1>0$.

3.30. By a *time dependent vector field* on a manifold M we mean a smooth mapping $X:J\times M\to TM$ with $\pi_M\circ X=pr_2$, where J is an open interval. An integral curve of X is a smooth curve $c:I\to M$ with $\dot c(t)=X(t,c(t))$ for all $t\in I$, where I is a subinterval of J.

There is an associated vector field $\bar X\in\mathfrak{X}(J\times M)$, given by $\bar X(t,x)=(\frac{\partial}{\partial t},X(t,x))\in T_t\mathbb{R}\times T_xM$.

By the *evolution operator* of X we mean the mapping $\Phi^X:J\times J\times M\to M$, defined in a maximal open neighborhood of $\Delta_J\times M$ (where Δ_J is the diagonal of J) and satisfying the differential equation

$$\begin{cases}\frac{d}{dt}\Phi^X(t,s,x)=X(t,\Phi^X(t,s,x))\\ \Phi^X(s,s,x)=x.\end{cases}$$

It is easily seen that $(t,\Phi^X(t,s,x))=\operatorname{Fl}^{\bar X}(t-s,(s,x))$, so the maximally defined evolution operator exists and is unique, and it satisfies

$$\Phi^X_{t,s}=\Phi^X_{t,r}\circ\Phi^X_{r,s}$$

whenever one side makes sense (with the restrictions of (3.7)), where $\Phi^X_{t,s}(x)=\Phi(t,s,x)$.

Examples and Exercises

3.31. Compute the flow of the vector field $\xi_0(x,y) := -y\frac{\partial}{\partial x} + x\frac{\partial}{\partial y}$ in $\mathbb{R}^2$. Draw the flow lines. Is this a global flow?

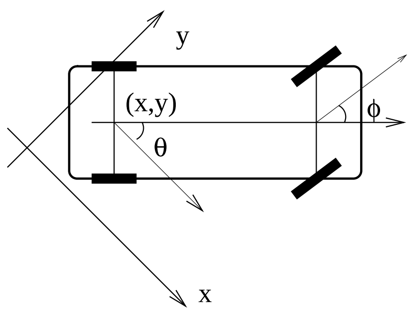
3.32. Compute the flow of the vector field $\xi_1(x,y) := y\frac{\partial}{\partial x}$ in $\mathbb{R}^2$. Is it a global flow? Answer the same questions for $\xi_2(x,y) := \frac{x^2}{2}\frac{\partial}{\partial y}$. Now compute $[\xi_1, \xi_2]$ and investigate its flow. This time it is not global! In fact, $Fl_t^{[\xi_1,\xi_2]}(x,y) = \Big(\frac{2x}{2+xt}, \frac{y}{4}(tx+2)^2\Big)$. Investigate the flow of $\xi_1 + \xi_2$. It is not global either! Thus the set of complete vector fields on $\mathbb{R}^2$ is neither a vector space nor closed under the Lie bracket.

3.33. Driving a car. The phase space consists of all $(x, y, \theta, \varphi) \in \mathbb{R}^2 \times S^1 \times (-\pi/4, \pi/4)$, where

$(x, y) \dots$ position of the midpoint of the rear axle,

$\theta \dots$ direction of the car axle,

$\phi \dots$ steering angle of the front wheels.



There are two 'control' vector fields:

$$\begin{aligned} \text{steer } &= \frac{\partial}{\partial \phi} \\ \text{drive } &= \cos(\theta)\frac{\partial}{\partial x} + \sin(\theta)\frac{\partial}{\partial y} + \tan(\phi)\frac{1}{l}\frac{\partial}{\partial \theta} \text{ (why?)} \end{aligned}$$

Compute $[\text{steer}, \text{drive}] =: \text{park}$ (why?) and $[\text{drive}, \text{park}]$, and interpret the results. Is it not convenient that the two control vector fields do not span an integrable distribution?

3.34. Describe the Lie algebra of all vectorfields on S^1 in terms of Fourier expansion. This is nearly (up to a central extension) the Virasoro algebra of theoretical physics.

CHAPTER II
Lie Groups

4. Lie Groups I

4.1. Definition. A *Lie group* G is a smooth manifold and a group such that the multiplication $\mu : G \times G \to G$ is smooth. We shall see in a moment, that then also the inversion $\nu : G \to G$ turns out to be smooth.

We shall use the following notation:
$\mu : G \times G \to G$, multiplication, $\mu(x, y) = x.y$.
$\mu_a : G \to G$, left translation, $\mu_a(x) = a.x$.
$\mu^a : G \to G$, right translation, $\mu^a(x) = x.a$.
$\nu : G \to G$, inversion, $\nu(x) = x^{-1}$.
$e \in G$, the unit element.
Then we have $\mu_a \circ \mu_b = \mu_{a.b}$, $\mu^a \circ \mu^b = \mu^{b.a}$, $\mu_a^{-1} = \mu_{a^{-1}}$, $(\mu^a)^{-1} = \mu^{a^{-1}}$, $\mu^a \circ \mu_b = \mu_b \circ \mu^a$. If $\varphi : G \to H$ is a smooth homomorphism between Lie groups, then we also have $\varphi \circ \mu_a = \mu_{\varphi(a)} \circ \varphi$, $\varphi \circ \mu^a = \mu^{\varphi(a)} \circ \varphi$, thus also $T\varphi.T\mu_a = T\mu_{\varphi(a)}.T\varphi$, etc. So $T_e\varphi$ is injective (surjective) if and only if $T_a\varphi$ is injective (surjective) for all $a \in G$.

4.2. Lemma. *$T_{(a,b)}\mu : T_aG \times T_bG \to T_{ab}G$ is given by*

$$T_{(a,b)}\mu.(X_a, Y_b) = T_a(\mu^b).X_a + T_b(\mu_a).Y_b.$$

Proof. Let $ri_a : G \to G \times G$, $ri_a(x) = (a, x)$ be the right insertion and let $li_b : G \to G \times G$, $li_b(x) = (x, b)$ be the left insertion. Then we have

$$\begin{aligned} T_{(a,b)}\mu.(X_a, Y_b) &= T_{(a,b)}\mu.(T_a(li_b).X_a + T_b(ri_a).Y_b) = \\ &= T_a(\mu \circ li_b).X_a + T_b(\mu \circ ri_a).Y_b = T_a(\mu^b).X_a + T_b(\mu_a).Y_b. \quad \square \end{aligned}$$

4.3. Corollary. *The inversion $\nu : G \to G$ is smooth and*

$$T_a\nu = -T_e(\mu^{a^{-1}}).T_a(\mu_{a^{-1}}) = -T_e(\mu_{a^{-1}}).T_a(\mu^{a^{-1}}).$$

Proof. The equation $\mu(x, \nu(x)) = e$ determines ν implicitly. Since $T_e(\mu(e, \quad)) = T_e(\mu_e) = Id$, the mapping ν is smooth in a neighborhood of e by the implicit function theorem. From $(\nu \circ \mu_a)(x) = x^{-1}.a^{-1} = (\mu^{a^{-1}} \circ \nu)(x)$ we may conclude that ν is everywhere smooth. Now we differentiate the equation $\mu(a, \nu(a)) = e$; this gives in turn

$$0_e = T_{(a,a^{-1})}\mu.(X_a, T_a\nu.X_a) = T_a(\mu^{a^{-1}}).X_a + T_{a^{-1}}(\mu_a).T_a\nu.X_a,$$
$$T_a\nu.X_a = -T_e(\mu_a)^{-1}.T_a(\mu^{a^{-1}}).X_a = -T_e(\mu_{a^{-1}}).T_a(\mu^{a^{-1}}).X_a. \quad \square$$

4.4. Example. The *general linear group* $GL(n, \mathbb{R})$ is the group of all invertible real $n \times n$-matrices. It is an open subset of $L(\mathbb{R}^n, \mathbb{R}^n)$, given by $\det \neq 0$ and a Lie group.

Similarly $GL(n, \mathbb{C})$, the group of invertible complex $n \times n$-matrices, is a Lie group; also $GL(n, \mathbb{H})$, the group of all invertible quaternionic $n \times n$-matrices, is a Lie group, since it is open in the real Banach algebra $L_{\mathbb{H}}(\mathbb{H}^n, \mathbb{H}^n)$ as a glance at the von Neumann series shows; but the quaternionic determinant is a more subtle instrument here.

4.5. Example. The *orthogonal group* $O(n, \mathbb{R})$ is the group of all linear isometries of $(\mathbb{R}^n, \langle \quad , \quad \rangle)$, where $\langle \quad , \quad \rangle$ is the standard positive definite inner product on $\mathbb{R}^n$. The *special orthogonal group* $SO(n, \mathbb{R}) := \{A \in O(n, \mathbb{R}) : \det A = 1\}$ is open in $O(n, \mathbb{R})$, since we have the disjoint union

$$O(n, \mathbb{R}) = SO(n, \mathbb{R}) \sqcup \begin{pmatrix} -1 & 0 \\ 0 & \mathbb{I}_{n-1} \end{pmatrix} SO(n, \mathbb{R}),$$

where $\mathbb{I}_k$ is short for the identity matrix $Id_{\mathbb{R}^k}$. We claim that $O(n, \mathbb{R})$ and $SO(n, \mathbb{R})$ are submanifolds of $L(\mathbb{R}^n, \mathbb{R}^n)$. For that we consider the mapping $f : L(\mathbb{R}^n, \mathbb{R}^n) \to L(\mathbb{R}^n, \mathbb{R}^n)$, given by $f(A) = A.A^t$. Then $O(n, \mathbb{R}) = f^{-1}(\mathbb{I}_n)$; so $O(n, \mathbb{R})$ is closed. Since it is also bounded, $O(n, \mathbb{R})$ is compact. We have $df(A).X = X.A^t + A.X^t$, so $\ker df(\mathbb{I}_n) = \{X : X + X^t = 0\}$ is the space $\mathfrak{o}(n, \mathbb{R})$ of all skew symmetric $n \times n$-matrices. Note that $\dim \mathfrak{o}(n, \mathbb{R}) = \frac{1}{2}(n-1)n$. If A is invertible, we get $\ker df(A) = \{Y : Y.A^t + A.Y^t = 0\} = \{Y : Y.A^t \in \mathfrak{o}(n, \mathbb{R})\} = \mathfrak{o}(n, \mathbb{R}).(A^{-1})^t$. The mapping f takes values in $L_{sym}(\mathbb{R}^n, \mathbb{R}^n)$, the space of all symmetric $n \times n$-matrices, and $\dim \ker df(A) + \dim L_{sym}(\mathbb{R}^n, \mathbb{R}^n) = \frac{1}{2}(n-1)n + \frac{1}{2}n(n+1) = n^2 = \dim L(\mathbb{R}^n, \mathbb{R}^n)$, so $f : GL(n, \mathbb{R}) \to L_{sym}(\mathbb{R}^n, \mathbb{R}^n)$ is a submersion. Since obviously $f^{-1}(\mathbb{I}_n) \subset GL(n, \mathbb{R})$, we conclude from (1.12) that $O(n, \mathbb{R})$ is a submanifold of $GL(n, \mathbb{R})$. It is also a Lie group, since the group operations are smooth as the restrictions of the ones from $GL(n, \mathbb{R})$.

4.6. Example. The *special linear group* $SL(n, \mathbb{R})$ is the group of all $n \times n$-matrices of determinant 1. The function $\det : L(\mathbb{R}^n, \mathbb{R}^n) \to \mathbb{R}$ is smooth and $d\det(A)X = \operatorname{trace}(C(A).X)$, where $C(A)^i_j$, the cofactor of A^j_i, is the determinant of the matrix, which results from putting 1 instead of A^j_i into A and 0 in the rest of the j-th row and the i-th column of A. We recall Cramers rule $C(A).A = A.C(A) = \det(A).\mathbb{I}_n$. So if $C(A) \neq 0$ (i.e. $\operatorname{rank}(A) \geq n-1$) then the linear functional $df(A)$ is non zero. So $\det : GL(n, \mathbb{R}) \to \mathbb{R}$ is a submersion and $SL(n, \mathbb{R}) = (\det)^{-1}(1)$ is a manifold and a Lie group of dimension $n^2 - 1$. Note finally that $T_{\mathbb{I}_n} SL(n, \mathbb{R}) = \ker d\det(\mathbb{I}_n) = \{X : \operatorname{trace}(X) = 0\}$. This space of traceless matrices is usually called $\mathfrak{sl}(n, \mathbb{R})$.

4.7. Example. The *symplectic group* $Sp(n,\mathbb{R})$ is the group of all $2n\times 2n$-matrices A such that $\omega(Ax,Ay)=\omega(x,y)$ for all $x,y\in\mathbb{R}^{2n}$, where ω is a (the standard) non degenerate skew symmetric bilinear form on $\mathbb{R}^{2n}$.

Such a form exists on a vector space if and only if the dimension is even, and on $\mathbb{R}^n\times(\mathbb{R}^n)^*$ the form $\omega((x,x^*),(y,y^*))=\langle x,y^*\rangle-\langle y,x^*\rangle$ (where we use the duality pairing), in coordinates $\omega((x^i)_{i=1}^{2n},(y^j)_{j=1}^{2n})=\sum_{i=1}^n(x^iy^{n+i}-x^{n+i}y^i)$, is such a form. Any symplectic form on $\mathbb{R}^{2n}$ looks like that after choosing a suitable basis. Let $(e_i)_{i=1}^{2n}$ be the standard basis in $\mathbb{R}^{2n}$. Then we have

$$(\omega(e_i,e_j)^i_j)=\begin{pmatrix}0 & \mathbb{I}_n\\ -\mathbb{I}_n & 0\end{pmatrix}=:J,$$

and the matrix J satisfies $J^t=-J$, $J^2=-\mathbb{I}_{2n}$, $J\binom{x}{y}=\binom{y}{-x}$ in $\mathbb{R}^n\times\mathbb{R}^n$, and $\omega(x,y)=\langle x,Jy\rangle$ in terms of the standard inner product on $\mathbb{R}^{2n}$.

For $A\in L(\mathbb{R}^{2n},\mathbb{R}^{2n})$ we have $\omega(Ax,Ay)=\langle Ax,JAy\rangle=\langle x,A^tJAy\rangle$. Thus $A\in Sp(n,\mathbb{R})$ if and only if $A^tJA=J$.

We consider now the mapping $f:L(\mathbb{R}^{2n},\mathbb{R}^{2n})\to L(\mathbb{R}^{2n},\mathbb{R}^{2n})$ given by $f(A)=A^tJA$. Then $f(A)^t=(A^tJA)^t=-A^tJA=-f(A)$, so f takes values in the space $\mathfrak{o}(2n,\mathbb{R})$ of skew symmetric matrices. We have $df(A)X=X^tJA+A^tJX$, and therefore

$$\begin{aligned}\ker df(\mathbb{I}_{2n})&=\{X\in L(\mathbb{R}^{2n},\mathbb{R}^{2n}):X^tJ+JX=0\}\\&=\{X: JX \text{ is symmetric}\}=:\mathfrak{sp}(n,\mathbb{R}).\end{aligned}$$

We see that $\dim\mathfrak{sp}(n,\mathbb{R})=\frac{2n(2n+1)}{2}=\binom{2n+1}{2}$. Furthermore $\ker df(A)=\{X: X^tJA+A^tJX=0\}$ and the mapping $X\mapsto A^tJX$ is an isomorphism $\ker df(A)\to L_{sym}(\mathbb{R}^{2n},\mathbb{R}^{2n})$, if A is invertible. Thus $\dim\ker df(A)=\binom{2n+1}{2}$ for all $A\in GL(2n,\mathbb{R})$. If $f(A)=J$, then $A^tJA=J$, so A has rank $2n$ and is invertible, and we have $\dim\ker df(A)+\dim\mathfrak{o}(2n,\mathbb{R})=\binom{2n+1}{2}+\frac{2n(2n-1)}{2}=4n^2=\dim L(\mathbb{R}^{2n},\mathbb{R}^{2n})$. So $f:GL(2n,\mathbb{R})\to\mathfrak{o}(2n,\mathbb{R})$ is a submersion and $f^{-1}(J)=Sp(n,\mathbb{R})$ is a manifold and a Lie group. It is the symmetry group of 'classical mechanics'.

4.8. Example. The complex general linear group $GL(n,\mathbb{C})$ of all invertible complex $n\times n$-matrices is open in $L_{\mathbb{C}}(\mathbb{C}^n,\mathbb{C}^n)$, so it is a real Lie group of real dimension $2n^2$; it is also a complex Lie group of complex dimension n^2. The complex special linear group $SL(n,\mathbb{C})$ of all matrices of determinant 1 is a submanifold of $GL(n,\mathbb{C})$ of complex codimension 1 (or real codimension 2).

The complex orthogonal group $O(n,\mathbb{C})$ is the set

$$\{A\in L(\mathbb{C}^n,\mathbb{C}^n):g(Az,Aw)=g(z,w)\text{ for all }z,w\},$$

where $g(z,w)=\sum_{i=1}^n z^iw^i$. This is a complex Lie group of complex dimension $\frac{(n-1)n}{2}$, and it is *not* compact. Since $O(n,\mathbb{C})=\{A:A^tA=\mathbb{I}_n\}$, we have $1=\det_{\mathbb{C}}(\mathbb{I}_n)=\det_{\mathbb{C}}(A^tA)=\det_{\mathbb{C}}(A)^2$, so $\det_{\mathbb{C}}(A)=\pm1$. Thus $SO(n,\mathbb{C}):=\{A\in O(n,\mathbb{C}):\det_{\mathbb{C}}(A)=1\}$ is an open subgroup of index 2 in $O(n,\mathbb{C})$.

The group $Sp(n,\mathbb{C}) = \{A \in L_{\mathbb{C}}(\mathbb{C}^{2n},\mathbb{C}^{2n}) : A^t J A = J\}$ is also a complex Lie group of complex dimension $n(2n+1)$.

The groups treated here are the *classical complex Lie groups*. The groups $SL(n,\mathbb{C})$ for $n \geq 2$, $SO(n,\mathbb{C})$ for $n \geq 3$, $Sp(n,\mathbb{C})$ for $n \geq 4$, and five more exceptional groups exhaust all simple complex Lie groups up to coverings.

4.9. Example. Let $\mathbb{C}^n$ be equipped with the standard hermitian inner product $(z,w) = \sum_{i=1}^n \overline{z}^i w^i$. The *unitary* group $U(n)$ consists of all complex $n \times n$-matrices A such that $(Az, Aw) = (z,w)$ for all z, w holds, or equivalently $U(n) = \{A : A^*A = \mathbb{I}_n\}$, where $A^* = \overline{A}^t$.

We consider the mapping $f : L_{\mathbb{C}}(\mathbb{C}^n,\mathbb{C}^n) \to L_{\mathbb{C}}(\mathbb{C}^n,\mathbb{C}^n)$, given by $f(A) = A^*A$. Then f is smooth but not holomorphic. Its derivative is $df(A)X = X^*A + A^*X$, so $\ker df(\mathbb{I}_n) = \{X : X^* + X = 0\} =: \mathfrak{u}(n)$, the space of all skew hermitian matrices. We have $\dim_{\mathbb{R}} \mathfrak{u}(n) = n^2$. As above we may check that $f : GL(n,\mathbb{C}) \to L_{herm}(\mathbb{C}^n,\mathbb{C}^n)$ is a submersion, so $U(n) = f^{-1}(\mathbb{I}_n)$ is a compact real Lie group of dimension n^2.

The *special unitary* group is $SU(n) = U(n) \cap SL(n,\mathbb{C})$. For $A \in U(n)$ we have $|\det_{\mathbb{C}}(A)| = 1$, thus $\dim_{\mathbb{R}} SU(n) = n^2 - 1$.

4.10. Example. The group $Sp(n)$. Let $\mathbb{H}$ be the division algebra of quaternions. We will use the following description of quaternions: Let $(\mathbb{R}^3, \langle\quad,\quad\rangle, \Delta)$ be the oriented Euclidean space of dimension 3, where Δ is a determinant function with value 1 on a positive oriented orthonormal basis. The *vector product* on R^3 is then given by $\langle X \times Y, Z\rangle = \Delta(X,Y,Z)$. Now we let $\mathbb{H} := \mathbb{R}^3 \times \mathbb{R}$, equipped with the following product:

$$(X,s)(Y,t) := (X \times Y + sY + tX, st - \langle X,Y\rangle).$$

Now we take a positively oriented orthonormal basis of $\mathbb{R}^3$, call it (i,j,k), and indentify $(0,1)$ with 1. Then the last formula implies visibly the usual product rules for the basis $(1,i,j,k)$ of the quaternions.

The group $Sp(1) := S^3 \subset \mathbb{H} \cong \mathbb{R}^4$ is then the group of unit quaternions, obviously a Lie group.

Now let V be a right vector space over $\mathbb{H}$. Since $\mathbb{H}$ is not commutative, we have to distinguish between left and right vector spaces and we choose right ones as basic, so that matrices can multiply from the left. By choosing a basis we get $V = \mathbb{R}^n \otimes_{\mathbb{R}} \mathbb{H} = \mathbb{H}^n$. For $u = (u^i)$, $v = (v^i) \in \mathbb{H}^n$ we put $\langle u,v\rangle := \sum_{i=1}^n \overline{u}^i v^i$. Then $\langle\quad,\quad\rangle$ is $\mathbb{R}$-bilinear and $\langle ua, vb\rangle = \overline{a}\langle u,v\rangle b$ for $a,b \in \mathbb{H}$.

An $\mathbb{R}$ linear mapping $A : V \to V$ is called $\mathbb{H}$-*linear* or *quaternionically linear* if $A(ua) = A(u)a$ holds. The space of all such mappings shall be denoted by $L_{\mathbb{H}}(V,V)$. It is real isomorphic to the space of all quaternionic $n \times n$-matrices with the usual multiplication, since for the standard basis $(e_i)_{i=1}^n$ in $V = \mathbb{H}^n$ we have $A(u) = A(\sum_i e_i u^i) = \sum_i A(e_i)u^i = \sum_{i,j} e_j A^j_i u^i$. Note that $L_{\mathbb{H}}(V,V)$ is only a real vector space, if V is a right quaternionic vector space - any further structure must come from a second (left) quaternionic vector space structure on V.

$GL(n,\mathbb{H})$, the group of invertible $\mathbb{H}$-linear mappings of $\mathbb{H}^n$, is a Lie group, because it is $GL(4n,\mathbb{R}) \cap L_{\mathbb{H}}(\mathbb{H}^n,\mathbb{H}^n)$, open in $L_{\mathbb{H}}(\mathbb{H}^n,\mathbb{H}^n)$.

A quaternionically linear mapping A is called isometric or *quaternionically unitary*, if $\langle A(u), A(v)\rangle = \langle u, v\rangle$ for all $u, v \in \mathbb{H}^n$. We denote by $Sp(n)$ the group of all quaternionic isometries of $\mathbb{H}^n$, the *quaternionic unitary group*. The reason for its name is that $Sp(n) = Sp(n,\mathbb{C}) \cap U(2n)$, since we can decompose the quaternionic hermitian form $\langle\ \ ,\ \ \rangle$ into a complex hermitian one and a complex symplectic one. Also we have $Sp(n) \subset O(4n,\mathbb{R})$, since the real part of $\langle\ \ ,\ \ \rangle$ is a positive definite real inner product. For $A \in L_{\mathbb{H}}(\mathbb{H}^n,\mathbb{H}^n)$ we put $A^* := \overline{A}^t$. Then we have $\langle u, A(v)\rangle = \langle A^*(u), v\rangle$, so $\langle A(u), A(v)\rangle = \langle A^*A(u), v\rangle$. Thus $A \in Sp(n)$ if and only if $A^*A = Id$.

Again $f : L_{\mathbb{H}}(\mathbb{H}^n,\mathbb{H}^n) \to L_{\mathbb{H},herm}(\mathbb{H}^n,\mathbb{H}^n) = \{A : A^* = A\}$, given by $f(A) = A^*A$, is a smooth mapping with $df(A)X = X^*A + A^*X$. So we have $\ker df(Id) = \{X : X^* = -X\} =: \mathfrak{sp}(n)$, the space of quaternionic skew hermitian matrices. The usual proof shows that f has maximal rank on $GL(n,\mathbb{H})$, so $Sp(n) = f^{-1}(Id)$ is a compact real Lie group of dimension $2n(n-1) + 3n$.

The groups $SO(n,\mathbb{R})$ for $n \ge 3$, $SU(n)$ for $n \ge 2$, $Sp(n)$ for $n \ge 2$ and the real forms of the five exceptional complex Lie groups exhaust all simple compact Lie groups up to coverings.

4.11. Invariant vector fields and Lie algebras. Let G be a (real) Lie group. A vector field ξ on G is called *left invariant*, if $\mu_a^*\xi = \xi$ for all $a \in G$, where $\mu_a^*\xi = T(\mu_{a^{-1}}) \circ \xi \circ \mu_a$ as in section 3. Since by (3.11) we have $\mu_a^*[\xi,\eta] = [\mu_a^*\xi, \mu_a^*\eta]$, the space $\mathfrak{X}_L(G)$ of all left invariant vector fields on G is closed under the Lie bracket, so it is a sub Lie algebra of $\mathfrak{X}(G)$. Any left invariant vector field ξ is uniquely determined by $\xi(e) \in T_eG$, since $\xi(a) = T_e(\mu_a).\xi(e)$. Thus the Lie algebra $\mathfrak{X}_L(G)$ of left invariant vector fields is linearly isomorphic to T_eG, and on T_eG the Lie bracket on $\mathfrak{X}_L(G)$ induces a Lie algebra structure, whose bracket is again denoted by $[\ \ ,\ \ ]$. This Lie algebra will be denoted as usual by $\mathfrak{g}$, sometimes by $Lie(G)$.

We will also give a name to the isomorphism with the space of left invariant vector fields: $L : \mathfrak{g} \to \mathfrak{X}_L(G)$, $X \mapsto L_X$, where $L_X(a) = T_e\mu_a.X$. Thus $[X,Y] = [L_X, L_Y](e)$.

A vector field η on G is called *right invariant*, if $(\mu^a)^*\eta = \eta$ for all $a \in G$. If ξ is left invariant, then $\nu^*\xi$ is right invariant, since $\nu \circ \mu^a = \mu_{a^{-1}} \circ \nu$ implies that $(\mu^a)^*\nu^*\xi = (\nu \circ \mu^a)^*\xi = (\mu_{a^{-1}} \circ \nu)^*\xi = \nu^*(\mu_{a^{-1}})^*\xi = \nu^*\xi$. The right invariant vector fields form a sub Lie algebra $\mathfrak{X}_R(G)$ of $\mathfrak{X}(G)$, which is again linearly isomorphic to T_eG and induces also a Lie algebra structure on T_eG. Since $\nu^* : \mathfrak{X}_L(G) \to \mathfrak{X}_R(G)$ is an isomorphism of Lie algebras by (3.11), $T_e\nu = -Id : T_eG \to T_eG$ is an isomorphism between the two Lie algebra structures. We will denote by $R : \mathfrak{g} = T_eG \to \mathfrak{X}_R(G)$ the isomorphism discussed, which is given by $R_X(a) = T_e(\mu^a).X$.

4.12. Lemma. *If L_X is a left invariant vector field and R_Y is a right invariant one, then $[L_X, R_Y] = 0$. Thus the flows of L_X and R_Y commute.*

Proof. We consider the vector field $0 \times L_X \in \mathfrak{X}(G \times G)$, given by $(0 \times L_X)(a, b) = (0_a, L_X(b))$. Then $T_{(a,b)}\mu.(0_a, L_X(b)) = T_a\mu^b.0_a + T_b\mu_a.L_X(b) = L_X(ab)$, so $0 \times L_X$ is μ-related to L_X. Likewise $R_Y \times 0$ is μ-related to R_Y. But then $0 = [0 \times L_X, R_Y \times 0]$ is μ-related to $[L_X, R_Y]$ by (3.10). Since μ is surjective, $[L_X, R_Y] = 0$ follows. □

4.13. Lemma. *Let $\varphi : G \to H$ be a smooth homomorphism of Lie groups.*

Then $\varphi' := T_e\varphi : \mathfrak{g} = T_eG \to \mathfrak{h} = T_eH$ is a Lie algebra homomorphism.

Later, in (4.21), we shall see that any continuous homomorphism between Lie groups is automatically smooth.

Proof. For $X \in \mathfrak{g}$ and $x \in G$ we have

$$\begin{aligned} T_x\varphi.L_X(x) &= T_x\varphi.T_e\mu_x.X = T_e(\varphi \circ \mu_x).X \\ &= T_e(\mu_{\varphi(x)} \circ \varphi).X = T_e(\mu_{\varphi(x)}).T_e\varphi.X = L_{\varphi'(X)}(\varphi(x)). \end{aligned}$$

So L_X is φ-related to $L_{\varphi'(X)}$. By (3.10) the field $[L_X, L_Y] = L_{[X,Y]}$ is φ-related to $[L_{\varphi'(X)}, L_{\varphi'(Y)}] = L_{[\varphi'(X),\varphi'(Y)]}$. So we have $T\varphi \circ L_{[X,Y]} = L_{[\varphi'(X),\varphi'(Y)]} \circ \varphi$. If we evaluate this at e the result follows. □

Now we will determine the Lie algebras of all the examples given above.

4.14. For the Lie group $GL(n, \mathbb{R})$ we have $T_eGL(n, \mathbb{R}) = L(\mathbb{R}^n, \mathbb{R}^n) =: \mathfrak{gl}(n, \mathbb{R})$ and $T\,GL(n, \mathbb{R}) = GL(n, \mathbb{R}) \times L(\mathbb{R}^n, \mathbb{R}^n)$ by the affine structure of the surrounding vector space. For $A \in GL(n, \mathbb{R})$ we have $\mu_A(B) = A.B$, so μ_A extends to a linear isomorphism of $L(\mathbb{R}^n, \mathbb{R}^n)$, and for $(B, X) \in T\,GL(n, \mathbb{R})$ we get $T_B(\mu_A).(B, X) = (A.B, A.X)$. So the left invariant vector field $L_X \in \mathfrak{X}_L(GL(n, \mathbb{R}))$ is given by $L_X(A) = T_e(\mu_A).X = (A, A.X)$.

Let $f : GL(n, \mathbb{R}) \to \mathbb{R}$ be the restriction of a linear functional on $L(\mathbb{R}^n, \mathbb{R}^n)$. Then we have $L_X(f)(A) = df(A)(L_X(A)) = df(A)(A.X) = f(A.X)$, which we may write as $L_X(f) = f(\quad .X)$. Therefore

$$\begin{aligned} L_{[X,Y]}(f) &= [L_X, L_Y](f) = L_X(L_Y(f)) - L_Y(L_X(f)) \\ &= L_X(f(\quad .Y)) - L_Y(f(\quad .X)) = f(\quad .X.Y) - f(\quad .Y.X) \\ &= f(\quad .(XY - YX)) = L_{XY-YX}(f). \end{aligned}$$

So the Lie bracket on $\mathfrak{gl}(n, \mathbb{R}) = L(\mathbb{R}^n, \mathbb{R}^n)$ is given by $[X, Y] = XY - YX$, the usual commutator.

4.15. Example. Let V be a vector space. Then $(V, +)$ is a Lie group, $T_0V = V$ is its Lie algebra, $TV = V \times V$, left translation is $\mu_v(w) = v + w$, $T_w(\mu_v).(w, X) = (v + w, X)$. So $L_X(v) = (v, X)$, a constant vector field. Thus the Lie bracket is 0.

4.16. Example. The special linear group is $SL(n,\mathbb{R}) = \det^{-1}(1)$ and its Lie algebra is given by $T_eSL(n,\mathbb{R}) = \ker d\det(\mathbb{I}) = \{X \in L(\mathbb{R}^n,\mathbb{R}^n) : \operatorname{trace} X = 0\} = \mathfrak{sl}(n,\mathbb{R})$ by (4.6). The injection $i : SL(n,\mathbb{R}) \to GL(n,\mathbb{R})$ is a smooth homomorphism of Lie groups, so $T_ei = i' : \mathfrak{sl}(n,\mathbb{R}) \to \mathfrak{gl}(n,\mathbb{R})$ is an injective homomorphism of Lie algebras. Thus the Lie bracket is given by $[X,Y] = XY - YX$.

The same argument gives the commutator as the Lie bracket in all other examples we have treated. We have already determined the Lie algebras as T_eG.

4.17. One parameter subgroups. Let G be a Lie group with Lie algebra $\mathfrak{g}$. A *one parameter subgroup* of G is a Lie group homomorphism $\alpha : (\mathbb{R},+) \to G$, i.e. a smooth curve α in G with $\alpha(s+t) = \alpha(s).\alpha(t)$, and hence $\alpha(0) = e$.

Lemma. *Let $\alpha : \mathbb{R} \to G$ be a smooth curve with $\alpha(0) = e$. Let $X \in \mathfrak{g}$. Then the following assertions are equivalent.*

(1) *α is a one parameter subgroup with $X = \frac{\partial}{\partial t}\big|_0 \alpha(t)$.*
(2) *$\alpha(t) = \operatorname{Fl}^{L_X}(t,e)$ for all t.*
(3) *$\alpha(t) = \operatorname{Fl}^{R_X}(t,e)$ for all t.*
(4) *$x.\alpha(t) = \operatorname{Fl}^{L_X}(t,x)$, or $\operatorname{Fl}^{L_X}_t = \mu^{\alpha(t)}$, for all t .*
(5) *$\alpha(t).x = \operatorname{Fl}^{R_X}(t,x)$, or $\operatorname{Fl}^{R_X}_t = \mu_{\alpha(t)}$, for all t.*

Proof. (1) $\implies$ (4). We have $\frac{d}{dt}x.\alpha(t) = \frac{d}{ds}|_0 x.\alpha(t+s) = \frac{d}{ds}|_0 x.\alpha(t).\alpha(s) = \frac{d}{ds}|_0 \mu_{x.\alpha(t)}\alpha(s) = T_e(\mu_{x.\alpha(t)}).\frac{d}{ds}|_0\alpha(s) = T_e(\mu_{x.\alpha(t)}).X = L_X(x.\alpha(t))$. By uniqueness of solutions we get $x.\alpha(t) = \operatorname{Fl}^{L_X}(t,x)$.

(4) $\implies$ (2). This is clear.

(2) $\implies$ (1). We have

$$\begin{aligned}\tfrac{d}{ds}\alpha(t)\alpha(s) &= \tfrac{d}{ds}(\mu_{\alpha(t)}\alpha(s)) = T(\mu_{\alpha(t)})\tfrac{d}{ds}\alpha(s)\\ &= T(\mu_{\alpha(t)})L_X(\alpha(s)) = L_X(\alpha(t)\alpha(s))\end{aligned}$$

and $\alpha(t)\alpha(0) = \alpha(t)$. So we get $\alpha(t)\alpha(s) = \operatorname{Fl}^{L_X}(s,\alpha(t)) = \operatorname{Fl}^{L_X}_s \operatorname{Fl}^{L_X}_t(e) = \operatorname{Fl}^{L_X}(t+s,e) = \alpha(t+s)$.

(4) $\iff$ (5). We have $\operatorname{Fl}^{\nu^*\xi}_t = \nu^{-1}\circ \operatorname{Fl}^{\xi}_t \circ\nu$ by (3.14). Therefore we have by (4.11)

$$\begin{aligned}(\operatorname{Fl}^{R_X}_t(x^{-1}))^{-1} &= (\nu\circ\operatorname{Fl}^{R_X}_t\circ\nu)(x) = \operatorname{Fl}^{\nu^*R_X}_t(x)\\ &= \operatorname{Fl}^{L_X}_{-t}(x) = x.\alpha(-t).\end{aligned}$$

So $\operatorname{Fl}^{R_X}_t(x^{-1}) = \alpha(t).x^{-1}$, and $\operatorname{Fl}^{R_X}_t(y) = \alpha(t).y$.

(5) $\implies$ (3) $\implies$ (1) can be shown in a similar way. $\square$

An immediate consequence of the foregoing lemma is that left invariant and right invariant vector fields on a Lie group are always complete, so they have global flows, because a locally defined one parameter group can always be extended to a globally defined one by multiplying it up.

4.18. Definition. The *exponential mapping* $\exp : \mathfrak{g} \to G$ of a Lie group is defined by

$$\exp X = \mathrm{Fl}^{L_X}(1, e) = \mathrm{Fl}^{R_X}(1, e) = \alpha_X(1),$$

where α_X is the one parameter subgroup of G with $\dot{\alpha}_X(0) = X$.

Theorem.

(1) $\exp : \mathfrak{g} \to G$ *is smooth.*
(2) $\exp(tX) = \mathrm{Fl}^{L_X}(t, e)$.
(3) $\mathrm{Fl}^{L_X}(t, x) = x.\exp(tX)$.
(4) $\mathrm{Fl}^{R_X}(t, x) = \exp(tX).x$.
(5) $\exp(0) = e$ *and* $T_0 \exp = Id : T_0\mathfrak{g} = \mathfrak{g} \to T_eG = \mathfrak{g}$, *thus* $\exp$ *is a diffeomorphism from a neighborhood of 0 in* $\mathfrak{g}$ *onto a neighborhood of* e *in* G.

Proof. (1) Let $0 \times L \in \mathfrak{X}(\mathfrak{g} \times G)$ be given by $(0 \times L)(X, x) = (0_X, L_X(x))$. Then $pr_2 \mathrm{Fl}^{0\times L}(t, (X, e)) = \alpha_X(t)$ is smooth in (t, X).

(2) $\exp(tX) = \mathrm{Fl}^{t.L_X}(1, e) = \mathrm{Fl}^{L_X}(t, e) = \alpha_X(t)$.

(3) and (4) follow from lemma (4.17).

(5) $T_0 \exp .X = \frac{d}{dt}|_0 \exp(0 + t.X) = \frac{d}{dt}|_0 \mathrm{Fl}^{L_X}(t, e) = X$. □

4.19. Remark. If G is connected and $U \subset \mathfrak{g}$ is open with $0 \in U$, then the group generated by $\exp(U)$ equals G.

For this group is a subgroup of G containing some open neighborhood of e, so it is open. The complement in G is also open (as union of the other cosets), so this subgroup is open and closed. Since G is connected, it coincides with G.

If G is not connected, then the subgroup generated by $\exp(U)$ is the connected component of e in G.

4.20. Remark. Let $\varphi : G \to H$ be a smooth homomorphism of Lie groups. Then the diagram

$$\begin{array}{ccc} \mathfrak{g} & \xrightarrow{\varphi'} & \mathfrak{h} \\ {\scriptstyle \exp^G}\downarrow & & \downarrow{\scriptstyle \exp^H} \\ G & \xrightarrow{\varphi} & H \end{array}$$

commutes, since $t \mapsto \varphi(\exp^G(tX))$ is a one parameter subgroup of H which satisfies $\frac{d}{dt}|_0\varphi(\exp^G tX) = \varphi'(X)$, so $\varphi(\exp^G tX) = \exp^H(t\varphi'(X))$.

If G is connected and $\varphi, \psi : G \to H$ are homomorphisms of Lie groups with $\varphi' = \psi' : \mathfrak{g} \to \mathfrak{h}$, then $\varphi = \psi$. For $\varphi = \psi$ on the subgroup generated by $\exp^G \mathfrak{g}$ which equals G by (4.19).

4.21. Theorem. *A continuous homomorphism* $\varphi : G \to H$ *between Lie groups is smooth. In particular a topological group can carry at most one compatible Lie group structure.*

Proof. Let first $\varphi = \alpha : (\mathbb{R}, +) \to G$ be a continuous one parameter subgroup. Then $\alpha(-\varepsilon, \varepsilon) \subset \exp(U)$, where U is an absolutely convex (i.e., $t_1 x_1 + t_2 x_2 \in U$ for all $|t_i| \le 1$ and $x_i \in U$) open neighborhood of 0 in $\mathfrak{g}$ such that $\exp \restriction 2U$ is a diffeomorphism, for some $\varepsilon > 0$. Put $\beta := (\exp \restriction 2U)^{-1} \circ \alpha : (-\varepsilon, \varepsilon) \to \mathfrak{g}$. Then for $|t| < \frac{\varepsilon}{2}$ we have $\exp(2\beta(t)) = \exp(\beta(t))^2 = \alpha(t)^2 = \alpha(2t) = \exp(\beta(2t))$, so $2\beta(t) = \beta(2t)$; thus $\beta(\frac{s}{2}) = \frac{1}{2}\beta(s)$ for $|s| < \varepsilon$. So we have $\alpha(\frac{s}{2}) = \exp(\beta(\frac{s}{2})) = \exp(\frac{1}{2}\beta(s))$ for all $|s| < \varepsilon$ and by recursion we get $\alpha(\frac{s}{2^n}) = \exp(\frac{1}{2^n}\beta(s))$ for $n \in \mathbb{N}$ and in turn $\alpha(\frac{k}{2^n}s) = \alpha(\frac{s}{2^n})^k = \exp(\frac{1}{2^n}\beta(s))^k = \exp(\frac{k}{2^n}\beta(s))$ for $k \in \mathbb{Z}$. Since the $\frac{k}{2^n}$ for $k \in \mathbb{Z}$ and $n \in \mathbb{N}$ are dense in R and since α is continuous we get $\alpha(ts) = \exp(t\beta(s))$ for all $t \in \mathbb{R}$. So α is smooth.

Now let $\varphi : G \to H$ be a continuous homomorphism. Let $X_1, \dots, X_n$ be a linear basis of $\mathfrak{g}$. We define $\psi : \mathbb{R}^n \to G$ by $\psi(t^1, \dots, t^n) = \exp(t^1 X_1) \cdots \exp(t^n X_n)$. Then $T_0\psi$ is invertible, so ψ is a diffeomorphism near 0. Sometimes ψ^{-1} is called a coordinate system of the second kind. $t \mapsto \varphi(\exp^G tX_i)$ is a continuous one parameter subgroup of H, so it is smooth by the first part of the proof.

We have $(\varphi \circ \psi)(t^1, \dots, t^n) = (\varphi \exp(t^1 X_1)) \cdots (\varphi \exp(t^n X_n))$, so $\varphi \circ \psi$ is smooth. Thus φ is smooth near $e \in G$ and consequently everywhere on G. □

4.22. Theorem. *Let G and H be Lie groups (G separable is essential here), and let $\varphi : G \to H$ be a continuous bijective homomorphism. Then φ is a diffeomorphism.*

Proof. Our first aim is to show that φ is a homeomorphism. Let V be an open e-neighborhood in G, and let K be a compact e-neighborhood in G such that $K.K^{-1} \subset V$. Since G is separable there is a sequence $(a_i)_{i\in\mathbb{N}}$ in G such that $G = \bigcup_{i=1}^{\infty} a_i.K$. Since H is locally compact, it is a Baire space (i.e., V_i open and dense for $i \in \mathbb{N}$ implies $\bigcap V_i$ dense). The set $\varphi(a_i)\varphi(K)$ is compact, thus closed. Since $H = \bigcup_i \varphi(a_i).\varphi(K)$, there is some i such that $\varphi(a_i)\varphi(K)$ has non empty interior, so $\varphi(K)$ has non empty interior. Choose $b \in G$ such that $\varphi(b)$ is an interior point of $\varphi(K)$ in H. Then $e_H = \varphi(b)\varphi(b^{-1})$ is an interior point of $\varphi(K)\varphi(K^{-1}) \subset \varphi(V)$. So if U is open in G and $a \in U$, then e_H is an interior point of $\varphi(a^{-1}U)$, so $\varphi(a)$ is in the interior of $\varphi(U)$. Thus $\varphi(U)$ is open in H, and φ is a homeomorphism.

Now by (4.21) φ and φ^{-1} are smooth. □

4.23. Examples. We first describe the exponential mapping of the general linear group $GL(n, \mathbb{R})$. Let $X \in \mathfrak{gl}(n, \mathbb{R}) = L(\mathbb{R}^n, \mathbb{R}^n)$, then the left invariant vector field is given by $L_X(A) = (A, A.X) \in GL(n, \mathbb{R}) \times \mathfrak{gl}(n, \mathbb{R})$ and the one parameter group $\alpha_X(t) = \mathrm{Fl}^{L_X}(t, \mathbb{I})$ is given by the differential equation $\frac{d}{dt}\alpha_X(t) = L_X(\alpha_X(t)) = \alpha_X(t).X$, with initial condition $\alpha_X(0) = \mathbb{I}$. But the unique solution of this equation is $\alpha_X(t) = e^{tX} = \sum_{k=0}^{\infty} \frac{t^k}{k!} X^k$. So

$$\exp^{GL(n,\mathbb{R})}(X) = e^X = \sum_{k=0}^{\infty} \frac{1}{k!}\, X^k.$$

If $n = 1$ we get the usual exponential mapping of one real variable. For all Lie subgroups of $GL(n, \mathbb{R})$, the exponential mapping is given by the same formula $\exp(X) = e^X$; this follows from (4.20).

4.24. The adjoint representation. A *representation* of a Lie group G on a finite dimensional vector space V (real or complex) is a homomorphism $\rho : G \to GL(V)$ of Lie groups. Then by (4.13) $\rho' : \mathfrak{g} \to \mathfrak{gl}(V) = L(V,V)$ is a Lie algebra homomorphism.

For $a \in G$ we define $\operatorname{conj}_a : G \to G$ by $\operatorname{conj}_a(x) = axa^{-1}$. It is called the *conjugation* or the *inner automorphism* by $a \in G$. We have $\operatorname{conj}_a(xy) = \operatorname{conj}_a(x)\operatorname{conj}_a(y)$, $\operatorname{conj}_{ab} = \operatorname{conj}_a \circ \operatorname{conj}_b$, and conj is smooth in all variables.

Next we define for $a \in G$ the mapping $\operatorname{Ad}(a) = (\operatorname{conj}_a)' = T_e(\operatorname{conj}_a) : \mathfrak{g} \to \mathfrak{g}$. By (4.13) $\operatorname{Ad}(a)$ is a Lie algebra homomorphism, so we have $\operatorname{Ad}(a)[X,Y] = [\operatorname{Ad}(a)X, \operatorname{Ad}(a)Y]$. Furthermore $\operatorname{Ad} : G \to GL(\mathfrak{g})$ is a representation, called the *adjoint representation* of G, since

$$\begin{aligned}\operatorname{Ad}(ab) &= T_e(\operatorname{conj}_{ab}) = T_e(\operatorname{conj}_a \circ \operatorname{conj}_b)\\ &= T_e(\operatorname{conj}_a) \circ T_e(\operatorname{conj}_b) = \operatorname{Ad}(a) \circ \operatorname{Ad}(b).\end{aligned}$$

The relations $\operatorname{Ad}(a) = T_e(\operatorname{conj}_a) = T_a(\mu^{a^{-1}}).T_e(\mu_a) = T_{a^{-1}}(\mu_a).T_e(\mu^{a^{-1}})$ will be used later.

Finally we define the (lower case) *adjoint representation* of the Lie algebra $\mathfrak{g}$, $\operatorname{ad} : \mathfrak{g} \to \mathfrak{gl}(\mathfrak{g}) = L(\mathfrak{g},\mathfrak{g})$, by $\operatorname{ad} := \operatorname{Ad}' = T_e \operatorname{Ad}$.

Lemma.

(1) $L_X(a) = R_{\operatorname{Ad}(a)X}(a)$ *for* $X \in \mathfrak{g}$ *and* $a \in G$.

(2) $\operatorname{ad}(X)Y = [X,Y]$ *for* $X, Y \in \mathfrak{g}$.

Proof. (1) $L_X(a) = T_e(\mu_a).X = T_e(\mu^a).T_e(\mu^{a^{-1}} \circ \mu_a).X = R_{\operatorname{Ad}(a)X}(a)$.

(2) Let $X_1, \dots, X_n$ be a linear basis of $\mathfrak{g}$ and fix $X \in \mathfrak{g}$. Then $\operatorname{Ad}(x)X = \sum_{i=1}^n f_i(x).X_i$ for $f_i \in C^\infty(G,\mathbb{R})$ and we have in turn

$$\begin{aligned}\operatorname{Ad}'(Y)X &= T_e(\operatorname{Ad}(\quad)X)Y = d(\operatorname{Ad}(\quad)X)|_e Y = d(\textstyle\sum f_i X_i)|_e Y\\ &= \textstyle\sum df_i|_e(Y)X_i = \sum L_Y(f_i)(e).X_i.\\ L_X(x) &= R_{\operatorname{Ad}(x)X}(x) = R(\textstyle\sum f_i(x)X_i)(x) = \sum f_i(x).R_{X_i}(x) \text{ by (1).}\\ [L_Y, L_X] &= [L_Y, \textstyle\sum f_i.R_{X_i}] = 0 + \sum L_Y(f_i).R_{X_i} \text{ by (3.4) and (4.12).}\\ [Y,X] &= [L_Y, L_X](e) = \textstyle\sum L_Y(f_i)(e).R_{X_i}(e) = \operatorname{Ad}'(Y)X = \operatorname{ad}(Y)X. \quad \square\end{aligned}$$

4.25. Corollary. *From* (4.20) *and* (4.23) *we have*

$$\begin{aligned}\operatorname{Ad} \circ exp^G &= exp^{GL(\mathfrak{g})} \circ \operatorname{ad}\\ \operatorname{Ad}(exp^G X)Y &= \sum_{k=0}^\infty \tfrac{1}{k!}\, (\operatorname{ad} X)^k Y = e^{\operatorname{ad} X} Y\\ &= Y + [X,Y] + \tfrac{1}{2!}[X,[X,Y]] + \tfrac{1}{3!}[X,[X,[X,Y]]] + \cdots\end{aligned}$$

so that also $\operatorname{ad}(X) = \frac{\partial}{\partial t}\big|_0 \operatorname{Ad}(\exp(tX))$.

4.26. The right logarithmic derivative. Let M be a manifold and let $f : M \to G$ be a smooth mapping into a Lie group G with Lie algebra $\mathfrak{g}$. We define the mapping $\delta f : TM \to \mathfrak{g}$ by the formula $\delta f(\xi_x) := T_{f(x)}(\mu^{f(x)^{-1}}).T_x f.\xi_x$. Then δf is a $\mathfrak{g}$-valued 1-form on M, $\delta f \in \Omega^1(M, \mathfrak{g})$, as we will write later. We call δf the *right logarithmic derivative* of f, since for $f : \mathbb{R} \to (\mathbb{R}^+, \cdot)$ we have $\delta f(x).1 = \frac{f'(x)}{f(x)} = (\log \circ f)'(x)$.

Lemma. *Let $f, g : M \to G$ be smooth. Then we have*

$$\delta(f.g)(x) = \delta f(x) + \mathrm{Ad}(f(x)).\delta g(x).$$

Proof.

$$\begin{aligned}
\delta(f.g)(x) &= T(\mu^{g(x)^{-1}.f(x)^{-1}}).T_x(f.g) \\
&= T(\mu^{f(x)^{-1}}).T(\mu^{g(x)^{-1}}).T_{(f(x),g(x))}\mu.(T_x f, T_x g) \\
&= T(\mu^{f(x)^{-1}}).T(\mu^{g(x)^{-1}}).\Big(T(\mu^{g(x)}).T_x f + T(\mu_{f(x)}).T_x g\Big) \\
&= \delta f(x) + \mathrm{Ad}(f(x)).\delta g(x). \quad \square
\end{aligned}$$

Remark. The *left logarithmic derivative* $\delta^{\text{left}} f \in \Omega^1(M, \mathfrak{g})$ of a smooth mapping $f : M \to G$ is given by $\delta^{\text{left}} f.\xi_x = T_{f(x)}(\mu_{f(x)^{-1}}).T_x f.\xi_x$. The corresponding Leibnitz rule for it is uglier that that for the right logarithmic derivative:

$$\delta^{\text{left}}(fg)(x) = \delta^{\text{left}} g(x) + Ad(g(x)^{-1})\delta^{\text{left}} f(x).$$

The form $\delta^{\text{left}}(Id_G) \in \Omega^1(G, \mathfrak{g})$ is also called the *Maurer-Cartan form* of the Lie group G.

4.27. Lemma. *For* $\exp : \mathfrak{g} \to G$ *and for* $g(z) := \dfrac{e^z - 1}{z}$ *we have*

$$\delta(\exp)(X) = T(\mu^{\exp(-X)}).T_X \exp = \sum_{p=0}^{\infty} \tfrac{1}{(p+1)!} \,(\mathrm{ad}\ X)^p = g(\mathrm{ad}\ X).$$

Proof. We put $M(X) = \delta(\exp)(X) : \mathfrak{g} \to \mathfrak{g}$. Then

$$\begin{aligned}
(s+t)M((s+t)X) &= (s+t)\delta(\exp)((s+t)X) \\
&= \delta(\exp((s+t) \quad))X \qquad \text{by the chain rule,} \\
&= \delta(\exp(s \quad).\exp(t \quad)).X \\
&= \delta(\exp(s \quad)).X + Ad(\exp(sX)).\delta(\exp(t \quad)).X \quad \text{by 4.26,} \\
&= s.\delta(\exp)(sX) + Ad(\exp(sX)).t.\delta(\exp)(tX) \\
&= s.M(sX) + Ad(\exp(sX)).t.M(tX).
\end{aligned}$$

Next we put $N(t) := t.M(tX) \in L(\mathfrak{g}, \mathfrak{g})$, then we obtain $N(s+t) = N(s) + \operatorname{Ad}(\exp(sX)).N(t)$. We fix t, apply $\frac{d}{ds}|_0$, and get $N'(t) = N'(0) + \operatorname{ad}(X).N(t)$, where $N'(0) = M(0) + 0 = \delta(\exp)(0) = Id_{\mathfrak{g}}$. So we have the differential equation $N'(t) = Id_{\mathfrak{g}} + \operatorname{ad}(X).N(t)$ in $L(\mathfrak{g}, \mathfrak{g})$ with initial condition $N(0) = 0$. The unique solution is

$$N(s) = \sum_{p=0}^{\infty} \tfrac{1}{(p+1)!}\ \operatorname{ad}(X)^p.s^{p+1}, \quad \text{and so}$$

$$\delta(\exp)(X) = M(X) = N(1) = \sum_{p=0}^{\infty} \tfrac{1}{(p+1)!}\ \operatorname{ad}(X)^p. \quad \square$$

4.28. Corollary. *$T_X \exp$ is bijective if and only if no eigenvalue of $\operatorname{ad}(X) : \mathfrak{g} \to \mathfrak{g}$ is of the form $\sqrt{-1}\,2k\pi$ for $k \in \mathbb{Z} \setminus \{0\}$.*

Proof. The zeros of $g(z) = \frac{e^z - 1}{z}$ are exactly $z = 2k\pi\sqrt{-1}$ for $k \in \mathbb{Z} \setminus \{0\}$. The linear mapping $T_X \exp$ is bijective if and only if no eigenvalue of $g(\operatorname{ad}(X)) = T(\mu^{\exp(-X)}).T_X \exp$ is 0. But the eigenvalues of $g(\operatorname{ad}(X))$ are the images under g of the eigenvalues of $\operatorname{ad}(X)$. $\square$

4.29. Theorem. The Baker-Campbell-Hausdorff formula.
Let G be a Lie group with Lie algebra $\mathfrak{g}$. For complex z near 1 we consider the function $f(z) := \frac{\log(z)}{z-1} = \sum_{n \ge 0} \frac{(-1)^n}{n+1}(z-1)^n$.

Then for X, Y near 0 in $\mathfrak{g}$ we have $\exp X . \exp Y = \exp C(X, Y)$, where

$$\begin{aligned}
C(X,Y) &= Y + \int_0^1 f(e^{t.\operatorname{ad} X}.e^{\operatorname{ad} Y}).X\,dt \\
&= X + Y + \sum_{n\ge 1} \frac{(-1)^n}{n+1} \int_0^1 \Bigg(\sum_{\substack{k,\ell \ge 0\\ k+\ell \ge 1}} \frac{t^k}{k!\,\ell!}\,(\operatorname{ad} X)^k (\operatorname{ad} Y)^\ell \Bigg)^n X\,dt \\
&= X + Y + \sum_{n\ge 1} \frac{(-1)^n}{n+1} \sum_{\substack{k_1,\dots,k_n \ge 0\\ \ell_1,\dots \ell_n \ge 0\\ k_i+\ell_i \ge 1}} \frac{(\operatorname{ad} X)^{k_1}(\operatorname{ad} Y)^{\ell_1}\dots(\operatorname{ad} X)^{k_n}(\operatorname{ad} Y)^{\ell_n}}{(k_1+\dots+k_n+1)k_1!\dots k_n!\ell_1!\dots\ell_n!} X \\
&= X + Y + \tfrac{1}{2}[X,Y] + \tfrac{1}{12}([X,[X,Y]] - [Y,[Y,X]]) + \cdots
\end{aligned}$$

Proof. Let $C(X, Y) := \exp^{-1}(\exp X . \exp Y)$ for X, Y near 0 in $\mathfrak{g}$, and let $C(t) := C(tX, Y)$. Then by (4.27) we have

$$\begin{aligned}
T(\mu^{\exp(-C(t))})\tfrac{d}{dt}\,(\exp C(t)) &= \delta(\exp\circ C)(t).1 = \delta\exp(C(t)).\dot C(t) \\
&= \textstyle\sum_{k\ge 0} \frac{1}{(k+1)!}(\operatorname{ad}\, C(t))^k \dot C(t) = g(\operatorname{ad}\, C(t)).\dot C(t),
\end{aligned}$$

where $g(z) := \frac{e^z-1}{z} = \sum_{k\geq 0} \frac{z^k}{(k+1)!}$. We have $\exp C(t) = \exp(tX)\exp Y$ and $\exp(-C(t)) = \exp(C(t))^{-1} = \exp(-Y)\exp(-tX)$, therefore

$$\begin{aligned}
T(\mu^{\exp(-C(t))})\tfrac{d}{dt}(\exp C(t)) &= T(\mu^{\exp(-Y)\exp(-tX)})\tfrac{d}{dt}(\exp(tX)\exp Y)\\
&= T(\mu^{\exp(-tX)})T(\mu^{\exp(-Y)})T(\mu^{\exp Y})\tfrac{d}{dt}\exp(tX)\\
&= T(\mu^{\exp(-tX)}).R_X(\exp(tX)) = X, \quad \text{by (4.18.4) and (4.11).}\\
X &= g(\mathrm{ad}\ C(t)).\dot C(t).\\
e^{\mathrm{ad}\ C(t)} &= \mathrm{Ad}(\exp\ C(t)) \qquad \text{by (4.25)}\\
&= \mathrm{Ad}(\exp(tX)\exp Y) = \mathrm{Ad}(\exp(tX)).\mathrm{Ad}(\exp Y)\\
&= e^{\mathrm{ad}(tX)}.e^{\mathrm{ad}\ Y} = e^{t.\ \mathrm{ad}\ X}.e^{\mathrm{ad}\ Y}.
\end{aligned}$$

If X, Y, and t are small enough we get $\mathrm{ad}\ C(t) = \log(e^{t.\ \mathrm{ad}\ X}.e^{\mathrm{ad}\ Y})$, where $\log(z) = \sum_{n\geq 1}\frac{(-1)^{n+1}}{n}(z-1)^n$, thus we have

$$X = g(\mathrm{ad}\ C(t)).\dot C(t) = g(\log(e^{t.\ \mathrm{ad}\ X}.e^{\mathrm{ad}\ Y})).\dot C(t).$$

For z near 1 we put $f(z) := \frac{\log(z)}{z-1} = \sum_{n\geq 0}\frac{(-1)^n}{n+1}(z-1)^n$, satisfying $g(\log(z)).f(z) = 1$. So we have

$$X = g(\log(e^{t.\ \mathrm{ad}\ X}.e^{\mathrm{ad}\ Y})).\dot C(t) = f(e^{t.\ \mathrm{ad}\ X}.e^{\mathrm{ad}\ Y})^{-1}.\dot C(t),$$

$$\begin{cases} \dot C(t) = f(e^{t.\ \mathrm{ad}\ X}.e^{\mathrm{ad}\ Y}).X,\\ C(0) = Y \end{cases}$$

Passing to the definite integral we get the desired formula

$$\begin{aligned}
C(X,Y) &= C(1) = C(0) + \int_0^1 \dot C(t)\,dt\\
&= Y + \int_0^1 f(e^{t.\ \mathrm{ad}\ X}.e^{\mathrm{ad}\ Y}).X\,dt\\
&= X + Y + \sum_{n\geq 1}\frac{(-1)^n}{n+1}\int_0^1\Bigg(\sum_{\substack{k,\ell\geq 0\\ k+\ell\geq 1}}\frac{t^k}{k!\,\ell!}\,(\mathrm{ad}\ X)^k(\mathrm{ad}\ Y)^\ell\Bigg)^n X\ dt\\
&= X + Y + \sum_{n\geq 1}\frac{(-1)^n}{n+1}\sum_{\substack{k_1,\dots,k_n\geq 0\\ \ell_1,\dots\ell_n\geq 0\\ k_i+\ell_i\geq 1}}\frac{(\mathrm{ad}\,X)^{k_1}(\mathrm{ad}\,Y)^{\ell_1}\dots(\mathrm{ad}\,X)^{k_n}(\mathrm{ad}\,Y)^{\ell_n}}{(k_1+\dots+k_n+1)k_1!\dots k_n!\ell_1!\dots\ell_n!}X\\
&= X + Y + \tfrac12[X,Y] + \tfrac1{12}([X,[X,Y]] - [Y,[Y,X]]) + \cdots \quad \square
\end{aligned}$$

Remark. If G is a Lie group of differentiability class C^2, then we may define TG and the Lie bracket of vector fields. The proof above then makes sense and the theorem shows, that in the chart given by $\exp^{-1}$ the multiplication $\mu : G\times G\to G$ is C^ω near e, hence everywhere. So in this case G is a real analytic Lie group. See also remark (5.6) below.

4.30. Example. The group $SO(3,\mathbb{R})$. From (4.5) and (4.16) we know that the Lie algebra $\mathfrak{o}(3,\mathbb{R})$ of $SO(3,\mathbb{R})$ is the space $L_{\text{skew}}(\mathbb{R}^3,\mathbb{R}^3)$ of all linear mappings which are skew symmetric with respect to the inner product, with the commutator as Lie bracket.

The group $Sp(1) = S^3$ of unit quaternions has as Lie algebra $T_1S^3 = 1^\perp$, the space of imaginary quaternions, with the commutator of the quaternion multiplications as bracket. From (4.10) we see that this is $[X,Y] = 2X \times Y$.

Then we observe that the mapping

$$\alpha : \mathfrak{sp}(1) \to \mathfrak{o}(3,\mathbb{R}) = L_{\text{skew}}(\mathbb{R}^3,\mathbb{R}^3), \qquad \alpha(X)Y = 2X \times Y,$$

is a linear isomorphism between two 3-dimesional vector spaces, and is also an isomorphism of Lie algebras because $[\alpha(X),\alpha(Y)]Z = 4(X \times (Y \times Z) - Y \times (X \times Z)) = 4(X \times (Y \times Z) + Y \times (Z \times X)) = -4(Z \times (Y \times X)) = 2(2X \times Y) \times Z = \alpha([X,Y])Z$. Since S^3 is simply connected we may conclude from (5.4) below that $Sp(1)$ is the universal cover of $SO(3)$.

We can also see this directly as follows: Consider the mapping $\tau : S^3 \subset \mathbb{H} \to SO(3,\mathbb{R})$ which is given by $\tau(P)X = PX\bar{P}$, where $X \in \mathbb{R}^3 \times \{0\} \subset \mathbb{H}$ is an imaginary quaternion. It is clearly a homomorphism $\tau : S^3 \to GL(3,\mathbb{R})$, and since $|\tau(P)X| = |PX\bar{P}| = |X|$ and S^3 is connected it has values in $SO(3,\mathbb{R})$. The tangent mapping of τ is computed as $(T_1\tau.X)Y = XY1 + 1Y(-X) = 2(X \times Y) = \alpha(X)Y$, which we already an injective linear mapping between two 3-dimensional vector spaces, an isomorphism. Thus τ is a local diffeomorphism, the image of τ is an open and compact (since S^3 is compact) subgroup of $SO(3,\mathbb{R})$, so τ is surjective since $SO(3,\mathbb{R})$ is connected. The kernel of τ is the set of all $P \in S^3$ with $PX\bar{P} = X$ for all $X \in \mathbb{R}^3$, that is the intersection of the center of $\mathbb{H}$ with S^3, the set $\{1,-1\}$. So τ is a two sheeted covering mapping.

So the universal cover of $SO(3,\mathbb{R})$ is the group $S^3 = Sp(1) = SU(2) = Spin(3)$. Here $Spin(n)$ is just a name for the universal cover of $SO(n)$, and the isomorphism $Sp(1) = SU(2)$ is just given by the fact that the quaternions can also be described as the set of all complex matrices

$$\begin{pmatrix} a & b \\ -\bar{b} & \bar{a} \end{pmatrix} \sim a1 + bj.$$

The fundamental group $\pi_1(SO(3,\mathbb{R})) = \mathbb{Z}_2 = \mathbb{Z}/2\mathbb{Z}$.

4.31. Example. The group $SO(4,\mathbb{R})$. We consider the smooth homomorphism $\rho : S^3 \times S^3 \to SO(4,\mathbb{R})$ given by $\rho(P,Q)Z := PZ\bar{Q}$ in terms of multiplications of quaternions. The derived mapping is $\rho'(X,Y)Z = (T_{(1,1)}\rho.(X,Y))Z = XZ1 + 1Z(-Y) = XZ - ZY$, and its kernel consists of all pairs of imaginary quaternions (X,Y) with $XZ = ZY$ for all $Z \in \mathbb{H}$. If we put $Z = 1$ we get $X = Y$, then X is in the center of $\mathbb{H}$ which intersects $\mathfrak{sp}(1)$ in 0 only. So ρ' is a Lie algebra isomorphism since the dimensions are equal, and ρ is a local diffeomorphism. Its image is open and closed in $SO(4,\mathbb{R})$, so ρ is surjective, a covering mapping. The kernel of ρ is easily seen to be $\{(1,1),(-1,-1)\} \subset S^3 \times S^3$. So the universal cover of $SO(4,\mathbb{R})$ is $S^3 \times S^3 = Sp(1) \times Sp(1) = Spin(4)$, and the fundamental group $\pi_1(SO(4,\mathbb{R})) = \mathbb{Z}_2$ again.

Examples and Exercises

4.32. Let $A \in L(\mathbb{R}^n, \mathbb{R}^n)$ be an $(n \times n)$ matrix. Let $C(A)$ be the matrix of the *signed algebraic complements* of A, i.e.

$$C(A)^i_j := \det \begin{pmatrix} A^1_1 & \dots & A^1_{i-1} & 0 & A^1_{i+1} & \dots & A^1_n \\ \vdots & & \vdots & \vdots & \vdots & & \vdots \\ A^{j-1}_1 & \dots & A^{j-1}_{i-1} & 0 & A^{j-1}_{i+1} & \dots & A^{j-1}_n \\ 0 & \dots & 0 & 1 & 0 & \dots & 0 \\ A^{j+1}_1 & \dots & A^{j+1}_{i-1} & 0 & A^{j+1}_{i+1} & \dots & A^{j+1}_n \\ \vdots & & \vdots & \vdots & \vdots & & \vdots \\ A^n_1 & \dots & A^n_{i-1} & 0 & A^n_{i+1} & \dots & A^n_n \end{pmatrix}$$

Prove that $C(A)A = AC(A) = \det(A) \cdot \mathcal{I}$ (Cramer's rule)! This can be done by remembering the the expansion formula for the determinant during multiplying it out.

Prove that $d(\det)(A)X = \operatorname{Trace}(C(A)X)$! There are two ways to do this. The first one is to check that the standard inner product on $L(\mathbb{R}^n, \mathbb{R}^n)$ is given by $\langle A, X\rangle = \operatorname{Trace}(A^\top X)$, and by computing the gradient of det at A.

The second way uses (12.19):

$$\det(A + t\,\mathrm{Id}) = t^n + t^{n-1}\,\operatorname{Trace}(A) + t^{n-2} c^n_2(A) + \dots + t\, c^n_{n-1}(A) + \det(A).$$

Assume that A is invertible. Then:

$$\begin{aligned}\det(A + tX) &= t^n \det(t^{-1}A + X) = t^n \det(A(A^{-1}X + t^{-1}\,\mathrm{Id})) \\ &= t^n \det(A) \det(A^{-1}X + t^{-1}\,\mathrm{Id}) \\ &= t^n \det(A)(t^{-n} + t^{1-n}\operatorname{Trace}(A^{-1}X) + \dots + \det(A^{-1}X)) \\ &= \det(A)(1 + t\operatorname{Trace}(A^{-1}X) + O(t^2)), \\ d\det(A)X &= \tfrac{\partial}{\partial t}\big|_0 \det(A + tX) = \tfrac{\partial}{\partial t}\big|_0 \det(A)(1 + t\operatorname{Trace}(A^{-1}X) + O(t^2)) \\ &= \det(A)\operatorname{Trace}(A^{-1}X) = \operatorname{Trace}(\det(A)A^{-1}X) \\ &= \operatorname{Trace}(C(A)X).\end{aligned}$$

Since invertible matrices are dense, the formula follows by continuity.
What about $\det_{\mathbb{C}} : L_{\mathbb{C}}(\mathbb{C}^n, \mathbb{C}^n) \to \mathbb{C}$?

4.33. For a matrix $A \in L(\mathbb{R}^n, \mathbb{R}^n)$ let $e^A := \sum_{k\ge 0} \frac{1}{k!}A^k$. Prove that e^A converges everywhere, that $\det(e^A) = e^{\operatorname{Trace}(A)}$, and thus $e^A \in GL(n, \mathbb{R})$ for all $A \in L(\mathbb{R}^n, \mathbb{R}^n)$.

4.34. We can insert matrices into real analytic functions in one variable:

$$f(A) := f(0) \cdot \mathrm{Id} + \sum_{n\ge 0} \frac{f^{(n)}(0)}{n!} A^n, \qquad \text{if the norm } |A| \le \rho,$$

where ρ is the radius of convergence of f at 0. Develop some theory about that (attention with constants): $(f\cdot g)(A) = f(A)\cdot g(A)$, $(f\circ g)(A) = f(g(A))$, $df(A)X = f'(A)X$ if $[A, X] = 0$. What about $df(A)X$ in the general case?

4.35. Quaternions. Let $\langle\ \ ,\ \ \rangle$ denote standard inner product on oriented $\mathbb{R}^4$. Put $1 := (0,0,0,1) \in \mathbb{R}^4$ and $\mathbb{R}^3 \cong \mathbb{R}^3 \times \{0\} = 1^\perp \subset \mathbb{R}^4$. The vector product on $\mathbb{R}^3$ is then given by $\langle x \times y, z\rangle := \det(x,y,z)$. We define a multiplication on $\mathbb{R}^4$ by $(X,s)(Y,t) := (X \times Y + sY + tX, st - \langle X,Y\rangle)$. Prove that we get the *skew field* of *quaternions* $\mathbb{H}$, and derive all properties: Associativity, $|p.q| = |p|.|q|$, $p.\bar{p} = |p|^2.1$, $p^{-1} = |p|^{-2}.p$, $\overline{p.q} = \bar{q}.\bar{p}$. How many representation of the form $x = x_0 1 + x_1 i + x_2 j + x_3 k$ can we find? Show that $\mathbb{H}$ is isomorphic to the algebra of all complex (2×2)-matrices of the form

$$\begin{pmatrix} u & v \\ -\bar{v} & \bar{u} \end{pmatrix}, \quad u, v \in \mathbb{C}.$$

5. Lie Groups II. Lie Subgroups and Homogeneous Spaces

5.1. Definition. Let G be a Lie group. A subgroup H of G is called a *Lie subgroup*, if H is itself a Lie group (so it is separable) and the inclusion $i : H \to G$ is smooth.

In this case the inclusion is even an immersion. For that it suffices to check that $T_e i$ is injective: If $X \in \mathfrak{h}$ is in the kernel of $T_e i$, then $i \circ \exp^H(tX) = \exp^G(t.T_e i.X) = e$. Since i is injective, $X = 0$.

From the next result it follows that $H \subset G$ is then an initial submanifold in the sense of (2.13): If H_0 is the connected component of H, then $i(H_0)$ is the Lie subgroup of G generated by $i'(\mathfrak{h}) \subset \mathfrak{g}$, which is an initial submanifold, and this is true for all components of H.

5.2. Theorem. *Let G be a Lie group with Lie algebra $\mathfrak{g}$. If $\mathfrak{h} \subset \mathfrak{g}$ is a Lie subalgebra, then there is a unique connected Lie subgroup H of G with Lie algebra $\mathfrak{h}$. H is an initial submanifold.*

Proof. Put $E_x := \{T_e(\mu_x).X : X \in \mathfrak{h}\} \subset T_x G$. Then $E := \bigsqcup_{x\in G} E_x$ is a distribution of constant rank on G. So by theorem (3.20) the distribution E is integrable and the leaf H through e is an initial submanifold. It is even a subgroup, since for $x \in H$ the initial submanifold $\mu_x H$ is again a leaf (since E is left invariant) and intersects H (in x), so $\mu_x(H) = H$. Thus $H.H = H$ and consequently $H^{-1} = H$. The multiplication $\mu : H \times H \to G$ is smooth by restriction, and smooth as a mapping $H \times H \to H$, since H is an initial submanifold, by lemma (2.15). □

5.3. Theorem. *Let $\mathfrak{g}$ be a finite dimensional real Lie algebra. Then there exists a connected Lie group G whose Lie algebra is $\mathfrak{g}$.*

Sketch of Proof. By the theorem of Ado (see [Jacobson, 1962, p??] or [Varadarajan, 1974, p 237]) $\mathfrak{g}$ has a faithful (i.e. injective) representation on a finite dimensional vector space V, i.e. $\mathfrak{g}$ can be viewed as a Lie subalgebra of $\mathfrak{gl}(V) = L(V,V)$. By theorem (5.2) above there is a Lie subgroup G of $GL(V)$ with $\mathfrak{g}$ as its Lie algebra. □

This is a rather involved proof, since the theorem of Ado needs the structure theory of Lie algebras for its proof. There are simpler proofs available, starting from a neighborhood of e in G (a neighborhood of 0 in $\mathfrak{g}$ with the Baker-Campbell-Hausdorff formula (4.29) as multiplication) and extending it.

5.4. Theorem. *Let G and H be Lie groups with Lie algebras $\mathfrak{g}$ and $\mathfrak{h}$, respectively. Let $f : \mathfrak{g} \to \mathfrak{h}$ be a homomorphism of Lie algebras. Then there is a Lie group homomorphism φ, locally defined near e, from G to H, such that $\varphi' = T_e\varphi = f$. If G is simply connected, then there is a globally defined homomorphism of Lie groups $\varphi : G \to H$ with this property.*

Proof. Let $\mathfrak{k} := \operatorname{graph}(f) \subset \mathfrak{g} \times \mathfrak{h}$. Then $\mathfrak{k}$ is a Lie subalgebra of $\mathfrak{g} \times \mathfrak{h}$, since f is a homomorphism of Lie algebras. $\mathfrak{g} \times \mathfrak{h}$ is the Lie algebra of $G \times H$, so by theorem (5.2) there is a connected Lie subgroup $K \subset G \times H$ with algebra $\mathfrak{k}$. We consider the homomorphism $g := pr_1 \circ incl : K \to G \times H \to G$, whose tangent mapping satisfies $T_e g(X, f(X)) = T_{(e,e)}pr_1.T_e incl.(X, f(X)) = X$, so is invertible. Thus g is a local diffeomorphism, so $g : K \to G_0$ is a covering of the connected component G_0 of e in G. If G is simply connected, g is an isomorphism. Now we consider the homomorphism $\psi := pr_2 \circ incl : K \to G \times H \to H$, whose tangent mapping satisfies $T_e\psi.(X, f(X)) = f(X)$. We see that $\varphi := \psi \circ (g \restriction U)^{-1} : G \supset U \to H$ solves the problem, where U is an e-neighborhood in K such that $g \restriction U$ is a diffeomorphism. If G is simply connected, $\varphi = \psi \circ g^{-1}$ is the global solution. □

5.5. Theorem. *Let H be a closed subgroup of a Lie group G. Then H is a Lie subgroup and a submanifold of G.*

Proof. Let $\mathfrak{g}$ be the Lie algebra of G. We consider the subset $\mathfrak{h} := \{c'(0) : c \in C^\infty(\mathbb{R}, G), c(\mathbb{R}) \subset H, c(0) = e\}$.

Claim 1. $\mathfrak{h}$ is a linear subspace.
If $c_i'(0) \in \mathfrak{h}$ and $t_i \in \mathbb{R}$, we define $c(t) := c_1(t_1.t).c_2(t_2.t)$. Then we have $c'(0) = T_{(e,e)}\mu.(t_1.c_1'(0), t_2.c_2'(0)) = t_1.c_1'(0) + t_2.c_2'(0) \in \mathfrak{h}$.

Claim 2. $\mathfrak{h} = \{X \in \mathfrak{g} : \exp(tX) \in H \text{ for all } t \in \mathbb{R}\}$.
Clearly we have '$\supseteq$'. To check the other inclusion, let $X = c'(0) \in \mathfrak{h}$ and consider $v(t) := (\exp^G)^{-1}c(t)$ for small t. Then we have $X = c'(0) = \frac{d}{dt}|_0 \exp(v(t)) = v'(0) = \lim_{n\to\infty} n.v(\frac{1}{n})$. We put $t_n := \frac{1}{n}$ and $X_n := n.v(\frac{1}{n})$, so that $\exp(t_n.X_n) = \exp(v(\frac{1}{n})) = c(\frac{1}{n}) \in H$. By claim 3 below we then get $\exp(tX) \in H$ for all t.

Claim 3. Let $X_n \to X$ in $\mathfrak{g}$, $0 < t_n \to 0$ in $\mathbb{R}$ with $\exp(t_nX_n) \in H$. Then $\exp(tX) \in H$ for all $t \in \mathbb{R}$.
Let $t \in \mathbb{R}$ and take $m_n \in (\frac{t}{t_n} - 1, \frac{t}{t_n}] \cap \mathbb{Z}$. Then $t_n.m_n \to t$ and $m_n.t_n.X_n \to tX$, and since H is closed we may conclude that

$$\exp(tX) = \lim_n \exp(m_n.t_n.X_n) = \lim_n \exp(t_n.X_n)^{m_n} \in H.$$

Claim 4. Let $\mathfrak{k}$ be a complementary linear subspace for $\mathfrak{h}$ in $\mathfrak{g}$. Then there is an open 0-neighborhood W in $\mathfrak{k}$ such that $\exp(W) \cap H = \{e\}$.

If not there are $0 \neq Y_k \in \mathfrak{k}$ with $Y_k \to 0$ such that $\exp(Y_k) \in H$. Choose a norm $|\quad|$ on $\mathfrak{g}$ and let $X_n = Y_n/|Y_n|$. Passing to a subsequence we may assume that $X_n \to X$ in $\mathfrak{k}$, then $|X| = 1$. But $\exp(|Y_n|.X_n) = \exp(Y_n) \in H$ and $0 < |Y_n| \to 0$, so by claim 3 we have $\exp(tX) \in H$ for all $t \in \mathbb{R}$. So by claim 2 $X \in \mathfrak{h}$, a contradiction.

Claim 5. Put $\varphi : \mathfrak{h} \times \mathfrak{k} \to G$, $\varphi(X, Y) = \exp X. \exp Y$. Then there are 0-neighborhoods V in $\mathfrak{h}$, W in $\mathfrak{k}$, and an e-neighborhood U in G such that $\varphi : V \times W \to U$ is a diffeomorphism and $U \cap H = \exp(V)$.

Choose V, W, and U so small that φ becomes a diffeomorphism. By claim 4 the set W may be chosen so small that $\exp(W) \cap H = \{e\}$. By claim 2 we have $\exp(V) \subseteq H \cap U$. Let $x \in H \cap U$. Since $x \in U$ we have $x = \exp X. \exp Y$ for unique $(X, Y) \in V \times W$. Then x and $\exp X \in H$, so $\exp Y \in H \cap \exp(W) = \{e\}$, thus $Y = 0$. So $x = \exp X \in \exp(V)$.

Claim 6. H is a submanifold and a Lie subgroup.

$(U, (\varphi \restriction V \times W)^{-1} =: u)$ is a submanifold chart for H centered at e by claim 5. For $x \in H$ the pair $(\mu_x(U), u \circ \mu_{x^{-1}})$ is a submanifold chart for H centered at x. So H is a closed submanifold of G, and the multiplication is smooth since it is a restriction. $\square$

5.6. Remark. The following stronger results on subgroups and the relation between topological groups and Lie groups in general are available.

Any arc wise connected subgroup of a Lie group is a connected Lie subgroup, [Yamabe, 1950].

Let G be a separable locally compact topological group. If it has an e-neighborhood which does not contain a proper subgroup, then G is a Lie group. This is the solution of the 5-th problem of Hilbert, see the book [Montgomery-Zippin, 1955, p. 107].

Any subgroup H of a Lie group G has a coarsest Lie group structure, but it might be non separable. To indicate a proof of this statement, consider all continuous curves $c : \mathbb{R} \to G$ with $c(\mathbb{R}) \subset H$, and equip H with the final topology with respect to them. Then the component of the identity satisfies the conditions of the Gleason-Yamabe theorem cited above.

5.7. Let $\mathfrak{g}$ be a Lie algebra. An *ideal* $\mathfrak{k}$ in $\mathfrak{g}$ is a linear subspace $\mathfrak{k}$ such that $[\mathfrak{k}, \mathfrak{g}] \subset \mathfrak{k}$. Then the quotient space $\mathfrak{g}/\mathfrak{k}$ carries a unique Lie algebra structure such that $\mathfrak{g} \to \mathfrak{g}/\mathfrak{k}$ is a Lie algebra homomorphism.

Lemma. *A connected Lie subgroup H of a connected Lie group G is a normal subgroup if and only if its Lie algebra $\mathfrak{h}$ is an ideal in $\mathfrak{g}$.*

Proof. H normal in G means $xHx^{-1} = \text{conj}_x(H) \subset H$ for all $x \in G$. By remark (4.20) this is equivalent to $T_e(\text{conj}_x)(\mathfrak{h}) \subset \mathfrak{h}$, i.e. $\text{Ad}(x)\mathfrak{h} \subset \mathfrak{h}$, for all $x \in G$. But this in turn is equivalent to $\text{ad}(X)\mathfrak{h} \subset \mathfrak{h}$ for all $X \in \mathfrak{g}$, so to the fact that $\mathfrak{h}$ is an ideal in $\mathfrak{g}$. $\square$

5.8. Let G be a connected Lie group. If $A \subset G$ is an arbitrary subset, the *centralizer* of A in G is the closed subgroup $Z_G(A) := \{x \in G : xa = ax \text{ for all } a \in A\}$.

The Lie algebra $\mathfrak{z}_{\mathfrak{g}}(A)$ of $Z_G(A)$ consists of all $X \in \mathfrak{g}$ such that $a.\exp(tX).a^{-1} = \exp(tX)$ for all $a \in A$, i.e. $\mathfrak{z}_{\mathfrak{g}}(A) = \{X \in \mathfrak{g} : \mathrm{Ad}(a)X = X \text{ for all } a \in A\}$.

If A is itself a connected Lie subgroup of G with Lie algebra $\mathfrak{a}$, then $\mathfrak{z}_{\mathfrak{g}}(A) = \{X \in \mathfrak{g} : \mathrm{ad}(Y)X = 0 \text{ for all } Y \in \mathfrak{a}\}$. This set is also called the *centralizer* of $\mathfrak{a}$ in $\mathfrak{g}$. If $A = G$ is connected then $Z_G = Z_G(G)$ is called the *center* of G and $\mathfrak{z}_{\mathfrak{g}}(G) = \mathfrak{z}_{\mathfrak{g}} = \{X \in \mathfrak{g} : [X, Y] = 0 \text{ for all } Y \in \mathfrak{g}\}$ is then the *center* of the Lie algebra $\mathfrak{g}$.

5.9. The *normalizer* of a subset A of a connected Lie group G is the subgroup $N_G(A) = \{x \in G : \mu_x(A) = \mu^x(A)\} = \{x \in G : \mathrm{conj}_x(A) = A\}$. If A is closed then $N_G(A)$ is also closed.

If A is a connected Lie subgroup of G then $N_G(A) = \{x \in G : \mathrm{Ad}(x)\mathfrak{a} \subset \mathfrak{a}\}$ and its Lie algebra is $\mathfrak{n}_G(A) = \{X \in \mathfrak{g} : \mathrm{ad}(X)\mathfrak{a} \subset \mathfrak{a}\} = \mathfrak{n}_{\mathfrak{g}}(\mathfrak{a})$ is then the *normalizer* or *idealizer* of $\mathfrak{a}$ in $\mathfrak{g}$.

5.10. Group actions. A *left action* of a Lie group G on a manifold M is a smooth mapping $\ell : G \times M \to M$ such that $\ell_g \circ \ell_h = \ell_{gh}$ and $\ell_e = Id_M$, where $\ell_g(z) = \ell(g, z)$.

A *right action* of a Lie group G on a manifold M is a smooth mapping $r : M \times G \to M$ such that $r^g \circ r^h = r^{hg}$ and $r^e = Id_M$, where $r^g(z) = r(z, g)$.

A G-space is a manifold M together with a right or left action of G on M.

We will describe the following notions only for a left action of G on M. They make sense also for right actions.

The *orbit* through $z \in M$ is the set $G.z = \ell(G, z) \subset M$. The action is called *transitive*, if M is one orbit, i.e. for all $z, w \in M$ there is some $g \in G$ with $g.z = w$. The action is called *free*, if $g_1.z = g_2.z$ for some $z \in M$ implies already $g_1 = g_2$. The action is called *effective*, if $\ell_g = \ell_h$ implies $g = h$, i.e. if $\ell : G \to \mathrm{Diff}(M)$ is injective, where $\mathrm{Diff}(M)$ denotes the group of all diffeomorphisms of M.

More generally, a continuous transformation group of a topological space M is a pair (G, M) where G is a topological group and where to each element $g \in G$ there is given a homeomorphism ℓ_g of M such that $\ell : G \times M \to M$ is continuous, and $\ell_g \circ \ell_h = \ell_{gh}$. The continuity is an obvious geometrical requirement, but in accordance with the general observation that group properties often force more regularity than explicitly postulated (cf. (5.6)), differentiability follows in many situations. So, if G is locally compact, M is a smooth or real analytic manifold, all ℓ_g are smooth or real analytic homeomorphisms and the action is effective, then G is a Lie group and ℓ is smooth or real analytic, respectively, see [Montgomery, Zippin, 55, p. 212].

5.11. Homogeneous spaces. Let G be a Lie group and let $H \subset G$ be a closed subgroup. By theorem (5.5) H is a Lie subgroup of G. We denote by G/H the space of all right cosets of G, i.e. $G/H = \{gH : g \in G\}$. Let $p : G \to G/H$ be the projection. We equip G/H with the quotient topology, i.e. $U \subset G/H$ is open if and only if $p^{-1}(U)$ is open in G. Since H is closed, G/H is a Hausdorff space.

G/H is called a *homogeneous space* of G. We have a left action of G on G/H, which is induced by the left translation and is given by $\bar{\mu}_g(g_1 H) = gg_1 H$.

Theorem. *If H is a closed subgroup of G, then there exists a unique structure of a smooth manifold on G/H such that $p : G \to G/H$ is a submersion. Thus* $\dim G/H = \dim G - \dim H$.

Proof. Surjective submersions have the universal property (2.4), thus the manifold structure on G/H is unique, if it exists. Let $\mathfrak{h}$ be the Lie algebra of the Lie subgroup H. We choose a complementary linear subspace $\mathfrak{k}$ such that $\mathfrak{g} = \mathfrak{h} \oplus \mathfrak{k}$.

Claim 1. We consider the mapping $f : \mathfrak{k} \times H \to G$, given by $f(X, h) := \exp X.h$. Then there is an open 0-neighborhood W in $\mathfrak{k}$ and an open e-neighborhood U in G such that $f : W \times H \to U$ is a diffeomorphism.
By claim 5 in the proof of theorem (5.5) there are open 0-neighborhoods V in $\mathfrak{h}$, W' in $\mathfrak{k}$, and an open e-neighborhood U' in G such that $\varphi : W' \times V \to U'$ is a diffeomorphism, where $\varphi(X, Y) = \exp X. \exp Y$, and such that $U' \cap H = \exp V$. Now we choose W in $W' \subset \mathfrak{k}$ so small that $\exp(W)^{-1}. \exp(W) \subset U'$. We will check that this W satisfies claim 1.

Claim 2. $f \restriction W \times H$ is injective.
$f(X_1, h_1) = f(X_2, h_2)$ means $\exp X_1.h_1 = \exp X_2.h_2$, thus we have $h_2 h_1^{-1} = (\exp X_2)^{-1} \exp X_1 \in \exp(W)^{-1} \exp(W) \cap H \subset U' \cap H = \exp V$. So there is a unique $Y \in V$ with $h_2 h_1^{-1} = \exp Y$. But then $\varphi(X_1, 0) = \exp X_1 = \exp X_2.h_2.h_1^{-1} = \exp X_2. \exp Y = \varphi(X_2, Y)$. Since φ is injective, $X_1 = X_2$ and $Y = 0$, so $h_1 = h_2$.

Claim 3. $f \restriction W \times H$ is a local diffeomorphism.
The diagram

$$\begin{array}{ccc} W \times V & \xrightarrow{Id \times \exp} & W \times (U' \cap H) \\ {\scriptstyle\varphi}\downarrow & & \downarrow{\scriptstyle f} \\ \varphi(W \times V) & \xrightarrow{incl} & U' \end{array}$$

commutes, and $Id_W \times \exp$ and φ are diffeomorphisms. So $f \restriction W \times (U' \cap H)$ is a diffeomorphism. Since $f(X, h) = f(X, e).h$ we conclude that $f \restriction W \times H$ is everywhere a local diffeomorphism. So finally claim 1 follows, where $U = f(W \times H)$.

Now we put $g := p \circ (\exp \restriction W) : \mathfrak{k} \supset W \to G/H$. Then the following diagram commutes:

$$\begin{array}{ccc} W \times H & \xrightarrow{f} & U \\ {\scriptstyle pr_1}\downarrow & & \downarrow{\scriptstyle p} \\ W & \xrightarrow{g} & G/H. \end{array}$$

Claim 4. g is a homeomorphism onto $p(U) =: \bar{U} \subset G/H$.
Clearly g is continuous, and g is open, since p is open. If $g(X_1) = g(X_2)$ then $\exp X_1 = \exp X_2.h$ for some $h \in H$, so $f(X_1, e) = f(X_2, h)$. By claim 1 we get $X_1 = X_2$, so g is injective. Finally $g(W) = \bar{U}$, so claim 4 follows.

For $a \in G$ we consider $\bar{U}_a = \bar{\mu}_a(\bar{U}) = a.\bar{U}$ and the mapping $u_a := g^{-1} \circ \bar{\mu}_{a^{-1}} : \bar{U}_a \to W \subset \mathfrak{k}$.

Claim 5. $(\bar{U}_a, u_a = g^{-1} \circ \bar{\mu}_{a^{-1}} : \bar{U}_a \to W)_{a \in G}$ is a smooth atlas for G/H.
Let a, $b \in G$ such that $\bar{U}_a \cap \bar{U}_b \neq \emptyset$. Then

$$\begin{aligned} u_a \circ u_b^{-1} &= g^{-1} \circ \bar{\mu}_{a^{-1}} \circ \bar{\mu}_b \circ g : u_b(\bar{U}_a \cap \bar{U}_b) \to u_a(\bar{U}_a \cap \bar{U}_b) \\ &= g^{-1} \circ \bar{\mu}_{a^{-1}b} \circ p \circ (\exp \restriction W) \\ &= g^{-1} \circ p \circ \mu_{a^{-1}b} \circ (\exp \restriction W) \\ &= pr_1 \circ f^{-1} \circ \mu_{a^{-1}b} \circ (\exp \restriction W) \quad \text{is smooth.} \quad \square \end{aligned}$$

5.12. Let $\ell : G \times M \to M$ be a left action. Then we have partial mappings $\ell_a : M \to M$ and $\ell^x : G \to M$, given by $\ell_a(x) = \ell^x(a) = \ell(a,x) = a.x$, where $a \in G$ and $x \in M$.

For any $X \in \mathfrak{g}$ we define the *fundamental vector field* $\zeta_X = \zeta_X^M \in \mathfrak{X}(M)$ by $\zeta_X(x) = T_e(\ell^x).X = T_{(e,x)}\ell.(X, 0_x)$.

Lemma. *In this situation the following assertions hold:*

(1) $\zeta : \mathfrak{g} \to \mathfrak{X}(M)$ *is a linear mapping.*
(2) $T_x(\ell_a).\zeta_X(x) = \zeta_{\mathrm{Ad}(a)X}(a.x)$.
(3) $R_X \times 0_M \in \mathfrak{X}(G \times M)$ *is ℓ-related to* $\zeta_X \in \mathfrak{X}(M)$.
(4) $[\zeta_X, \zeta_Y] = -\zeta_{[X,Y]}$.

Proof. (1) is clear.

(2) We have $\ell_a \ell^x(b) = abx = aba^{-1}ax = \ell^{ax}\operatorname{conj}_a(b)$, so

$$\begin{aligned} T_x(\ell_a).\zeta_X(x) &= T_x(\ell_a).T_e(\ell^x).X = T_e(\ell_a \circ \ell^x).X \\ &= T_e(\ell^{ax}).\mathrm{Ad}(a).X = \zeta_{\mathrm{Ad}(a)X}(ax). \end{aligned}$$

(3) We have $\ell \circ (Id \times \ell_a) = \ell \circ (\mu^a \times Id) : G \times M \to M$, so

$$\begin{aligned} \zeta_X(\ell(a,x)) &= T_{(e,ax)}\ell.(X, 0_{ax}) = T\ell.(Id \times T(\ell_a)).(X, 0_x) \\ &= T\ell.(T(\mu^a) \times Id).(X, 0_x) = T\ell.(R_X \times 0_M)(a,x). \end{aligned}$$

(4) $[R_X \times 0_M, R_Y \times 0_M] = [R_X, R_Y] \times 0_M = -R_{[X,Y]} \times 0_M$ is ℓ-related to $[\zeta_X, \zeta_Y]$ by (3) and by (3.10). On the other hand $-R_{[X,Y]} \times 0_M$ is ℓ-related to $-\zeta_{[X,Y]}$ by (3) again. Since ℓ is surjective we get $[\zeta_X, \zeta_Y] = -\zeta_{[X,Y]}$. $\square$

5.13. Let $r : M \times G \to M$ be a right action, so $\check{r} : G \to \mathrm{Diff}(M)$ is a group anti homomorphism. We will use the following notation: $r^a : M \to M$ and $r_x : G \to M$, given by $r_x(a) = r^a(x) = r(x,a) = x.a$.

For any $X \in \mathfrak{g}$ we define the *fundamental vector field* $\zeta_X = \zeta_X^M \in \mathfrak{X}(M)$ by $\zeta_X(x) = T_e(r_x).X = T_{(x,e)}r.(0_x, X)$.

Lemma. *In this situation the following assertions hold:*

(1) $\zeta : \mathfrak{g} \to \mathfrak{X}(M)$ *is a linear mapping.*
(2) $T_x(r^a).\zeta_X(x) = \zeta_{\operatorname{Ad}(a^{-1})X}(x.a)$.
(3) $0_M \times L_X \in \mathfrak{X}(M \times G)$ *is* r*-related to* $\zeta_X \in \mathfrak{X}(M)$.
(4) $[\zeta_X, \zeta_Y] = \zeta_{[X,Y]}$. □

5.14. Theorem. *Let* $\ell : G \times M \to M$ *be a smooth left action. For* $x \in M$ *let* $G_x = \{a \in G : ax = x\}$ *be the isotropy subgroup or fixpoint group of* x *in* G*, a closed subgroup of* G*. Then* $\ell^x : G \to M$ *factors over* $p : G \to G/G_x$ *to an injective immersion* $i^x : G/G_x \to M$*, which is* G*-equivariant, i.e.* $\ell_a \circ i^x = i^x \circ \bar\mu_a$ *for all* $a \in G$*. The image of* i^x *is the orbit through* x*.*

The fundamental vector fields span an integrable distribution on M *in the sense of* (3.23)*. Its leaves are the connected components of the orbits, and each orbit is an initial submanifold.*

Proof. Clearly ℓ^x factors over p to an injective mapping $i^x : G/G_x \to M$; by the universal property of surjective submersions i^x is smooth, and obviously it is equivariant. Thus $T_{p(a)}(i^x).T_{p(e)}(\bar\mu_a) = T_{p(e)}(i^x \circ \bar\mu_a) = T_{p(e)}(\ell_a \circ i^x) = T_x(\ell_a).T_{p(e)}(i^x)$ for all $a \in G$ and it suffices to show that $T_{p(e)}(i^x)$ is injective.

Let $X \in \mathfrak{g}$ and consider its fundamental vector field $\zeta_X \in \mathfrak{X}(M)$. By (3.14) and (5.12.3) we have

$$\ell(\exp(tX), x) = \ell(\operatorname{Fl}_t^{R_X \times 0_M}(e, x)) = \operatorname{Fl}_t^{\zeta_X}(\ell(e, x)) = \operatorname{Fl}_t^{\zeta_X}(x).$$

So $\exp(tX) \in G_x$, i.e. $X \in \mathfrak{g}_x$, if and only if $\zeta_X(x) = 0_x$. In other words, $0_x = \zeta_X(x) = T_e(\ell^x).X = T_{p(e)}(i^x).T_e p.X$ if and only if $T_e p.X = 0_{p(e)}$. Thus i^x is an immersion.

Since the connected components of the orbits are integral manifolds, the fundamental vector fields span an integrable distribution in the sense of (3.23); but also the condition (3.28.2) is satisfied. So by theorem (3.25) each orbit is an initial submanifold in the sense of (2.13). □

5.15. Theorem. [Palais, 1957] *Let* M *be a smooth manifold and let* $\zeta : \mathfrak{g} \to \mathfrak{X}(M)$ *be a homomorphism from a finite dimensional Lie algebra* $\mathfrak{g}$ *into the Lie algebra of vector fields on* M *such that each element* ζ_X *in the image of* ζ *is a complete vector field. Let* G *be a simply connected Lie group with Lie algebra* $\mathfrak{g}$*.*

Then there exists a left action $l : G \times M \to M$ *of the Lie group* G *on the manifold* M *whose fundamental vector field mapping equals* $-\zeta$*.*

Proof. On the product manifold $G \times M$ we consider the sub vector bundle $E = \{(L_X(g), \zeta_X(x) : (g, x) \in G \times M, X \in \mathfrak{g}\} \subset TG \times TM$ with global frame $L_{X_i} \times \zeta_{X_i}$, where the X_i form a basis of $\mathfrak{g}$, and where $L_X \in \mathfrak{X}(G)$ is the left invariant vector field generated by $X \in \mathfrak{g}$. Then E is an integrable subbundle since $[L_X \times \zeta_X, L_Y \times \zeta_Y] = [L_X, L_Y] \times [\zeta_X, \zeta_Y] = L_{[X,Y]} \times \zeta_{[X,Y]}$. Thus by theorem (3.20) (or (3.28)) the bundle E induces a foliation on $G \times M$. Note that by (4.18.3) for the flow we have

(1) $$\operatorname{Fl}_t^{L_X \times \zeta_X}(g, x) = (g.\exp(tX), \operatorname{Fl}_t^{\zeta_X}(x)).$$

Claim. For any leaf $L \subset G \times M$, the restriction $\operatorname{pr}_1 |L : L \to G$ is a covering map.

For $(g,x) \in L$ we have $T_{(g,x)}(\operatorname{pr}_1)(L_X(g), \zeta_X(x)) = L_X(g)$, thus $\operatorname{pr}_1 |L$ is locally a diffeomorphism. For any $g_1 \in G$ we can find a piecewise smooth curve c in G connecting g with g_1 consisting of pieces of the form $t \mapsto g_i.\exp(tX_i)$. Starting from $(g,x) \in L$ we can fit together corresponding pieces of the form $\operatorname{Fl}_t^{L_{X_i}\times\zeta_{X_i}}$ to obtain a curve $\tilde c$ in L with $\operatorname{pr}_1 \circ \tilde c = c$ which connects (g,x) with $(g_1,x_1) \in L$ for some $x_1 \in M$. Thus $\operatorname{pr}_1 : L \to G$ is surjective. Next we consider some absolutely convex ball $B \subset \mathfrak g$ such that $\exp : \mathfrak g \supset B \to U \subset G$ is a diffeomorphism onto an open neighborhood U of e in G. We consider the inverse image $(\operatorname{pr}_1 |L)^{-1}(g.U) \subset L$ and decompose it into its connected components, $(\operatorname{pr}_1 |L)^{-1}(g.U) = \bigsqcup V_i \subset L$. Any point in $g.U$ is of the form $g.\exp(X)$ for a unique $X \in B$, and we may lift the curve $t \mapsto g.\exp(tX)$ in G to the curve $\operatorname{Fl}_t^{L_X\times\zeta_X}(g,x_i)$ in V_i. So each V_i is diffeomorphic to $g.U$ via $\operatorname{pr}_1 |V_i$, and the claim follows.

Since G is simply connected we conclude that for each leaf L the mapping $\operatorname{pr}_1 |L : L \to G$ is a diffeomorphism. We now define the action as follows: For $g \in G$ and $x \in M$ consider the leaf $L(e,x)$ through (e,x) and put

$$(2) \qquad l(g,x) = g.x = \operatorname{pr}_2((\operatorname{pr}_1 |L(e,x))^{-1}(g)) \in M.$$

From the considerations in the proof of the claim and from (1) it follows that for $X \in \mathfrak g$ we also have

$$(3) \qquad l(\exp(X),x) = \exp(X).x = \operatorname{Fl}_1^{\zeta_X}(x) \in M.$$

By (2) the mapping $l : G \times M \to M$ is well defined, and by (3) it is an action and smooth near $\{e\} \times M$, thus everywhere. □

5.16. Semidirect products of Lie groups. Let H and K be two Lie groups and let $\ell : H \times K \to K$ be a smooth left action of H in K such that each $\ell_h : K \to K$ is a group automorphism. So the associated mapping $\check\ell : H \to \operatorname{Aut}(K)$ is a smooth homomorphism into the automorphism group of K. Then we can introduce the following multiplication on $K \times H$

$$(1) \qquad (k,h)(k',h') := (k\ell_h(k'), hh').$$

It is easy to see that this defines a Lie group $G = K \rtimes_\ell H$ called the *semidirect product* of H and K with respect to ℓ. If the action ℓ is clear from the context we write $G = K \rtimes H$ only. The second projection $pr_2 : K \rtimes H \to H$ is a surjective smooth homomorphism with kernel $K \times \{e\}$, and the insertion $\operatorname{ins}_e : H \to K \rtimes H$, $\operatorname{ins}_e(h) = (e,h)$ is a smooth group homomorphism with $pr_2 \circ \operatorname{ins}_e = Id_H$.

Conversely we consider an exact sequence of Lie groups and homomorphisms

$$(2) \qquad \{e\} \to K \xrightarrow{j} G \xrightarrow{p} H \to \{e\}.$$

So j is injective, p is surjective, and the kernel of p equals the image of j. We suppose furthermore that the sequence splits, so that there is a smooth homomorphism

$s : H \to G$ with $p \circ s = Id_H$. Then the rule $\ell_h(k) = s(h)ks(h^{-1})$ (where we suppress j) defines a left action of H on K by automorphisms. It is easily seen that the mapping $K \rtimes_\ell H \to G$ given by $(k,h) \mapsto k.s(h)$ is an isomorphism of Lie groups. So we see that semidirect products of Lie groups correspond exactly to splitting short exact sequences.

5.17. The tangent group of a Lie group. Let G be a Lie group with Lie algebra $\mathfrak{g}$. We will use the notation from (4.1). First note that TG is also a Lie group with multiplication $T\mu$ and inversion $T\nu$, given by (see (4.2)) $T_{(a,b)}\mu.(\xi_a,\eta_b) = T_a(\mu^b).\xi_a + T_b(\mu_a).\eta_b$ and $T_a\nu.\xi_a = -T_e(\mu_{a^{-1}}).T_a(\mu^{a^{-1}}).\xi_a$.

Lemma. *Via the isomomorphism given by the right trivialization $\mathfrak{g} \times G \to TG$, $(X,g) \mapsto T_e(\mu^g).X$, the group structure on TG looks as follows: $(X,a).(Y,b) = (X + \operatorname{Ad}(a)Y, a.b)$ and $(X,a)^{-1} = (-\operatorname{Ad}(a^{-1})X, a^{-1})$. So TG is isomorphic to the semidirect product $\mathfrak{g} \rtimes G$.*

Proof. $T_{(a,b)}\mu.(T\mu^a.X, T\mu^b.Y) = T\mu^b.T\mu^a.X + T\mu_a.T\mu^b.Y =$

$= T\mu^{ab}.X + T\mu^b.T\mu^a.T\mu^{a^{-1}}.T\mu_a.Y = T\mu^{ab}(X + \operatorname{Ad}(a)Y)$.
$T_a\nu.T\mu^a.X = -T\mu^{a^{-1}}.T\mu_{a^{-1}}.T\mu^a.X = -T\mu^{a^{-1}}.\operatorname{Ad}(a^{-1})X$. □

Remark. In the left trivialisation $T\lambda : G \times \mathfrak{g} \to TG$, $T\lambda.(g,X) = T_e(\mu_g).X$, the semidirect product structure looks awkward: $(a,X).(b,Y) = (ab, \operatorname{Ad}(b^{-1})X + Y)$ and $(a,X)^{-1} = (a^{-1}, -\operatorname{Ad}(a)X)$.

CHAPTER III
Differential Forms and De Rham Cohomology

6. Vector Bundles

6.1. Vector bundles. Let $p : E \to M$ be a smooth mapping between manifolds. By a *vector bundle chart* on (E, p, M) we mean a pair (U, ψ), where U is an open subset in M and where ψ is a fiber respecting diffeomorphism as in the following diagram:

$$\begin{array}{ccc} E \restriction U := p^{-1}(U) & \xrightarrow{\quad\psi\quad} & U \times V \\ & {}_{p}\searrow \quad \swarrow_{pr_1} & \\ & U & \end{array}$$

Here V is a fixed finite dimensional vector space, called the *standard fiber* or the *typical fiber*, real for the moment.

Two vector bundle charts (U_1, ψ_1) and (U_2, ψ_2) are called *compatible*, if $\psi_1 \circ \psi_2^{-1}$ is a fiber linear isomorphism, i.e. $(\psi_1 \circ \psi_2^{-1})(x, v) = (x, \psi_{1,2}(x)v)$ for some mapping $\psi_{1,2} : U_{1,2} := U_1 \cap U_2 \to GL(V)$. The mapping $\psi_{1,2}$ is then unique and smooth, and it is called the *transition function* between the two vector bundle charts.

A *vector bundle atlas* $(U_\alpha, \psi_\alpha)_{\alpha \in A}$ for (E, p, M) is a set of pairwise compatible vector bundle charts (U_α, ψ_α) such that $(U_\alpha)_{\alpha \in A}$ is an open cover of M. Two vector bundle atlases are called *equivalent*, if their union is again a vector bundle atlas.

A *vector bundle* (E, p, M) consists of manifolds E (the *total space*), M (the *base*), and a smooth mapping $p : E \to M$ (the *projection*) together with an equivalence class of vector bundle atlases: So we must know at least one vector bundle atlas. p turns out to be a surjective submersion.

6.2. Let us fix a vector bundle (E, p, M) for the moment. On each *fiber* $E_x := p^{-1}(x)$ (for $x \in M$) there is a unique structure of a real vector space, induced from any vector bundle chart (U_α, ψ_α) with $x \in U_\alpha$. So $0_x \in E_x$ is a special element and $0 : M \to E$, $0(x) = 0_x$, is a smooth mapping, the *zero section*.

A *section* u of (E, p, M) is a smooth mapping $u : M \to E$ with $p \circ u = Id_M$. The *support* of the section u is the closure of the set $\{x \in M : u(x) \neq 0_x\}$ in M.

The space of all smooth sections of the bundle (E, p, M) will be denoted by either $\Gamma(E) = \Gamma(E, p, M) = \Gamma(E \to M)$. Clearly it is a vector space with fiber wise addition and scalar multiplication.

If $(U_\alpha, \psi_\alpha)_{\alpha\in A}$ is a vector bundle atlas for (E, p, M), then any smooth mapping $f_\alpha : U_\alpha \to V$ (the standard fiber) defines a local section $x \mapsto \psi_\alpha^{-1}(x, f_\alpha(x))$ on U_α. If $(g_\alpha)_{\alpha\in A}$ is a partition of unity subordinated to (U_α), then a global section can be formed by $x \mapsto \sum_\alpha g_\alpha(x) \cdot \psi_\alpha^{-1}(x, f_\alpha(x))$. So a smooth vector bundle has 'many' smooth sections.

6.3. We will now give a formal description of the amount of vector bundles with fixed base M and fixed standard fiber V.

Let us first fix an open cover $(U_\alpha)_{\alpha\in A}$ of M. If (E, p, M) is a vector bundle which admits a vector bundle atlas (U_α, ψ_α) with the given open cover, then we have $\psi_\alpha \circ \psi_\beta^{-1}(x, v) = (x, \psi_{\alpha\beta}(x)v)$ for transition functions $\psi_{\alpha\beta} : U_{\alpha\beta} = U_\alpha \cap U_\beta \to GL(V)$, which are smooth. This family of transition functions satisfies

$$(1) \qquad \begin{cases} \psi_{\alpha\beta}(x) \cdot \psi_{\beta\gamma}(x) = \psi_{\alpha\gamma}(x) & \text{for each } x \in U_{\alpha\beta\gamma} = U_\alpha \cap U_\beta \cap U_\gamma \\ \psi_{\alpha\alpha}(x) = e & \text{for all } x \in U_\alpha \end{cases}$$

Condition (1) is called a *cocycle condition* and thus we call the family $(\psi_{\alpha\beta})$ the *cocycle of transition functions* for the vector bundle atlas (U_α, ψ_α).

Let us suppose now that the same vector bundle (E, p, M) is described by an equivalent vector bundle atlas $(U_\alpha, \varphi_\alpha)$ with the same open cover (U_α). Then the vector bundle charts (U_α, ψ_α) and $(U_\alpha, \varphi_\alpha)$ are compatible for each α, so $\varphi_\alpha \circ \psi_\alpha^{-1}(x, v) = (x, \tau_\alpha(x)v)$ for some $\tau_\alpha : U_\alpha \to GL(V)$. But then we have

$$\begin{aligned} (x, \tau_\alpha(x)\psi_{\alpha\beta}(x)v) &= (\varphi_\alpha \circ \psi_\alpha^{-1})(x, \psi_{\alpha\beta}(x)v) \\ &= (\varphi_\alpha \circ \psi_\alpha^{-1} \circ \psi_\alpha \circ \psi_\beta^{-1})(x, v) = (\varphi_\alpha \circ \psi_\beta^{-1})(x, v) \\ &= (\varphi_\alpha \circ \varphi_\beta^{-1} \circ \varphi_\beta \circ \psi_\beta^{-1})(x, v) = (x, \varphi_{\alpha\beta}(x)\tau_\beta(x)v). \end{aligned}$$

So we get

$$(2) \qquad \tau_\alpha(x)\psi_{\alpha\beta}(x) = \varphi_{\alpha\beta}(x)\tau_\beta(x) \quad \text{for all } x \in U_{\alpha\beta}.$$

We say that the two cocycles $(\psi_{\alpha\beta})$ and $(\varphi_{\alpha\beta})$ of transition functions over the cover (U_α) are *cohomologous*. The *cohomology classes* of cocycles $(\psi_{\alpha\beta})$ over the open cover (U_α) (where we identify cohomologous ones) form a set $\check{H}^1((U_\alpha), \underline{GL}(V))$ the first *Čech cohomology set* of the open cover (U_α) with values in the sheaf $C^\infty(\quad, GL(V)) =: \underline{GL}(V)$.

Now let $(W_i)_{i\in I}$ be an open cover of M that refines (U_α) with $W_i \subset U_{\varepsilon(i)}$, where $\varepsilon : I \to A$ is some refinement mapping, then for any cocycle $(\psi_{\alpha\beta})$ over (U_α) we define the cocycle $\varepsilon^*(\psi_{\alpha\beta}) =: (\varphi_{ij})$ by the prescription $\varphi_{ij} := \psi_{\varepsilon(i),\varepsilon(j)} \restriction W_{ij}$. The mapping ε^* respects the cohomology relations and induces therefore a mapping $\varepsilon^\sharp : \check{H}^1((U_\alpha), \underline{GL}(V)) \to \check{H}^1((W_i), \underline{GL}(V))$. One can show that the mapping ε^* depends on the choice of the refinement mapping ε only up to cohomology (use $\tau_i = \psi_{\varepsilon(i),\eta(i)} \restriction W_i$ if ε and η are two refinement mappings), so we may form the inductive limit $\varinjlim \check{H}^1(\mathcal{U}, \underline{GL}(V)) =: \check{H}^1(M, \underline{GL}(V))$ over all open covers of M directed by refinement.

Theorem. *There is a bijective correspondence between $\check{H}^1(M, \underline{GL}(V))$ and the set of all isomorphism classes of vector bundles over M with typical fiber V.*

Proof. Let $(\psi_{\alpha\beta})$ be a cocycle of transition functions $\psi_{\alpha\beta} : U_{\alpha\beta} \to GL(V)$ over some open cover (U_α) of M. We consider the disjoint union $\bigsqcup_{\alpha\in A}\{\alpha\} \times U_\alpha \times V$ and the following relation on it: $(\alpha, x, v) \sim (\beta, y, w)$ if and only if $x = y$ and $\psi_{\beta\alpha}(x)v = w$.

By the cocycle property (1) of $(\psi_{\alpha\beta})$ this is an equivalence relation. The space of all equivalence classes is denoted by $E = VB(\psi_{\alpha\beta})$ and it is equipped with the quotient topology. We put $p : E \to M$, $p[(\alpha, x, v)] = x$, and we define the vector bundle charts (U_α, ψ_α) by $\psi_\alpha[(\alpha, x, v)] = (x, v)$, $\psi_\alpha : p^{-1}(U_\alpha) =: E \restriction U_\alpha \to U_\alpha \times V$. Then the mapping $\psi_\alpha \circ \psi_\beta^{-1}(x, v) = \psi_\alpha[(\beta, x, v)] = \psi_\alpha[(\alpha, x, \psi_{\alpha\beta}(x)v)] = (x, \psi_{\alpha\beta}(x)v)$ is smooth, so E becomes a smooth manifold. E is Hausdorff: let $u \neq v$ in E; if $p(u) \neq p(v)$ we can separate them in M and take the inverse image under p; if $p(u) = p(v)$, we can separate them in one chart. So (E, p, M) is a vector bundle.

Now suppose that we have two cocycles $(\psi_{\alpha\beta})$ over (U_α), and (φ_{ij}) over (V_i). Then there is a common refinement (W_γ) for the two covers (U_α) and (V_i). The construction described a moment ago gives isomorphic vector bundles if we restrict the cocycle to a finer open cover. So we may assume that $(\psi_{\alpha\beta})$ and $(\varphi_{\alpha\beta})$ are cocycles over the same open cover (U_α). If the two cocycles are cohomologous, so $\tau_\alpha \cdot \psi_{\alpha\beta} = \varphi_{\alpha\beta} \cdot \tau_\beta$ on $U_{\alpha\beta}$, then a fiber linear diffeomorphism $\tau : VB(\psi_{\alpha\beta}) \to VB(\varphi_{\alpha\beta})$ is given by $\varphi_\alpha \tau[(\alpha, x, v)] = (x, \tau_\alpha(x)v)$. By relation (2) this is well defined, so the vector bundles $VB(\psi_{\alpha\beta})$ and $VB(\varphi_{\alpha\beta})$ are isomorphic.

Most of the converse direction was already shown in the discussion before the theorem, and the argument can be easily refined to show also that isomorphic bundles give cohomologous cocycles. □

6.4. Remark. If $GL(V)$ is an abelian group (only if V is of real or complex dimension 1), then $\check{H}^1(M, \underline{GL}(V))$ is a usual cohomology group with coefficients in the sheaf $\underline{GL}(V)$ and it can be computed with the methods of algebraic topology. We will treat the two situation in a moment. If $GL(V)$ is not abelian, then the situation is rather mysterious: there is no clear definition for $\check{H}^2(M, \underline{GL}(V))$ for example. So $\check{H}^1(M, \underline{GL}(V))$ is more a notation than a mathematical concept.

A coarser relation on vector bundles (stable isomorphism) leads to the concept of topological K-theory, which can be handled much better, but is only a quotient of the real situation.

Example: Real line bundles. As an example we want to determine here the set of all *real line bundles* on a smooth manifold M. Let us first consider the following exact sequence of abelian Lie groups:

$$0 \to (\mathbb{R}, +) \xrightarrow{\exp} GL(1, \mathbb{R}) = (\mathbb{R} \setminus 0, \cdot) \xrightarrow{p} \mathbb{Z}_2 \to 0. \to 0$$

where $\mathbb{Z}_2 := \mathbb{Z}/2\mathbb{Z}$ is the two element group. This gives rise to an exact sequence of sheafs with values in abelian groups:

$$0 \to C^\infty(\quad, \mathbb{R}) \xrightarrow{\exp_*} C^\infty(\quad, GL(1, \mathbb{R})) \xrightarrow{p_*} \mathbb{Z}_2 \to 0$$

where in the end we find the constant sheaf. This induces the following long exact sequence in cohomology (the Bockstein sequence):

$$\dots \to 0 = \check{H}^1(M, C^\infty(\quad, \mathbb{R})) \xrightarrow{\exp_*} \check{H}^1(M, C^\infty(\quad, GL(1,\mathbb{R})) \xrightarrow{p_*}$$
$$\xrightarrow{p_*} H^1(M, \mathbb{Z}_2) \xrightarrow{\delta} \check{H}^2(M, C^\infty(\quad, \mathbb{R})) = 0 \to \dots$$

Here the sheaf $C^\infty(\quad, \mathbb{R})$ has 0 cohomology in dimensions ≥ 1 since this is a fine sheaf, i.e. it admits partitions of unity. Thus $p_* : \check{H}^1(M, C^\infty(\quad, GL(1,\mathbb{R})) \to H^1(M, \mathbb{Z}_2)$ is an isomorphism, and by the theorem above a real line bundle E over M is uniquely determined by a certain cohomology class in $H^1(M, \mathbb{Z}_2)$, namely the *first Stiefel-Whitney class* $w_1(E)$ of this line bundle.

Example: Complex line bundles. As another example we want to determine here the set of all smooth *complex line bundles* on a smooth manifold M. Again we first consider the following exact sequence of abelian Lie groups:

$$0 \to \mathbb{Z} \xrightarrow{2\pi\sqrt{-1}} (\mathbb{C}, +) \xrightarrow{\exp} GL(1, \mathbb{C}) = (\mathbb{C} \setminus 0, \cdot) \to 0.$$

This gives rise to the following exact sequence of sheafs with values in abelian groups:

$$0 \to \mathbb{Z} \to C^\infty(\quad, \mathbb{C}) \xrightarrow{\exp_*} C^\infty(\quad, GL(1, \mathbb{C})) \to 0$$

where in the beginning we find the constant sheaf. This induces the following long exact sequence in cohomology (the Bockstein sequence):

$$\dots \to 0 = \check{H}^1(M, C^\infty(\quad, \mathbb{C})) \xrightarrow{\exp_*} \check{H}^1(M, C^\infty(\quad, GL(1,\mathbb{C})) \xrightarrow{\delta}$$
$$\xrightarrow{\delta} H^2(M, \mathbb{Z}) \xrightarrow{2\pi\sqrt{-1}} \check{H}^2(M, C^\infty(\quad, \mathbb{C})) = 0 \to \dots$$

Again the sheaf $C^\infty(\quad, \mathbb{R})$ has 0 cohomology in dimensions ≥ 1 since it is a fine sheaf. Thus $\delta : \check{H}^1(M, C^\infty(\quad, GL(1,\mathbb{C})) \to H^2(M, \mathbb{Z})$ is an isomorphism, and by the theorem above a complex smooth line bundle E over M is uniquely determined by a certain cohomology class in $H^2(M, \mathbb{Z})$, namely the *first Chern class* $c_1(E)$ of this line bundle.

6.5. Let (U_α, ψ_α) be a vector bundle atlas for a vector bundle (E, p, M). Let $(e_j)_{j=1}^k$ be a basis of the standard fiber V. We consider the section $s_j(x) := \psi_\alpha^{-1}(x, e_j)$ for $x \in U_\alpha$. Then the $s_j : U_\alpha \to E$ are local sections of E such that $(s_j(x))_{j=1}^k$ is a basis of E_x for each $x \in U_\alpha$: we say that $s = (s_1, \dots, s_k)$ is a local *frame field* for E over U_α.

Now let conversely $U \subset M$ be an open set and let $s_j : U \to E$ be local sections of E such that $s = (s_1, \dots, s_k)$ is a local frame field of E over U. Then s determines a unique vector bundle chart (U, ψ) of E such that $s_j(x) = \psi^{-1}(x, e_j)$, in the following way. We define $f : U \times \mathbb{R}^k \to E \restriction U$ by $f(x, v^1, \dots, v^k) := \sum_{j=1}^k v^j s_j(x)$. Then f is smooth, invertible, and a fiber linear isomorphism, so $(U, \psi = f^{-1})$ is the vector bundle chart promised above.

6.6. Let (E, p, M) and (F, q, N) be vector bundles. A *vector bundle homomorphism* $\varphi : E \to F$ is a fiber respecting, fiber linear smooth mapping

$$\begin{array}{ccc} E & \xrightarrow{\varphi} & F \\ {\scriptstyle p}\downarrow & & \downarrow{\scriptstyle q} \\ M & \xrightarrow{\underline{\varphi}} & N. \end{array}$$

So we require that $\varphi_x : E_x \to F_{\underline{\varphi}(x)}$ is linear. We say that φ covers $\underline{\varphi}$. If φ is invertible, it is called a *vector bundle isomorphism.*

6.7. A *vector subbundle* (F, p, M) of a vector bundle (E, p, M) is a vector bundle and a vector bundle homomorphism $\tau : F \to E$, which covers Id_M, such that $\tau_x : F_x \to E_x$ is a linear embedding for each $x \in M$.

Lemma. *Let $\varphi : (E, p, M) \to (E', q, N)$ be a vector bundle homomorphism such that* $\operatorname{rank}(\varphi_x : E_x \to E'_{\underline{\varphi}(x)})$ *is locally constant in $x \in M$. Then* $\ker \varphi$*, given by* $(\ker \varphi)_x = \ker(\varphi_x)$*, is a vector subbundle of* (E, p, M)*.*

Proof. This is a local question, so we may assume that both bundles are trivial: let $E = M \times \mathbb{R}^p$ and let $F = N \times \mathbb{R}^q$, then $\varphi(x, v) = (\underline{\varphi}(x), \overline{\varphi}(x).v)$, where $\overline{\varphi} : M \to L(\mathbb{R}^p, \mathbb{R}^q)$. The matrix $\overline{\varphi}(x)$ has rank k, so by the elimination procedure we can find $p - k$ linearly independent solutions $v_i(x)$ of the equation $\overline{\varphi}(x).v = 0$. The elimination procedure (with the same lines) gives solutions $v_i(y)$ for y near x which are smooth in y, so near x we get a local frame field $v = (v_1, \dots, v_{p-k})$ for $\ker \varphi$. By (6.5) $\ker \varphi$ is then a vector subbundle. □

6.8. Constructions with vector bundles. Let $\mathcal{F}$ be a covariant functor from the category of finite dimensional vector spaces and linear mappings into itself, such that $\mathcal{F} : L(V, W) \to L(\mathcal{F}(V), \mathcal{F}(W))$ is smooth. Then $\mathcal{F}$ will be called a *smooth functor* for shortness sake. Well known examples of smooth functors are $\mathcal{F}(V) = \Lambda^k(V)$ (the k-th exterior power), or $\mathcal{F}(V) = \bigotimes^k V$, and the like.

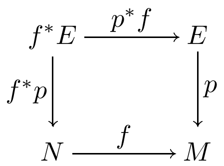
If (E, p, M) is a vector bundle, described by a vector bundle atlas with cocycle of transition functions $\varphi_{\alpha\beta} : U_{\alpha\beta} \to GL(V)$, where (U_α) is an open cover of M, then we may consider the smooth functions $\mathcal{F}(\varphi_{\alpha\beta}) : x \mapsto \mathcal{F}(\varphi_{\alpha\beta}(x))$, $U_{\alpha\beta} \to GL(\mathcal{F}(V))$. Since $\mathcal{F}$ is a covariant functor, $\mathcal{F}(\varphi_{\alpha\beta})$ satisfies again the cocycle condition (6.3.1), and cohomology of cocycles (6.3.2) is respected, so there exists a unique vector bundle $(\mathcal{F}(E) := VB(\mathcal{F}(\varphi_{\alpha\beta})), p, M)$, the value at the vector bundle (E, p, M) of the canonical extension of the functor $\mathcal{F}$ to the category of vector bundles and their homomorphisms.

If $\mathcal{F}$ is a contravariant smooth functor like duality functor $\mathcal{F}(V) = V^*$, then we have to consider the new cocycle $\mathcal{F}(\varphi_{\alpha\beta}^{-1})$ instead of $\mathcal{F}(\varphi_{\alpha\beta})$.

If $\mathcal{F}$ is a contra-covariant smooth bifunctor like $L(V, W)$, then the construction $\mathcal{F}(VB(\psi_{\alpha\beta}), VB(\varphi_{\alpha\beta})) := VB(\mathcal{F}(\psi_{\alpha\beta}^{-1}, \varphi_{\alpha\beta}))$ describes the induced canonical vector bundle construction, and similarly in other constructions.

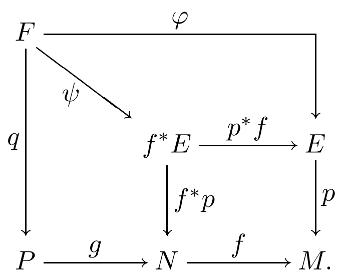
So for vector bundles (E, p, M) and (F, q, M) we have the following vector bundles with base M: $\Lambda^k E$, $E \oplus F$, E^*, $\Lambda E = \bigoplus_{k\geq 0} \Lambda^k E$, $E \otimes F$, $L(E, F) \cong E^* \otimes F$, and so on.

6.9. Pullbacks of vector bundles. Let (E, p, M) be a vector bundle and let $f : N \to M$ be smooth. Then the *pullback vector bundle* (f^*E, f^*p, N) with the same typical fiber and a vector bundle homomorphism



is defined as follows. Let E be described by a cocycle $(\psi_{\alpha\beta})$ of transition functions over an open cover (U_α) of M, $E = VB(\psi_{\alpha\beta})$. Then $(\psi_{\alpha\beta} \circ f)$ is a cocycle of transition functions over the open cover $(f^{-1}(U_\alpha))$ of N and the bundle is given by $f^*E := VB(\psi_{\alpha\beta} \circ f)$. As a manifold we have $f^*E = N \underset{(f,M,p)}{\times} E$ in the sense of (2.17).

The vector bundle f^*E has the following universal property: For any vector bundle (F, q, P), vector bundle homomorphism $\varphi : F \to E$ and smooth $g : P \to N$ such that $f \circ g = \underline{\varphi}$, there is a unique vector bundle homomorphism $\psi : F \to f^*E$ with $\underline{\psi} = g$ and $p^*f \circ \psi = \varphi$.



6.10. Theorem. *Any vector bundle admits a finite vector bundle atlas.*

Proof. Let (E, p, M) be the vector bundle in question, where $\dim M = m$. Let $(U_\alpha, \psi_\alpha)_{\alpha\in A}$ be a vector bundle atlas. By topological dimension theory, since M is separable, there exists a refinement of the open cover $(U_\alpha)_{\alpha\in A}$ of the form $(V_{ij})_{i=1,\dots,m+1; j\in\mathbb{N}}$, such that $V_{ij} \cap V_{ik} = \emptyset$ for $j \neq k$, see the remarks at the end of (1.1). We define the set $W_i := \bigsqcup_{j\in\mathbb{N}} V_{ij}$ (a disjoint union) and $\psi_i \restriction V_{ij} = \psi_{\alpha(i,j)}$, where $\alpha : \{1, \dots, m + 1\} \times \mathbb{N} \to A$ is a refining map. Then $(W_i, \psi_i)_{i=1,\dots,m+1}$ is a finite vector bundle atlas of E. □

6.11. Theorem. *For any vector bundle (E, p, M) there is a second vector bundle (F, p, M) such that $(E \oplus F, p, M)$ is a trivial vector bundle, i.e. isomorphic to $M \times \mathbb{R}^N$ for some $N \in \mathbb{N}$.*

Proof. Let $(U_i, \psi_i)_{i=1}^n$ be a finite vector bundle atlas for (E, p, M). Let (g_i) be a smooth partition of unity subordinated to the open cover (U_i). Let $\ell_i : \mathbb{R}^k \to (\mathbb{R}^k)^n = \mathbb{R}^k \times \cdots \times \mathbb{R}^k$ be the embedding on the i-th factor, where $\mathbb{R}^k$ is the typical fiber of E. Let us define $\psi : E \to M \times \mathbb{R}^{nk}$ by

$$\psi(u) = \left(p(u), \sum_{i=1}^n g_i(p(u))\, (\ell_i \circ pr_2 \circ \psi_i)(u) \right),$$

then ψ is smooth, fiber linear, and an embedding on each fiber, so E is a vector subbundle of $M \times \mathbb{R}^{nk}$ via ψ. Now we define $F_x = E_x^\perp$ in $\{x\} \times \mathbb{R}^{nk}$ with respect to the standard inner product on $\mathbb{R}^{nk}$. Then $F \to M$ is a vector bundle and $E \oplus F \cong M \times \mathbb{R}^{nk}$. □

6.12. The tangent bundle of a vector bundle. Let (E, p, M) be a vector bundle with fiber addition $+_E : E \times_M E \to E$ and fiber scalar multiplication $m_t^E : E \to E$. Then (TE, π_E, E), the tangent bundle of the manifold E, is itself a vector bundle, with fiber addition denoted by $+_{TE}$ and scalar multiplication denoted by m_t^{TE}.

If $(U_\alpha, \psi_\alpha : E \restriction U_\alpha \to U_\alpha \times V)_{\alpha \in A}$ is a vector bundle atlas for E, such that (U_α, u_α) is also a manifold atlas for M, then $(E \restriction U_\alpha, \psi'_\alpha)_{\alpha \in A}$ is an atlas for the manifold E, where

$$\psi'_\alpha := (u_\alpha \times Id_V) \circ \psi_\alpha : E \restriction U_\alpha \to U_\alpha \times V \to u_\alpha(U_\alpha) \times V \subset \mathbb{R}^m \times V.$$

Hence the family $(T(E \restriction U_\alpha), T\psi'_\alpha : T(E \restriction U_\alpha) \to T(u_\alpha(U_\alpha) \times V) = u_\alpha(U_\alpha) \times V \times \mathbb{R}^m \times V)_{\alpha \in A}$ is the atlas describing the canonical vector bundle structure of (TE, π_E, E). The transition functions are in turn:

$$\begin{aligned}
(\psi_\alpha \circ \psi_\beta^{-1})(x, v) &= (x, \psi_{\alpha\beta}(x)v) \quad \text{ for } x \in U_{\alpha\beta} \\
(u_\alpha \circ u_\beta^{-1})(y) &= u_{\alpha\beta}(y) \quad \text{ for } y \in u_\beta(U_{\alpha\beta}) \\
(\psi'_\alpha \circ (\psi'_\beta)^{-1})(y, v) &= (u_{\alpha\beta}(y), \psi_{\alpha\beta}(u_\beta^{-1}(y))v) \\
(T\psi'_\alpha \circ T(\psi'_\beta)^{-1})(y, v; \xi, w) &= \big(u_{\alpha\beta}(y), \psi_{\alpha\beta}(u_\beta^{-1}(y))v; d(u_{\alpha\beta})(y)\xi, \\
&\qquad (d(\psi_{\alpha\beta} \circ u_\beta^{-1})(y)\xi)v + \psi_{\alpha\beta}(u_\beta^{-1}(y))w\big).
\end{aligned}$$

So we see that for fixed (y, v) the transition functions are linear in $(\xi, w) \in \mathbb{R}^m \times V$. This describes the vector bundle structure of the tangent bundle (TE, π_E, E).

For fixed (y, ξ) the transition functions of TE are also linear in $(v, w) \in V \times V$. This gives a vector bundle structure on (TE, Tp, TM). Its fiber addition will be denoted by $T(+_E) : T(E \times_M E) = TE \times_{TM} TE \to TE$, since it is the tangent mapping of $+_E$. Likewise its scalar multiplication will be denoted by $T(m_t^E)$. One may say that the second vector bundle structure on TE, that one over TM, is the derivative of the original one on E.

The space $\{\Xi \in TE : Tp.\Xi = 0 \text{ in } TM\} = (Tp)^{-1}(0)$ is denoted by VE and is called the *vertical bundle* over E. The local form of a vertical vector Ξ is $T\psi'_\alpha.\Xi = (y, v; 0, w)$, so the transition function looks like

$$(T\psi'_\alpha \circ T(\psi'_\beta)^{-1})(y, v; 0, w) = (u_{\alpha\beta}(y), \psi_{\alpha\beta}(u_\beta^{-1}(y))v; 0, \psi_{\alpha\beta}(u_\beta^{-1}(y))w).$$

They are linear in $(v,w)\in V\times V$ for fixed y, so VE is a vector bundle over M. It coincides with $0_M^*(TE,Tp,TM)$, the pullback of the bundle $TE\to TM$ over the zero section. We have a canonical isomorphism $\mathrm{vl}_E : E\times_M E\to VE$, called the *vertical lift*, given by $\mathrm{vl}_E(u_x,v_x) := \frac{d}{dt}|_0(u_x+tv_x)$, which is fiber linear over M. The local representation of the vertical lift is $(T\psi'_\alpha\circ\mathrm{vl}_E\circ(\psi'_\alpha\times\psi'_\alpha)^{-1})((y,u),(y,v)) = (y,u;0,v)$.

If (and only if) $\varphi : (E,p,M)\to(F,q,N)$ is a vector bundle homomorphism, then we have $\mathrm{vl}_F\circ(\varphi\times_M\varphi) = T\varphi\circ\mathrm{vl}_E : E\times_M E\to VF\subset TF$. So vl is a natural transformation between certain functors on the category of vector bundles and their homomorphisms.

The mapping $\mathrm{vpr}_E := pr_2\circ\mathrm{vl}_E^{-1} : VE\to E$ is called the *vertical projection*. Note also the relation $pr_1\circ\mathrm{vl}_E^{-1} = \pi_E\restriction VE$.

6.13. The second tangent bundle of a manifold. All of (6.12) is valid for the second tangent bundle $T^2M = TTM$ of a manifold, but here we have one more natural structure at our disposal. The *canonical flip* or *involution* $\kappa_M : T^2M\to T^2M$ is defined locally by

$$(T^2u\circ\kappa_M\circ T^2u^{-1})(x,\xi;\eta,\zeta) = (x,\eta;\xi,\zeta),$$

where (U,u) is a chart on M. Clearly this definition is invariant under changes of charts.

The flip κ_M has the following properties:

(1) $\kappa_N\circ T^2f = T^2f\circ\kappa_M$ for each $f\in C^\infty(M,N)$.
(2) $T(\pi_M)\circ\kappa_M = \pi_{TM}$.
(3) $\pi_{TM}\circ\kappa_M = T(\pi_M)$.
(4) $\kappa_M^{-1} = \kappa_M$.
(5) κ_M is a linear isomorphism from the bundle $(TTM,T(\pi_M),TM)$ to the bundle (TTM,π_{TM},TM), so it interchanges the two vector bundle structures on TTM.
(6) It is the unique smooth mapping $TTM\to TTM$ which satisfies the equation $\frac{\partial}{\partial t}\frac{\partial}{\partial s}c(t,s) = \kappa_M\frac{\partial}{\partial s}\frac{\partial}{\partial t}c(t,s)$ for each $c:\mathbb{R}^2\to M$.

All this follows from the local formula given above.

6.14. Lemma. *For vector fields $X,\ Y\in\mathfrak{X}(M)$ we have*

$$[X,Y] = \mathrm{vpr}_{TM}\circ(TY\circ X-\kappa_M\circ TX\circ Y),$$
$$TY\circ X-\kappa_M\circ TX\circ Y = \mathrm{vl}_{TM}(Y,[X,Y]).$$

We will give global proofs of this result later on: the first one is (6.19).

Proof. We prove this locally, so we may assume that M is open in $\mathbb{R}^m$, $X(x) = (x,\bar X(x))$, and $Y(x) = (x,\bar Y(x))$. Then by (3.4) we have

$$[X,Y](x) = (x, d\bar Y(x).\bar X(x) - d\bar X(x).\bar Y(x)),$$

and thus

$$\begin{aligned}
&(TY\circ X-\kappa_M\circ TX\circ Y)(x)=TY.(x,\bar X(x))-\kappa_M\circ TX.(x,\bar Y(x))=\\
&=(x,\bar Y(x);\bar X(x),d\bar Y(x).\bar X(x))-\kappa_M(x,\bar X(x);\bar Y(x),d\bar X(x).\bar Y(x))=\\
&=(x,\bar Y(x);0,d\bar Y(x).\bar X(x)-d\bar X(x).\bar Y(x))\\
&\operatorname{vpr}_{TM}\circ(TY\circ X-\kappa_M\circ TX\circ Y)(x)=(x,d\bar Y(x).\bar X(x)-d\bar X(x).\bar Y(x)).\quad\square
\end{aligned}$$

6.15. Natural vector bundles or **vector bundle functors.** Let $\mathcal{M}f_m$ denote the category of all m-dimensional smooth manifolds and local diffeomorphisms (i.e. immersions) between them. A *vector bundle functor* or *natural vector bundle* is a functor F which associates a vector bundle $(F(M),p_M,M)$ to each m-manifold M and a vector bundle homomorphism

$$\begin{array}{ccc}
F(M) & \xrightarrow{F(f)} & F(N)\\
{\scriptstyle p_M}\downarrow & & \downarrow{\scriptstyle p_N}\\
M & \xrightarrow{\quad f\quad} & N
\end{array}$$

to each $f:M\to N$ in $\mathcal{M}f_m$, which covers f and is fiberwise a linear isomorphism. We also require that for smooth $f:\mathbb{R}\times M\to N$ the mapping $(t,x)\mapsto F(f_t)(x)$ is also smooth $\mathbb{R}\times F(M)\to F(N)$. We will say that F maps smoothly parametrized families to smoothly parametrized families.

Examples. 1. TM, the tangent bundle. This is even a functor on the category $\mathcal{M}f$ of all manifolds and all smooth mappings, not only local diffeomorphisms.

2. T^*M, the cotangent bundle, where by (6.8) the action on morphisms is given by $(T^*f)_x:=((T_xf)^{-1})^*:T^*_xM\to T^*_{f(x)}N$. This functor is defined on $\mathcal{M}f_m$ only.

3. Λ^kT^*M, $\Lambda T^*M=\bigoplus_{k\ge0}\Lambda^kT^*M$.

4. $\bigotimes^k T^*M\otimes\bigotimes^\ell TM=T^*M\otimes\dots\otimes T^*M\otimes TM\otimes\dots\otimes TM$, where the action on morphisms involves Tf^{-1} in the T^*M-parts and Tf in the TM-parts.

5. $\mathcal{F}(TM)$, where $\mathcal{F}$ is any smooth functor on the category of finite dimensional vector spaces and linear mappings, as in (6.8).

6. All examples discussed till now are of the following form: For a manifold of dimesion m, consider the *linear frame bundle* $GL(\mathbb{R}^m,TM)=invJ^1_0(\mathbb{R}^m,M)$ (see (21.11) and (24.6)) and a representation of the structure group $\rho:GL(m,\mathbb{R})\to GL(V)$ on some vector space V. Then the associated bundle $GL(\mathbb{R}^m,TM)\times_{GL(m,\mathbb{R})}V$ is a natural bundle. This can be generalized to frame bundles of higher order, which is described in (24.6).

6.16. Lie derivative. Let F be a vector bundle functor on $\mathcal{M}f_m$ as described in (6.15). Let M be a manifold and let $X\in\mathfrak{X}(M)$ be a vector field on M. Then the flow Fl^X_t, for fixed t, is a diffeomorphism defined on an open subset of M, which we do not specify. The mapping

$$\begin{array}{ccc} F(M) & \xrightarrow{F(\mathrm{Fl}^X_t)} & F(M) \\ {\scriptstyle p_M}\downarrow & & \downarrow{\scriptstyle p_M} \\ M & \xrightarrow{\mathrm{Fl}^X_t} & M \end{array}$$

is then a vector bundle isomorphism, defined over an open subset of M.

We consider a section $s \in \Gamma(F(M))$ of the vector bundle $(F(M), p_M, M)$ and we define for $t \in \mathbb{R}$

$$(\mathrm{Fl}^X_t)^* s := F(\mathrm{Fl}^X_{-t}) \circ s \circ \mathrm{Fl}^X_t,$$

a local section of the bundle $F(M)$. For each $x \in M$ the value $((\mathrm{Fl}^X_t)^* s)(x) \in F(M)_x$ is defined, if t is small enough (depending on x). So in the vector space $F(M)_x$ the expression $\frac{d}{dt}|_0((\mathrm{Fl}^X_t)^* s)(x)$ makes sense and therefore the section

$$\mathcal{L}_X s := \tfrac{d}{dt}|_0 (\mathrm{Fl}^X_t)^* s$$

is globally defined and is an element of $\Gamma(F(M))$. It is called the *Lie derivative* of s along X.

Lemma. *In this situation we have*

(1) $(\mathrm{Fl}^X_t)^*(\mathrm{Fl}^X_r)^* s = (\mathrm{Fl}^X_{t+r})^* s$, *wherever defined.*
(2) $\frac{d}{dt}(\mathrm{Fl}^X_t)^* s = (\mathrm{Fl}^X_t)^* \mathcal{L}_X s = \mathcal{L}_X (\mathrm{Fl}^X_t)^* s$, *so*
$[\mathcal{L}_X, (\mathrm{Fl}^X_t)^*] := \mathcal{L}_X \circ (\mathrm{Fl}^X_t)^* - (\mathrm{Fl}^X_t)^* \circ \mathcal{L}_X = 0$, *whenever defined.*
(3) $(\mathrm{Fl}^X_t)^* s = s$ *for all relevant* t *if and only if* $\mathcal{L}_X s = 0$.

Proof. (1) is clear. (2) is seen by the following computations.

$$\begin{aligned} \tfrac{d}{dt}(\mathrm{Fl}^X_t)^* s &= \tfrac{d}{dr}|_0 (\mathrm{Fl}^X_r)^*(\mathrm{Fl}^X_t)^* s = \mathcal{L}_X (\mathrm{Fl}^X_t)^* s. \\ \tfrac{d}{dt}((\mathrm{Fl}^X_t)^* s)(x) &= \tfrac{d}{dr}|_0 ((\mathrm{Fl}^X_t)^*(\mathrm{Fl}^X_r)^* s)(x) \\ &= \tfrac{d}{dr}|_0 F(\mathrm{Fl}^X_{-t})(F(\mathrm{Fl}^X_{-r}) \circ s \circ \mathrm{Fl}^X_r)(\mathrm{Fl}^X_t(x)) \\ &= F(\mathrm{Fl}^X_{-t}) \tfrac{d}{dr}|_0 (F(\mathrm{Fl}^X_{-r}) \circ s \circ \mathrm{Fl}^X_r)(\mathrm{Fl}^X_t(x)) \\ &= ((\mathrm{Fl}^X_t)^* \mathcal{L}_X s)(x), \end{aligned}$$

since $F(\mathrm{Fl}^X_{-t}) : F(M)_{\mathrm{Fl}^X_t(x)} \to F(M)_x$ is linear.

(3) follows from (2). $\square$

6.17. Let F_1, F_2 be two vector bundle functors on $\mathcal{M}f_m$. Then the (fiberwise) tensor product $(F_1 \otimes F_2)(M) := F_1(M) \otimes F_2(M)$ is again a vector bundle functor and for $s_i \in \Gamma(F_i(M))$ there is a section $s_1 \otimes s_2 \in \Gamma((F_1 \otimes F_2)(M))$, given by the pointwise tensor product.

Lemma. *In this situation, for $X \in \mathfrak{X}(M)$ we have*

$$\mathcal{L}_X(s_1 \otimes s_2) = \mathcal{L}_X s_1 \otimes s_2 + s_1 \otimes \mathcal{L}_X s_2.$$

In particular, for $f \in C^\infty(M)$ we have $\mathcal{L}_X(fs) = df(X)\, s + f\, \mathcal{L}_X s$.

Proof. Using the bilinearity of the tensor product we have

$$\begin{aligned}
\mathcal{L}_X(s_1 \otimes s_2) &= \tfrac{d}{dt}|_0 (\mathrm{Fl}^X_t)^*(s_1 \otimes s_2)\\
&= \tfrac{d}{dt}|_0 ((\mathrm{Fl}^X_t)^* s_1 \otimes (\mathrm{Fl}^X_t)^* s_2)\\
&= \tfrac{d}{dt}|_0 (\mathrm{Fl}^X_t)^* s_1 \otimes s_2 + s_1 \otimes \tfrac{d}{dt}|_0 (\mathrm{Fl}^X_t)^* s_2\\
&= \mathcal{L}_X s_1 \otimes s_2 + s_1 \otimes \mathcal{L}_X s_2. \quad \square
\end{aligned}$$

6.18. Let $\varphi : F_1 \to F_2$ be a linear *natural transformation* between vector bundle functors on $\mathcal{M}f_m$. So for each $M \in \mathcal{M}f_m$ we have a vector bundle homomorphism $\varphi_M : F_1(M) \to F_2(M)$ covering the identity on M, such that $F_2(f) \circ \varphi_M = \varphi_N \circ F_1(f)$ holds for any $f : M \to N$ in $\mathcal{M}f_m$.

Example. A *tensor field* of type $\binom{p}{q}$ is a smooth section of the natural bundle $\bigotimes^q T^*M \otimes \bigotimes^p TM$. For such tensor fields, by (6.16) the Lie derivative along any vector field is defined, by (6.17) it is a derivation with respect to the tensor product. For functions and vector fields the Lie derivative was already defined in section 3. This natural bundle admits many natural transformations: Any 'contraction' like the trace $T^*M \otimes TM = L(TM, TM) \to M \times \mathbb{R}$, but applied just to one specified factor T^*M and another one of type TM, is a natural transformation. And any 'permutation of the same kind of factors' is a natural tranformation.

Lemma. *In this situation we have $\mathcal{L}_X(\varphi_M\, s) = \varphi_M(\mathcal{L}_X s)$, for $s \in \Gamma(F_1(M))$ and $X \in \mathfrak{X}(M)$.*

Proof. Since φ_M is fiber linear and natural we can compute as follows.

$$\begin{aligned}
\mathcal{L}_X(\varphi_M\, s)(x) &= \tfrac{d}{dt}|_0 ((\mathrm{Fl}^X_t)^*(\varphi_M\, s))(x) = \tfrac{d}{dt}|_0 (F_2(\mathrm{Fl}^X_{-t}) \circ \varphi_M \circ s \circ \mathrm{Fl}^X_t)(x)\\
&= \varphi_M \circ \tfrac{d}{dt}|_0 (F_1(\mathrm{Fl}^X_{-t}) \circ s \circ \mathrm{Fl}^X_t)(x) = (\varphi_M\, \mathcal{L}_X s)(x). \quad \square
\end{aligned}$$

Thus the Lie derivative on tensor fields commutes with any kind of 'contraction' or 'permutation of the indices'.

6.19. Let F be a vector bundle functor on $\mathcal{M}f_m$ and let $X \in \mathfrak{X}(M)$ be a vector field. We consider the local vector bundle homomorphism $F(\mathrm{Fl}^X_t)$ on $F(M)$. Since $F(\mathrm{Fl}^X_t) \circ F(\mathrm{Fl}^X_s) = F(\mathrm{Fl}^X_{t+s})$ and $F(\mathrm{Fl}^X_0) = Id_{F(M)}$ we have $\frac{d}{dt} F(\mathrm{Fl}^X_t) = \frac{d}{ds}|_0 F(\mathrm{Fl}^X_s) \circ F(\mathrm{Fl}^X_t) = X^F \circ F(\mathrm{Fl}^X_t)$, so we get $F(\mathrm{Fl}^X_t) = \mathrm{Fl}^{X^F}_t$, where $X^F = \frac{d}{ds}|_0 F(\mathrm{Fl}^X_s) \in \mathfrak{X}(F(M))$ is a vector field on $F(M)$, which is called the *flow prolongation* or the *natural lift* of X to $F(M)$.

Lemma.

(1) $X^T = \kappa_M \circ TX$.
(2) $[X,Y]^F = [X^F, Y^F]$.
(3) $X^F : (F(M), p_M, M) \to (TF(M), T(p_M), TM)$ *is a vector bundle homomorphism for the* $T(+)$*-structure.*
(4) *For* $s \in \Gamma(F(M))$ *and* $X \in \mathfrak{X}(M)$ *we have* $\mathcal{L}_X s = vpr_{F(M)} \circ (Ts \circ X - X^F \circ s)$.
(5) $\mathcal{L}_X s$ *is linear in* X *and* s.

Proof. (1) is an easy computation. $F(\mathrm{Fl}^X_t)$ is fiber linear and this implies (3). (4) is seen as follows:

$$\begin{aligned}
(\mathcal{L}_X s)(x) &= \tfrac{d}{dt}|_0 (F(\mathrm{Fl}^X_{-t}) \circ s \circ \mathrm{Fl}^X_t)(x) \quad \text{in } F(M)_x \\
&= vpr_{F(M)}(\tfrac{d}{dt}|_0 (F(\mathrm{Fl}^X_{-t}) \circ s \circ \mathrm{Fl}^X_t)(x) \text{ in } VF(M)) \\
&= vpr_{F(M)}(-X^F \circ s \circ \mathrm{Fl}^X_0(x) + T(F(\mathrm{Fl}^X_0)) \circ Ts \circ X(x)) \\
&= vpr_{F(M)}(Ts \circ X - X^F \circ s)(x).
\end{aligned}$$

(5) $\mathcal{L}_X s$ is homogeneous of degree 1 in X by formula (4), and it is smooth as a mapping $\mathfrak{X}(M) \to \Gamma(F(M))$, so it is linear. See [Frölicher, Kriegl, 88] or [Kriegl, Michor, 97] for the convenient calculus in infinite dimensions.

(2) Note first that F induces a smooth mapping between appropriate spaces of local diffeomorphisms which are infinite dimensional manifolds (see [Kriegl, Michor, 91]). By (3.16) we have

$$\begin{aligned}
0 &= \tfrac{\partial}{\partial t}\big|_0 (\mathrm{Fl}^Y_{-t} \circ \mathrm{Fl}^X_{-t} \circ \mathrm{Fl}^Y_t \circ \mathrm{Fl}^X_t), \\
[X,Y] &= \tfrac12 \tfrac{\partial^2}{\partial t^2}|_0 (\mathrm{Fl}^Y_{-t} \circ \mathrm{Fl}^X_{-t} \circ \mathrm{Fl}^Y_t \circ \mathrm{Fl}^X_t) \\
&= \tfrac{\partial}{\partial t}\big|_0 \mathrm{Fl}^{[X,Y]}_t .
\end{aligned}$$

Applying F to these curves (of local diffeomorphisms) we get

$$\begin{aligned}
0 &= \tfrac{\partial}{\partial t}\big|_0 (\mathrm{Fl}^{Y^F}_{-t} \circ \mathrm{Fl}^{X^F}_{-t} \circ \mathrm{Fl}^{Y^F}_t \circ \mathrm{Fl}^{X^F}_t), \\
[X^F, Y^F] &= \tfrac12 \tfrac{\partial^2}{\partial t^2}|_0 (\mathrm{Fl}^{Y^F}_{-t} \circ \mathrm{Fl}^{X^F}_{-t} \circ \mathrm{Fl}^{Y^F}_t \circ \mathrm{Fl}^{X^F}_t) \\
&= \tfrac12 \tfrac{\partial^2}{\partial t^2}|_0 F(\mathrm{Fl}^Y_{-t} \circ \mathrm{Fl}^X_{-t} \circ \mathrm{Fl}^Y_t \circ \mathrm{Fl}^X_t) \\
&= \tfrac{\partial}{\partial t}\big|_0 F(\mathrm{Fl}^{[X,Y]}_t) = [X,Y]^F. \quad \square
\end{aligned}$$

6.20. Theorem. *For any vector bundle functor* F *on* $\mathcal{M}f_m$ *and* $X, Y \in \mathfrak{X}(M)$ *we have*

$$[\mathcal{L}_X, \mathcal{L}_Y] := \mathcal{L}_X \circ \mathcal{L}_Y - \mathcal{L}_Y \circ \mathcal{L}_X = \mathcal{L}_{[X,Y]} : \Gamma(F(M)) \to \Gamma(F(M)).$$

So $\mathcal{L} : \mathfrak{X}(M) \to \operatorname{End}\Gamma(F(M))$ *is a Lie algebra homomorphism.*

REWORK

Proof. We need some preparations. The first one is:

(1)
$$\begin{aligned}X^F \circ vpr_{F(M)} &= \tfrac{d}{dt}|_0 F(\mathrm{Fl}^X_t) \circ vpr_{F(M)}\\ &= \tfrac{d}{dt}|_0 vpr_{F(M)} \circ TF(\mathrm{Fl}^X_t) \restriction VF(M)\\ &= T(vpr_{F(M)}) \circ \tfrac{d}{dt}|_0 TF(\mathrm{Fl}^X_t) \restriction VF(M)\\ &= T(vpr_{F(M)}) \circ \kappa_{F(M)} \circ T(\tfrac{d}{dt}|_0 F(\mathrm{Fl}^X_t)) \restriction VF(M)\\ &= T(vpr_{F(M)}) \circ \kappa_{F(M)} \circ T(X^F) \restriction VF(M).\end{aligned}$$

(2) **Sublemma.** *For any vector bundle (E,p,M) we have*

$$vpr_E \circ T(vpr_E) \circ \kappa_E = vpr_E \circ T(vpr_E) = vpr_E \circ vpr_{TE} : VTE \cap TVE \to E,$$

and this is linear for all three vector bundle structures on TTE.

The assertion of this sublemma is local over M, so one may assume that (E,p,M) is trivial. Then one may carefully write out the action of the three mappings on a typical element $(x,v;0,w;;0,0;0,w') \in VTE \cap TVE$ and get the result.

Now we can start the actual proof.

$$\begin{aligned}&\mathcal{L}_{[X,Y]}s = vpr_{F(M)}(Ts \circ [X,Y] - [X,Y]^F \circ s) \quad \text{by (6.19)}\\ &= vpr_{F(M)} \circ \big(Ts \circ vpr_{TM} \circ (TY \circ X - \kappa_M \circ TX \circ Y) -\\ &\qquad - vpr_{TF(M)} \circ (TY^F \circ X^F - \kappa_{F(M)} \circ TX^F \circ Y^F) \circ s\big)\\ &= vpr_{F(M)} \circ vpr_{TF(M)} \circ \big(T^2s \circ TY \circ X - \kappa_{F(M)} \circ T^2 s \circ TX \circ Y -\\ &\qquad - TY^F \circ X^F \circ s - \kappa_{F(M)} \circ TX^F \circ Y^F \circ s\big).\\ &\mathcal{L}_X \mathcal{L}_Y s = \mathcal{L}_X (vpr_{F(M)} \circ (Ts \circ Y - Y^F \circ s))\\ &= vpr_{F(M)} \circ \big(T(vpr_{F(M)}) \circ (T^2 s \circ TY\ T(-)\ T(Y^F) \circ Ts) \circ X -\\ &\qquad - X^F \circ vpr_{F(M)} \circ (Ts \circ Y - Y^F \circ s)\big)\\ &= vpr_{F(M)} \circ T(vpr_{F(M)}) \circ (T^2 s \circ TY \circ X\ T(-)\ T(Y^F) \circ Ts \circ X) -\\ &\qquad - vpr_{F(M)} \circ T(vpr_{F(M)}) \circ \kappa_{F(M)} \circ T(X^F) \circ (Ts \circ Y - Y^F \circ s)\\ &= vpr_{F(M)} \circ vpr_{TF(M)} \circ \big(T^2 s \circ TY \circ X - T(Y^F) \circ Ts \circ X -\\ &\qquad - \kappa_{F(M)} \circ T(X^F) \circ Ts \circ Y + \kappa_{F(M)} \circ T(X^F) \circ Y^F \circ s\big).\end{aligned}$$

Finally we have

$$\begin{aligned}&[\mathcal{L}_X, \mathcal{L}_Y]s = \mathcal{L}_X \mathcal{L}_Y s - \mathcal{L}_Y \mathcal{L}_X s\\ &= vpr_{F(M)} \circ vpr_{TF(M)} \circ \big(T^2 s \circ TY \circ X - T(Y^F) \circ Ts \circ X -\\ &\qquad - \kappa_{F(M)} \circ T(X^F) \circ Ts \circ Y + \kappa_{F(M)} \circ T(X^F) \circ Y^F \circ s\big)\\ &- vpr_{F(M)} \circ vpr_{TF(M)} \circ \kappa_{F(M)} \circ \big(T^2 s \circ TY \circ X\ T(-)\ T(Y^F) \circ Ts \circ X\\ &\qquad T(-)\ \kappa_{F(M)} \circ T(X^F) \circ Ts \circ Y\ T(+)\ \kappa_{F(M)} \circ T(X^F) \circ Y^F \circ s\big)\\ &\qquad = \mathcal{L}_{[X,Y]}s. \quad \square\end{aligned}$$

7. Differential Forms

7.1. The *cotangent bundle* of a manifold M is the vector bundle $T^*M := (TM)^*$, the (real) dual of the tangent bundle.

If (U,u) is a chart on M, then $(\frac{\partial}{\partial u^1},\dots,\frac{\partial}{\partial u^m})$ is the associated frame field over U of TM. Since $\frac{\partial}{\partial u^i}|_x(u^j) = du^j(\frac{\partial}{\partial u^i}|_x) = \delta_i^j$ we see that $(du^1,\dots,du^m)$ is the dual frame field on T^*M over U. It is also called a *holonomous* frame field. A section of T^*M is also called a 1-*form*.

7.2. According to (6.18) a *tensor field* of type $\binom{p}{q}$ on a manifold M is a smooth section of the vector bundle

$$\bigotimes^p TM \otimes \bigotimes^q T^*M = TM \overbrace{\otimes\cdots\otimes}^{p \text{ times}} TM \otimes T^*M \overbrace{\otimes\cdots\otimes}^{q \text{ times}} T^*M.$$

The position of p (up) and q (down) can be explained as follows: If (U,u) is a chart on M, we have the holonomous frame field

$$\left(\frac{\partial}{\partial u^{i_1}}\otimes\frac{\partial}{\partial u^{i_2}}\otimes\cdots\otimes\frac{\partial}{\partial u^{i_p}}\otimes du^{j_1}\otimes\cdots\otimes du^{j_q}\right)_{i\in\{1,\dots,m\}^p, j\in\{1,\dots,m\}^q}$$

over U of this tensor bundle, and for any $\binom{p}{q}$-tensor field A we have

$$A \mid U = \sum_{i,j} A^{i_1\dots i_p}_{j_1\dots j_q}\frac{\partial}{\partial u^{i_1}}\otimes\cdots\otimes\frac{\partial}{\partial u^{i_p}}\otimes du^{j_1}\otimes\cdots\otimes du^{j_q}.$$

The coefficients have p indices up and q indices down, they are smooth functions on U.

From a categorical point of view one should look, where the indices of the frame field are, but this convention here has a long tradition.

7.3. Lemma. *Let $\Phi : \mathfrak{X}(M)\times\cdots\times\mathfrak{X}(M) = \mathfrak{X}(M)^k \to \Gamma(\bigotimes^l TM)$ be a mapping which is k-linear over $C^\infty(M)$ then Φ is given by the action of a $\binom{l}{k}$-tensor field.*

Proof. For simplicity's sake we put $k=1$, $\ell=0$, so $\Phi : \mathfrak{X}(M) \to C^\infty(M)$ is a $C^\infty(M)$-linear mapping: $\Phi(f.X) = f.\Phi(X)$. In the general case we subject each entry to the treatment described below.

Claim 1. If $X \mid U = 0$ for some open subset $U \subset M$, then we have $\Phi(X) \mid U = 0$. Let $x \in U$. We choose $f \in C^\infty(M)$ with $f(x) = 0$ and $f \mid M\setminus U = 1$. Then $f.X = X$, so $\Phi(X)(x) = \Phi(f.X)(x) = f(x).\Phi(X)(x) = 0$.

Claim 2. If $X(x) = 0$ then also $\Phi(X)(x) = 0$.
Let (U,u) be a chart centered at x, let V be open with $x \in V \subset \bar V \subset U$. Then $X \mid U = \sum X^i\frac{\partial}{\partial u^i}$ and $X^i(x) = 0$. We choose $g \in C^\infty(M)$ with $g \mid V \equiv 1$ and $\operatorname{supp} g \subset U$. Then $(g^2.X) \mid V = X \mid V$ and by claim 1 $\Phi(X) \mid V$ depends only on $X \mid V$ and $g^2.X = \sum_i (g.X^i)(g.\frac{\partial}{\partial u^i})$ is a decomposition which is globally defined

on M. Therefore we have $\Phi(X)(x) = \Phi(g^2.X)(x) = \Phi\left(\sum_i (g.X^i)(g.\frac{\partial}{\partial u^i})\right)(x) = \sum(g.X^i)(x).\Phi(g.\frac{\partial}{\partial u^i})(x) = 0$.

So we see that for a general vector field X the value $\Phi(X)(x)$ depends only on the value $X(x)$, for each $x \in M$. So there is a linear map $\varphi_x : T_xM \to \mathbb{R}$ for each $x \in M$ with $\Phi(X)(x) = \varphi_x(X(x))$. Then $\varphi : M \to T^*M$ is smooth since $\varphi \mid V = \sum_i \Phi(g.\frac{\partial}{\partial u^i})\, du^i$ in the setting of claim 2. □

7.4. Definition. A *differential form* of degree k or a *k-form* for short is a section of the (natural) vector bundle $\Lambda^k T^*M$. The space of all k-forms will be denoted by $\Omega^k(M)$. It may also be viewed as the space of all skew symmetric $\binom{0}{k}$-tensor fields, i. e. (by (7.3)) the space of all mappings

$$\varphi : \mathfrak{X}(M) \times \cdots \times \mathfrak{X}(M) = \mathfrak{X}(M)^k \to C^\infty(M),$$

which are k-linear over $C^\infty(M)$ and are skew symmetric:

$$\varphi(X_{\sigma 1}, \dots , X_{\sigma k}) = \operatorname{sign}\sigma \cdot \varphi(X_1, \dots, X_k)$$

for each permutation $\sigma \in \mathcal{S}_k$.

We put $\Omega^0(M) := C^\infty(M)$. Then the space

$$\Omega(M) := \bigoplus_{k=0}^{\dim M} \Omega^k(M)$$

is an algebra with the following product, called *wedge product.* For $\varphi \in \Omega^k(M)$ and $\psi \in \Omega^\ell(M)$ and for X_i in $\mathfrak{X}(M)$ (or in T_xM) we put

$$\begin{aligned}&(\varphi \wedge \psi)(X_1, \dots , X_{k+\ell}) = \\ &= \tfrac{1}{k!\,\ell!} \sum_{\sigma\in\mathcal{S}_{k+\ell}} \operatorname{sign}\sigma \cdot \varphi(X_{\sigma 1}, \dots , X_{\sigma k}).\psi(X_{\sigma(k+1)}, \dots , X_{\sigma(k+\ell)}).\end{aligned}$$

This product is defined fiber wise, i. e. $(\varphi \wedge \psi)_x = \varphi_x \wedge \psi_x$ for each $x \in M$. It is also associative, i.e $(\varphi \wedge \psi) \wedge \tau = \varphi \wedge (\psi \wedge \tau)$, and graded commutative, i. e. $\varphi\wedge\psi = (-1)^{k\ell}\psi\wedge\varphi$. There are differing conventions for the factor in the definition of the wedge product: in [Penrose, Rindler, ??] the factor $\frac{1}{(k+\ell)!}$ is used. But then the insertion operator of (7.7) is no longer a graded derivation. These properties are proved in multilinear algebra. REVISE: APPENDIX

7.5. If $f : N \to M$ is a smooth mapping and $\varphi \in \Omega^k(M)$, then the pullback $f^*\varphi \in \Omega^k(N)$ is defined for $X_i \in T_xN$ by

$$(f^*\varphi)_x(X_1, \dots, X_k) := \varphi_{f(x)}(T_xf.X_1, \dots, T_xf.X_k). \tag{1}$$

Then we have $f^*(\varphi \wedge \psi) = f^*\varphi \wedge f^*\psi$, so the linear mapping $f^* : \Omega(M) \to \Omega(N)$ is an algebra homomorphism. Moreover we have $(g \circ f)^* = f^* \circ g^* : \Omega(P) \to \Omega(N)$ if $g : M \to P$, and $(Id_M)^* = Id_{\Omega(M)}$.

So $M \mapsto \Omega(M) = \Gamma(\Lambda T^*M)$ is a contravariant functor from the category $\mathcal{M}f$ of all manifolds and all smooth mappings into the category of real graded commutative algebras, whereas $M \mapsto \Lambda T^*M$ is a covariant vector bundle functor defined only on $\mathcal{M}f_m$, the category of m-dimensional manifolds and local diffeomorphisms, for each m separately.

7.6. The Lie derivative of differential forms. Since $M \mapsto \Lambda^k T^*M$ is a vector bundle functor on $\mathcal{M}f_m$, by (6.16) for $X \in \mathfrak{X}(M)$ the *Lie derivative* of a k-form φ along X is defined by

$$\mathcal{L}_X \varphi = \tfrac{d}{dt}|_0 (\mathrm{Fl}^X_t)^*\varphi.$$

Lemma. *The Lie derivative has the following properties.*

(1) $\mathcal{L}_X(\varphi \wedge \psi) = \mathcal{L}_X\varphi \wedge \psi + \varphi \wedge \mathcal{L}_X\psi$, *so* $\mathcal{L}_X$ *is a derivation.*

(2) *For* $Y_i \in \mathfrak{X}(M)$ *we have*

$$(\mathcal{L}_X\varphi)(Y_1, \dots, Y_k) = X(\varphi(Y_1, \dots, Y_k)) - \sum_{i=1}^k \varphi(Y_1, \dots, [X, Y_i], \dots, Y_k).$$

(3) $[\mathcal{L}_X, \mathcal{L}_Y]\varphi = \mathcal{L}_{[X,Y]}\varphi$.

(4) $\frac{\partial}{\partial t}(\mathrm{Fl}^X_t)^*\varphi = (\mathrm{Fl}^X_t)^*\mathcal{L}_X\varphi = \mathcal{L}_X((\mathrm{Fl}^X_t)^*\varphi)$.

Proof. (1) The mapping $Alt : \bigotimes^k T^*M \to \Lambda^k T^*M$, given by

$$(Alt A)(Y_1, \dots, Y_k) := \tfrac{1}{k!}\sum_\sigma \mathrm{sign}(\sigma)\; A(Y_{\sigma 1}, \dots , Y_{\sigma k}),$$

is a linear natural transformation in the sense of (6.18) and induces an algebra homomorphism from $\bigoplus_{k\ge 0}\Gamma(\bigotimes^k T^*M)$ onto $\Omega(M)$. So (1) follows from (6.17) and (6.18).

Second, direct proof, using the definition and (7.5):

$$\begin{aligned}
\mathcal{L}_X(\varphi\wedge\psi) &= \tfrac{d}{dt}|_0(\mathrm{Fl}^X_t)^*(\varphi\wedge\psi) = \tfrac{d}{dt}|_0\Big((\mathrm{Fl}^X_t)^*\varphi \wedge (\mathrm{Fl}^X_t)^*\psi\Big)\\
&= \tfrac{d}{dt}|_0(\mathrm{Fl}^X_t)^*\varphi \wedge (\mathrm{Fl}^X_0)^*\psi + (\mathrm{Fl}^X_0)^*\varphi \wedge \tfrac{d}{dt}|_0(\mathrm{Fl}^X_t)^*\psi\\
&= \mathcal{L}_X\varphi\wedge\psi + \varphi\wedge\mathcal{L}_X\psi.
\end{aligned}$$

(2) Again by (6.17) and (6.18) we may compute as follows, where Trace is the full evaluation of the form on all vector fields:

$$\begin{aligned}
X(\varphi(Y_1, \dots, Y_k)) &= \mathcal{L}_X \circ \mathrm{Trace}(\varphi\otimes Y_1\otimes\dots\otimes Y_k)\\
&= \mathrm{Trace}\circ\mathcal{L}_X(\varphi\otimes Y_1\otimes\dots\otimes Y_k)\\
&= \mathrm{Trace}\big(\mathcal{L}_X\varphi\otimes(Y_1\otimes\dots\otimes Y_k)\\
&\qquad + \varphi\otimes(\textstyle\sum_i Y_1\otimes\dots\otimes\mathcal{L}_X Y_i\otimes\dots\otimes Y_k)\big).
\end{aligned}$$

Now we use $\mathcal{L}_X Y_i = [X, Y_i]$ from (3.13).

Second, independent proof:

$$\begin{aligned}
X(\varphi(Y_1, \dots, Y_k)) &= \tfrac{d}{dt}|_0(\mathrm{Fl}^X_t)^*(\varphi(Y_1, \dots, Y_k))\\
&= \tfrac{d}{dt}|_0((\mathrm{Fl}^X_t)^*\varphi)((\mathrm{Fl}^X_t)^*Y_1, \dots, (\mathrm{Fl}^X_t)^*Y_k))\\
&= (\mathcal{L}_X\varphi)(Y_1, \dots, Y_k) + \sum_{i=1}^k \varphi(Y_1, \dots, \mathcal{L}_X Y_i, \dots, Y_k).
\end{aligned}$$

(3) is a special case of (6.20). See (7.9.7) below for another proof.

$$\begin{aligned}
(4)\qquad \tfrac{\partial}{\partial t}(\mathrm{Fl}^X_t)^*\varphi &= \tfrac{\partial}{\partial s}|_0\left(\Lambda^k T(\mathrm{Fl}^X_{-t})\circ T(\mathrm{Fl}^X_{-s})^*\circ\varphi\circ\mathrm{Fl}^X_s\circ\mathrm{Fl}^X_t\right)\\
&= \Lambda^k T(\mathrm{Fl}^X_{-t})^*\circ\tfrac{\partial}{\partial s}|_0\left(\Lambda^k T(\mathrm{Fl}^X_{-s})^*\circ\varphi\circ\mathrm{Fl}^X_s\right)\circ\mathrm{Fl}^X_t\\
&= \Lambda^k T(\mathrm{Fl}^X_{-t})^*\circ\mathcal{L}_X\varphi\circ\mathrm{Fl}^X_t = (\mathrm{Fl}^X_t)^*\mathcal{L}_X\varphi\\
\tfrac{\partial}{\partial t}(\mathrm{Fl}^X_t)^*Y &= \tfrac{\partial}{\partial s}|_0(\mathrm{Fl}^X_s)^*(\mathrm{Fl}^X_t)^*Y = \mathcal{L}_X(\mathrm{Fl}^X_t)^*\varphi. \quad\square
\end{aligned}$$

7.7. The insertion operator. For a vector field $X\in\mathfrak{X}(M)$ we define the *insertion operator* $i_X = i(X):\Omega^k(M)\to\Omega^{k-1}(M)$ by

$$(i_X\varphi)(Y_1,\dots,Y_{k-1}) := \varphi(X,Y_1,\dots,Y_{k-1}).$$

Lemma.

(1) *i_X is a graded derivation of degree -1 of the graded algebra $\Omega(M)$, so we have $i_X(\varphi\wedge\psi) = i_X\varphi\wedge\psi + (-1)^{-\deg\varphi}\varphi\wedge i_X\psi$.*
(2) *$i_X\circ i_Y + i_Y\circ i_X = 0$.*
(3) *$[\mathcal{L}_X, i_Y] := \mathcal{L}_X\circ i_Y - i_Y\circ\mathcal{L}_X = i_{[X,Y]}$.*

Proof. (1) For $\varphi\in\Omega^k(M)$ and $\psi\in\Omega^\ell(M)$ we have

$$\begin{aligned}
(i_{X_1}(\varphi\wedge\psi))(X_2,\dots,X_{k+\ell}) &= (\varphi\wedge\psi)(X_1,\dots,X_{k+\ell})\\
&= \tfrac{1}{k!\,\ell!}\sum_\sigma \mathrm{sign}(\sigma)\,\varphi(X_{\sigma1},\dots,X_{\sigma k})\psi(X_{\sigma(k+1)},\dots,X_{\sigma(k+\ell)}).
\end{aligned}$$

$$\begin{aligned}
&(i_{X_1}\varphi\wedge\psi + (-1)^k\varphi\wedge i_{X_1}\psi)(X_2,\dots,X_{k+\ell})\\
&\quad= \tfrac{1}{(k-1)!\,\ell!}\sum_\sigma \mathrm{sign}(\sigma)\,\varphi(X_1,X_{\sigma2},\dots,X_{\sigma k})\psi(X_{\sigma(k+1)},\dots,X_{\sigma(k+\ell)})\\
&\qquad+ \frac{(-1)^k}{k!\,(\ell-1)!}\sum_\sigma \mathrm{sign}(\sigma)\,\varphi(X_{\sigma2},\dots,X_{\sigma(k+1)})\psi(X_1,X_{\sigma(k+2)},\dots).
\end{aligned}$$

Using the skew symmetry of φ and ψ we may distribute X_1 to each position by adding an appropriate sign. These are $k+\ell$ summands. Since $\frac{1}{(k-1)!\,\ell!}+\frac{1}{k!\,(\ell-1)!} = \frac{k+\ell}{k!\,\ell!}$, and since we can generate each permutation in $\mathcal{S}_{k+\ell}$ in this way, the result follows.

$$\begin{aligned}
(2)\quad (i_Xi_Y\varphi)(Z_1,\dots,Z_{k-2}) &= \varphi(Y,X,Z_1,\dots,Z_n) =\\
&= -\varphi(X,Y,Z_1,\dots,Z_n) = -(i_Yi_X\varphi)(Z_1,\dots,Z_{k-2}).
\end{aligned}$$

(3) By (6.17) and (6.18) we have:

$$\begin{aligned}
\mathcal{L}_X i_Y\varphi &= \mathcal{L}_X\,\mathrm{Trace}_1(Y\otimes\varphi) = \mathrm{Trace}_1\,\mathcal{L}_X(Y\otimes\varphi)\\
&= \mathrm{Trace}_1(\mathcal{L}_XY\otimes\varphi + Y\otimes\mathcal{L}_X\varphi) = i_{[X,Y]}\varphi + i_Y\mathcal{L}_X\varphi.
\end{aligned}$$

See (7.9.6) below for another proof. $\square$

7.8. The exterior differential. We want to construct a differential operator $\Omega^k(M) \to \Omega^{k+1}(M)$ which is natural. We will show that the simplest choice will work and (later) that it is essentially unique.

Let U be open in $\mathbb{R}^n$, let $\varphi \in \Omega^k(U) = C^\infty(U, L^k_{alt}(\mathbb{R}^n, \mathbb{R}))$. We consider the derivative $D\varphi \in C^\infty(U, L(\mathbb{R}^n, L^k_{alt}(\mathbb{R}^n, \mathbb{R})))$, and we take its canonical image in $C^\infty(U, L^{k+1}_{alt}(\mathbb{R}^n, \mathbb{R}))$. Here we write D for the derivative in order to distinguish it from the exterior differential, which we define as $d\varphi := (k+1) \operatorname{Alt} D\varphi$, more explicitly as

$$(1) \qquad (d\varphi)_x(X_0, \dots, X_k) = \tfrac{1}{k!} \sum_\sigma \operatorname{sign}(\sigma)\, D\varphi(x)(X_{\sigma 0})(X_{\sigma 1}, \dots, X_{\sigma k})$$
$$= \sum_{i=0}^k (-1)^i D\varphi(x)(X_i)(X_0, \dots, \widehat{X_i}, \dots, X_k),$$

where the hat over a symbol means that this is to be omitted, and where $X_i \in \mathbb{R}^n$.

Now we pass to an arbitrary manifold M. For a k-form $\varphi \in \Omega^k(M)$ and vector fields $X_i \in \mathfrak{X}(M)$ we try to replace $D\varphi(x)(X_i)(X_0, \dots)$ in formula (1) by Lie derivatives. We differentiate

$$X_i(\varphi(x)(X_0, \dots)) = D\varphi(x)(X_i)(X_0, \dots) + \sum_{0 \le j \le k, j \ne i} \varphi(x)(X_0, \dots, DX_j(x)X_i, \dots)$$

and insert this expression into formula (1) in order to get (cf. (3.4)) our working definition

$$(2) \quad d\varphi(X_0, \dots, X_k) := \sum_{i=0}^k (-1)^i X_i(\varphi(X_0, \dots, \widehat{X_i}, \dots, X_k)) +$$
$$+ \sum_{i<j} (-1)^{i+j} \varphi([X_i, X_j], X_0, \dots, \widehat{X_i}, \dots, \widehat{X_j}, \dots, X_k).$$

$d\varphi$, given by this formula, is $(k+1)$-linear over $C^\infty(M)$, as a short computation involving 3.4 shows. It is obviously skew symmetric, so $d\varphi$ is a $(k+1)$-form by (7.3), and the operator $d : \Omega^k(M) \to \Omega^{k+1}(M)$ is called the *exterior derivative*.

If (U, u) is a chart on M, then we have

$$\varphi \restriction U = \sum_{i_1 < \dots < i_k} \varphi_{i_1, \dots, i_k} du^{i_1} \wedge \dots \wedge du^{i_k},$$

where $\varphi_{i_1, \dots, i_k} = \varphi(\frac{\partial}{\partial u^{i_1}}, \dots, \frac{\partial}{\partial u^{i_k}})$. An easy computation shows that (2) leads to

$$(3) \qquad d\varphi \restriction U = \sum_{i_1 < \dots < i_k} d\varphi_{i_1, \dots, i_k} \wedge du^{i_1} \wedge \dots \wedge du^{i_k},$$

so that formulas (1) and (2) really define the same operator.

7.9. Theorem. *The exterior derivative* $d : \Omega^k(M) \to \Omega^{k+1}(M)$ *has the following properties:*

(1) $d(\varphi \wedge \psi) = d\varphi \wedge \psi + (-1)^{\deg \varphi}\varphi \wedge d\psi$, *so* d *is a graded derivation of degree 1.*
(2) $\mathcal{L}_X = i_X \circ d + d \circ i_X$ *for any vector field* X.
(3) $d^2 = d \circ d = 0$.
(4) $f^* \circ d = d \circ f^*$ *for any smooth* $f : N \to M$.
(5) $\mathcal{L}_X \circ d = d \circ \mathcal{L}_X$ *for any vector field* X.
(6) $[\mathcal{L}_X, i_Y] := \mathcal{L}_X \circ i_Y - i_Y \circ \mathcal{L}_X = i_{[X,Y]}$. *See also* (7.7.3).
(7) $[\mathcal{L}_X, \mathcal{L}_Y] = \mathcal{L}_{[X,Y]}$ *for any two vector fields* X, Y.

Remark. In terms of the graded commutator

$$[D_1, D_2] := D_1 \circ D_2 - (-1)^{\deg(D_1)\deg(D_2)} D_2 \circ D_1$$

for graded homomorphisms and graded derivations (see (19.1)) the assertions of this theorem take the following form:

(2) $\mathcal{L}_X = [i_X, d]$.
(3) $\frac{1}{2}[d, d] = 0$.
(4) $[f^*, d] = 0$.
(5) $[\mathcal{L}_X, d] = 0$.

This point of view will be developed in section (19) below. The equation (7) is a special case of (6.20).

Proof. (2) For $\varphi \in \Omega^k(M)$ and $X_i \in \mathfrak{X}(M)$ we have

$$\begin{aligned}
(\mathcal{L}_{X_0}\varphi)(X_1, \dots, X_k) &= X_0(\varphi(X_1, \dots, X_k)) + \\
&\quad + \sum_{j=1}^k (-1)^{0+j} \varphi([X_0, X_j], X_1, \dots, \widehat{X_j}, \dots, X_k) \text{ by (7.6.2)},\\
(i_{X_0} d\varphi)(X_1, \dots, X_k) &= d\varphi(X_0, \dots, X_k)\\
&= \sum_{i=0}^k (-1)^i X_i(\varphi(X_0, \dots, \widehat{X_i}, \dots, X_k)) + \\
&\quad + \sum_{0 \le i < j} (-1)^{i+j} \varphi([X_i, X_j], X_0, \dots, \widehat{X_i}, \dots, \widehat{X_j}, \dots, X_k).\\
(d i_{X_0}\varphi)(X_1, \dots, X_k) &= \sum_{i=1}^k (-1)^{i-1} X_i((i_{X_0}\varphi)(X_1, \dots, \widehat{X_i}, \dots, X_k)) + \\
&\quad + \sum_{1 \le i < j} (-1)^{i+j-2} (i_{X_0}\varphi)([X_i, X_j], X_1, \dots, \widehat{X_i}, \dots, \widehat{X_j}, \dots, X_k)\\
&= -\sum_{i=1}^k (-1)^i X_i(\varphi(X_0, X_1, \dots, \widehat{X_i}, \dots, X_k)) - \\
&\quad - \sum_{1 \le i < j} (-1)^{i+j} \varphi([X_i, X_j], X_0, X_1, \dots, \widehat{X_i}, \dots, \widehat{X_j}, \dots, X_k).
\end{aligned}$$

By summing up the result follows.

(1) Let $\varphi \in \Omega^p(M)$ and $\psi \in \Omega^q(M)$. We prove the result by induction on $p+q$.
$p+q=0$: $d(f\cdot g) = df\cdot g + f\cdot dg$.
Suppose that (1) is true for $p+q<k$. Then for $X \in \mathfrak{X}(M)$ we have by part (2) and (7.6), (7.7) and by induction

$$\begin{aligned}
i_X\, d(\varphi\wedge\psi) &= \mathcal{L}_X(\varphi\wedge\psi) - d\,i_X(\varphi\wedge\psi)\\
&= \mathcal{L}_X\varphi\wedge\psi + \varphi\wedge\mathcal{L}_X\psi - d(i_X\varphi\wedge\psi + (-1)^p\varphi\wedge i_X\psi)\\
&= i_X d\varphi\wedge\psi + di_X\varphi\wedge\psi + \varphi\wedge i_X d\psi + \varphi\wedge di_X\psi - di_X\varphi\wedge\psi\\
&\quad - (-1)^{p-1} i_X\varphi\wedge d\psi - (-1)^p d\varphi\wedge i_X\psi - \varphi\wedge di_X\psi\\
&= i_X(d\varphi\wedge\psi + (-1)^p\varphi\wedge d\psi).
\end{aligned}$$

Since X is arbitrary, (1) follows.

(3) By (1) d is a graded derivation of degree 1, so $d^2 = \frac{1}{2}[d,d]$ is a graded derivation of degree 2 (see (19.1)), and is obviously local: $d^2(\varphi\wedge\psi) = d^2(\varphi)\wedge\psi + \varphi\wedge d(\psi)$. Since $\Omega(M)$ is locally generated as an algebra by $C^\infty(M)$ and $\{df : f\in C^\infty(M)\}$, it suffices to show that $d^2 f = 0$ for each $f\in C^\infty(M)$ ($d^3 f = 0$ is a consequence). But this is easy:

$$d^2 f(X,Y) = Xdf(Y) - Ydf(X) - df([X,Y]) = XYf - YXf - [X,Y]f = 0.$$

(4) $f^*:\Omega(M)\to\Omega(N)$ is an algebra homomorphism by (7.6), so $f^*\circ d$ and $d\circ f^*$ are both graded derivations over f^* of degree 1. So if $f^*\circ d$ and $d\circ f^*$ agree on φ and on ψ, then also on $\varphi\wedge\psi$. By the same argument as in the proof of (3) above it suffices to show that they agree on g and dg for all $g\in C^\infty(M)$. We have

$$(f^*dg)_y(Y) = (dg)_{f(y)}(T_yf.Y) = (T_yf.Y)(g) = Y(g\circ f)(y) = (df^*g)_y(Y),$$

thus also $df^*dg = ddf^*g = 0$, and $f^*ddg = 0$.

(5) $d\mathcal{L}_X = d\,i_X\,d + ddi_X = di_Xd + i_Xdd = \mathcal{L}_Xd$.

(6) We use the graded commutator alluded to in the remarks. Both $\mathcal{L}_X$ and i_Y are graded derivations, thus graded commutator $[L_X, i_Y]$ is also a graded derivation as is $i_{[X,Y]}$. Thus it suffices to show that they agree on 0-forms $g\in C^\infty(M)$ and on exact 1-forms dg. We have

$$\begin{aligned}
[\mathcal{L}_X, i_Y]g &= \mathcal{L}_X i_Y g - i_Y\mathcal{L}_X g = \mathcal{L}_X 0 - i_Y(dg(X)) = 0 = i_{[X,Y]}g,\\
[\mathcal{L}_X, i_Y]dg &= \mathcal{L}_X i_Y dg - i_Y\mathcal{L}_X dg = \mathcal{L}_X\mathcal{L}_Y g - i_Y d\mathcal{L}_X g = (XY-YX)g = [X,Y]g\\
&= i_{[X,Y]}dg.
\end{aligned}$$

(7) By the (graded) Jacobi identity and by (6) (or lemma (7.7.3)) we have

$$[\mathcal{L}_X,\mathcal{L}_Y] = [\mathcal{L}_X,[i_Y,d]] = [[\mathcal{L}_X,i_Y],d] + [i_Y,[\mathcal{L}_X,d]] = [i_{[X,Y]},d] + 0 = \mathcal{L}_{[X,Y]}. \quad \square$$

7.10. A differential form $\omega \in \Omega^k(M)$ is called *closed* if $d\omega = 0$, and it is called *exact* if $\omega = d\varphi$ for some $\varphi \in \Omega^{k-1}(M)$. Since $d^2 = 0$, any exact form is closed. The quotient space

$$H^k(M) := \frac{\ker(d : \Omega^k(M) \to \Omega^{k+1}(M))}{\operatorname{im}(d : \Omega^{k-1}(M) \to \Omega^k(M))}$$

is called the k-th De Rham cohomology space of M. As a preparation for our treatment of cohomology we finish with the

Lemma of Poincaré. *A closed differential form of degree $k \geq 1$ is locally exact. More precisely: let $\omega \in \Omega^k(M)$ with $d\omega = 0$. Then for any $x \in M$ there is an open neighborhood U of x in M and a $\varphi \in \Omega^{k-1}(U)$ with $d\varphi = \omega \restriction U$.*

Proof. Let (U, u) be chart on M centered at x such that $u(U) = \mathbb{R}^m$. So we may just assume that $M = \mathbb{R}^m$.

We consider $\alpha : \mathbb{R} \times \mathbb{R}^m \to \mathbb{R}^m$, given by $\alpha(t, x) = \alpha_t(x) = tx$. Let $I \in \mathfrak{X}(\mathbb{R}^m)$ be the vector field $I(x) = x$, then $\alpha(e^t, x) = \mathrm{Fl}^I_t(x)$. So for $t > 0$ we have

$$\begin{aligned} \tfrac{d}{dt}\alpha_t^*\omega &= \tfrac{d}{dt}(\mathrm{Fl}^I_{\log t})^*\omega = \tfrac{1}{t}(\mathrm{Fl}^I_{\log t})^*\mathcal{L}_I\omega \\ &= \tfrac{1}{t}\alpha_t^*(i_I d\omega + d i_I\omega) = \tfrac{1}{t} d\alpha_t^* i_I\omega. \end{aligned}$$

Note that $T_x(\alpha_t) = t.Id$. Therefore

$$\begin{aligned} (\tfrac{1}{t}\alpha_t^* i_I\omega)_x(X_2, \dots, X_k) &= \tfrac{1}{t}(i_I\omega)_{tx}(tX_2, \dots, tX_k) \\ &= \tfrac{1}{t}\omega_{tx}(tx, tX_2, \dots, tX_k) = \omega_{tx}(x, tX_2, \dots, tX_k). \end{aligned}$$

So if $k \geq 1$, the $(k-1)$-form $\frac{1}{t}\alpha_t^* i_I\omega$ is defined and smooth in (t, x) for all $t \in \mathbb{R}$. Clearly $\alpha_1^*\omega = \omega$ and $\alpha_0^*\omega = 0$, thus

$$\begin{aligned} \omega = \alpha_1^*\omega - \alpha_0^*\omega &= \int_0^1 \tfrac{d}{dt}\alpha_t^*\omega dt \\ &= \int_0^1 d(\tfrac{1}{t}\alpha_t^* i_I\omega)dt = d\left(\int_0^1 \tfrac{1}{t}\alpha_t^* i_I\omega dt\right) = d\varphi. \quad \square \end{aligned}$$

8. Integration on Manifolds

8.1. Let $U \subset \mathbb{R}^n$ be an open subset, let dx denote Lebesque-measure on $\mathbb{R}^n$ (which depends on the Euclidean structure), let $g : U \to g(U)$ be a diffeomorphism onto some other open subset in $\mathbb{R}^n$, and let $f : g(U) \to \mathbb{R}$ be an integrable continuous function. Then the *transformation formula for multiple integrals* reads

$$\int_{g(U)} f(y)\, dy = \int_U f(g(x)) |\det dg(x)| dx.$$

This suggests that the suitable objects for integration on a manifold are sections of 1-dimensional vector bundle whose cocycle of transition functions is given by the absolute value of the Jacobi matrix of the chart changes. They will be called *densities* below.

8.2. The volume bundle. Let M be a manifold and let (U_α, u_α) be a smooth atlas for it. The *volume bundle* $(\mathrm{Vol}(M), \pi_M, M)$ of M is the one dimensional vector bundle (line bundle) which is given by the following cocycle of transition functions, see (6.3):

$$\psi_{\alpha\beta} : U_{\alpha\beta} = U_\alpha \cap U_\beta \to \mathbb{R} \setminus \{0\} = GL(1, \mathbb{R}),$$
$$\psi_{\alpha\beta}(x) = |\det d(u_\beta \circ u_\alpha^{-1})(u_\alpha(x))| = \frac{1}{|\det d(u_\alpha \circ u_\beta^{-1})(u_\beta(x))|}.$$

Lemma. Vol(M) *is a trivial line bundle over M.*

But there is no natural trivialization.

Proof. We choose a positive local section over each U_α and we glue them with a partition of unity. Since positivity is invariant under the transitions, the resulting global section μ is nowhere 0. By (6.5) μ is a global frame field and trivializes $\mathrm{Vol}(M)$. $\square$

Definition. Sections of the line bundle $\mathrm{Vol}(M)$ are called densities.

8.3. Integral of a density. Let $\mu \in \Gamma(\mathrm{Vol}(M))$ be a density with compact support on the manifold M. We define the *integral of the density* μ as follows:

Let (U_α, u_α) be an atlas on M, let f_α be a partition of unity with $\mathrm{supp}(f_\alpha) \subset U_\alpha$. Then we put

$$\int_M \mu = \sum_\alpha \int_{U_\alpha} f_\alpha \mu := \sum_\alpha \int_{u_\alpha(U_\alpha)} f_\alpha(u_\alpha^{-1}(y)).\psi_\alpha(\mu(u_\alpha^{-1}(y)))\, dy.$$

If μ does not have compact support we require that $\sum \int_{U_\alpha} f_\alpha\, |\mu| < \infty$. The series is then absolutely convergent.

Lemma. $\int_M \mu$ *is well defined.*

Proof. Let (V_β, v_β) be another atlas on M, let (g_β) be a partition of unity with $\mathrm{supp}(g_\beta) \subset V_\beta$. Let (U_α, ψ_α) be the vector bundle atlas of $\mathrm{Vol}(M)$ induced by the atlas (U_α, u_α), and let (V_β, φ_β) be the one induced by (V_β, v_β). Then we have by the transition formula for the diffeomorphisms $u_\alpha \circ v_\beta^{-1} : v_\beta(U_\alpha \cap V_\beta) \to u_\alpha(U_\alpha \cap V_\beta)$

$$\begin{aligned}
\sum_\alpha \int_{U_\alpha} f_\alpha\, \mu &= \sum_\alpha \int_{u_\alpha(U_\alpha)} (f_\alpha \circ u_\alpha^{-1})(y) \psi_\alpha(\mu(u_\alpha^{-1}(y)))\, dy \\
&= \sum_\alpha \int_{u_\alpha(U_\alpha)} \sum_\beta (g_\beta \circ u_\alpha^{-1})(y)(f_\alpha \circ u_\alpha^{-1})(y) \psi_\alpha(\mu(u_\alpha^{-1}(y)))\, dy \\
&= \sum_{\alpha\beta} \int_{u_\alpha(U_\alpha \cap V_\beta)} (g_\beta \circ u_\alpha^{-1})(y)(f_\alpha \circ u_\alpha^{-1})(y) \psi_\alpha(\mu(u_\alpha^{-1}(y)))\, dy
\end{aligned}$$

$$= \sum_{\alpha\beta} \int_{v_\beta(U_\alpha \cap V_\beta)} (g_\beta \circ v_\beta^{-1})(x)(f_\alpha \circ v_\beta^{-1})(x)$$
$$\psi_\alpha(\mu(v_\beta^{-1}(x)))|\det d(u_\alpha \circ v_\beta^{-1})(x)|\,dx$$
$$= \sum_{\alpha\beta} \int_{v_\beta(U_\alpha \cap V_\beta)} (g_\beta \circ v_\beta^{-1})(x)(f_\alpha \circ v_\beta^{-1})(x)\varphi_\beta(\mu(v_\beta^{-1}(x)))\,dx$$
$$= \sum_\beta \int_{V_\beta} g_\beta\,\mu. \quad \square$$

Remark. If $\mu \in \Gamma(\operatorname{Vol}(M))$ is an arbitrary section and $f \in C_c^\infty(M)$ is a function with compact support, then we may define the integral of f with respect to μ by $\int_M f\mu$, since $f\mu$ is a density with compact support. In this way μ defines a Radon measure on M.

For the converse we note first that (C^1 suffices) diffeomorphisms between open subsets on $\mathbb{R}^m$ map sets of Lebesque measure zero to sets of Lebesque measure zero. Thus on a manifold we have a well defined notion of sets of Lebesque measure zero — but no measure. If ν is a Radon measure on M which is absolutely continuous, i. e. the $|\nu|$-measure of a set of Lebesque measure zero is zero, then is given by a uniquely determined measurable section of the line bundle Vol. Here a section is called measurable if in any line bundle chart it is given by a measurable function.

8.4. p-densities. For $0 \le p \le 1$ let $\operatorname{Vol}^p(M)$ be the line bundle defined by the cocycle of transition functions

$$\psi^p_{\alpha\beta} : U_{\alpha\beta} \to \mathbb{R} \setminus \{0\}$$
$$\psi^p_{\alpha\beta}(x) = |\det d(u_\alpha \circ u_\beta^{-1})(u_\beta(x))|^{-p}.$$

This is also a trivial line bundle. Its sections are called p-densities. 1-densities are just densities, 0-densities are functions. If μ is a p-density and ν is a q-density with $p+q \le 1$ then $\mu.\nu := \mu \otimes \nu$ is a $p+q$-density, i. e. $\operatorname{Vol}^p(M) \otimes \operatorname{Vol}^q(M) = \operatorname{Vol}^{p+q}(M)$. Thus the product of two $\frac{1}{2}$-densities with compact support can be integrated, so $\Gamma_c(\operatorname{Vol}^{1/2}(M))$ is a pre Hilbert space in a natural way.

Distributions on M (in the sense of generalized functions) are elements of the dual space of the space $\Gamma_c(\operatorname{Vol}(M))$ of densities with compact support equipped with the inductive limit topology — so they contain functions.

8.5. Example. The density of a Riemann metric. Let g be a Riemann metric on a manifold M, see section (13) below. So g is a symmetric $\binom{0}{2}$ tensor field such that g_x is a positive definite inner product on T_xM for each $x \in M$. If (U, u) is a chart on M then we have

$$g|U = \sum_{i,j=1}^m g^u_{ij}\,du^i \otimes du^j$$

where the functions $g^u_{ij} = g(\frac{\partial}{\partial u^i}, \frac{\partial}{\partial u^j})$ form a positive definite symmetric matrix. So $\det(g^u_{ij}) = \det((g(\frac{\partial}{\partial u^i}, \frac{\partial}{\partial u^j}))^m_{i,j=1}) > 0$. We put

$$\operatorname{vol}(g)^u := \sqrt{\det((g(\tfrac{\partial}{\partial u^i}, \tfrac{\partial}{\partial u^j}))^m_{i,j=1})}.$$

If (V, v) is another chart we have

$$\begin{aligned}
\operatorname{vol}(g)^u &= \sqrt{\det((g(\tfrac{\partial}{\partial u^i}, \tfrac{\partial}{\partial u^j}))^m_{i,j=1})} \\
&= \sqrt{\det((g(\sum_k \tfrac{\partial v^k}{\partial u^i}\tfrac{\partial}{\partial v^k}, \sum_\ell \tfrac{\partial v^\ell}{\partial u^j}\tfrac{\partial}{\partial v^\ell}))^m_{i,j=1})} \\
&= \sqrt{\det((\tfrac{\partial v^k}{\partial u^i})_{k,i})^2 \det((g(\tfrac{\partial}{\partial v^\ell}, \tfrac{\partial}{\partial v^j}))_{\ell,j})} \\
&= |\det d(v \circ u^{-1})| \operatorname{vol}(g)^v,
\end{aligned}$$

so these local representatives determine a section $\operatorname{vol}(g) \in \Gamma(\operatorname{Vol}(M))$, which is called the *density or volume of the Riemann metric g*. If M is compact then $\int_M \operatorname{vol}(g)$ is called the *volume* of the Riemann manifold (M, g).

8.6. The orientation bundle. For a manifold M with $\dim M = m$ and an atlas (U_α, u_α) for M the line bundle $\Lambda^m T^*M$ is given by the cocycle of transition functions

$$\varphi_{\alpha\beta}(x) = \det d(u_\beta \circ u_\alpha^{-1})(u_\alpha(x)) = \Lambda^m d(u_\beta \circ u_\alpha^{-1})(u_\alpha(x)).$$

We consider the line bundle $\operatorname{Or}(M)$ which is given by the cocycle of transition functions

$$\tau_{\alpha\beta}(x) = \operatorname{sign} \varphi_{\alpha\beta}(x) = \operatorname{sign} \det d(u_\beta \circ u_\alpha^{-1})(u_\alpha(x)).$$

Since $\tau_{\alpha\beta}(x)\varphi_{\alpha\beta}(x) = \psi_{\alpha\beta}(x)$, the cocycle of the volume bundle of (8.2), we have

$$\begin{aligned}
\operatorname{Vol}(M) &= \operatorname{Or}(M) \otimes \Lambda^m T^*M \\
\Lambda^m T^*M &= \operatorname{Or}(M) \otimes \operatorname{Vol}(M)
\end{aligned}$$

8.7. Definition. A manifold M is called *orientable* if the orientation bundle $\operatorname{Or}(M)$ is trivial. Obviously this is the case if and only if there exists an atlas (U_α, u_α) for the smooth structure of M such that $\det d(u_\alpha \circ u_\beta^{-1})(u_\beta(x)) > 0$ for all $x \in U_{\alpha\beta}$.

Since the transition functions of $\operatorname{Or}(M)$ take only the values $+1$ and -1 there is a well defined notion of a fiberwise absolute value on $\operatorname{Or}(M)$, given by $|s(x)| := pr_2\, \tau_\alpha(s(x))$, where (U_α, τ_α) is a vector bundle chart of $\operatorname{Or}(M)$ induced by an atlas for M. If M is orientable there are two distinguished global frames for the orientation bundle $\operatorname{Or}(M)$, namely those with absolute value $|s(x)| = 1$.

The two normed frames s_1 and s_2 of $\operatorname{Or}(M)$ will be called the two possible *orientations* of the orientable manifold M. M is called an *oriented manifold* if one of these two normed frames of $\operatorname{Or}(M)$ is specified: it is denoted by $\mathfrak{o}_M$.

If M is oriented then $\operatorname{Or}(M) \cong M \times \mathbb{R}$ with the help of the orientation, so we have also

$$\Lambda^m T^*M = \operatorname{Or}(M) \otimes \operatorname{Vol}(M) = (M \times \mathbb{R}) \otimes \operatorname{Vol}(M) = \operatorname{Vol}(M).$$

So an orientation gives us a canonical identification of m-forms and densities. Thus for any m-form $\omega \in \Omega^m(M)$ the *integral* $\int_M \omega$ is defined by the isomorphism above as the integral of the associated density, see (8.3). If (U_α, u_α) is an oriented atlas (i. e. in each induced vector bundle chart (U_α, τ_α) for $\operatorname{Or}(M)$ we have $\tau_\alpha(\mathfrak{o}_M) = 1$) then the integral of the m-form ω is given by

$$\begin{aligned}\int_M \omega &= \sum_\alpha \int_{U_\alpha} f_\alpha \omega := \sum_\alpha \int_{U_\alpha} f_\alpha . \omega^\alpha \, du^1 \wedge \dots \wedge du^m \\ &:= \sum_\alpha \int_{u_\alpha(U_\alpha)} f_\alpha(u_\alpha^{-1}(y)) . \omega^\alpha(u_\alpha^{-1}(y)) \, dy^1 \wedge \dots \wedge dy^m,\end{aligned}$$

where the last integral has to be interpreted as an oriented integral on an open subset in $\mathbb{R}^m$.

8.8. Manifolds with boundary. A *manifold with boundary* M is a second countable metrizable topological space together with an equivalence class of smooth atlases (U_α, u_α) which consist of *charts with boundary*: So $u_\alpha : U_\alpha \to u_\alpha(U_\alpha)$ is a homeomorphism from U_α onto an open subset of a *half space* $(-\infty, 0] \times \mathbb{R}^{m-1} = \{(x_1, \dots, x_m) : x_1 \le 0\}$, and all chart changes $u_{\alpha\beta} : u_\beta(U_\alpha \cap U_\beta) \to u_\alpha(U_\alpha \cap U_\beta)$ are smooth in the sense that they are restrictions of smooth mappings defined on open (in $\mathbb{R}^m$) neighborhoods of the respective domains. There is a more intrinsic treatment of this notion of smoothness by means of Whitney jets, [Whitney, 1934], [Tougeron, 1972], and for the case of half-spaces and quadrants like here, [Seeley, 1964].

We have $u_{\alpha\beta}(u_\beta(U_\alpha \cap U_\beta) \cap (0 \times \mathbb{R}^{m-1})) = u_\alpha(U_\alpha \cap U_\beta) \cap (0 \times \mathbb{R}^{m-1})$ since interiour points (with respect to $\mathbb{R}^m$) are mapped to interior points by the inverse function theorem.

Thus the boundary of M, denoted by ∂M, is uniquely given as the set of all points $x \in M$ such that $u_\alpha(x) \in 0 \times \mathbb{R}^{m-1}$ for one (equivalently any) chart (U_α, u_α) of M. Obviously the boundary ∂M is itself a smooth manifold of dimension $m - 1$.

A simple example: the closed unit ball $B^m = \{x \in \mathbb{R}^m : |x| \le 1\}$ is a manifold with boundary, its boundary is $\partial B^m = S^{m-1}$.

The notions of smooth functions, smooth mappings, tangent bundle (use the approach (1.9) without any change in notation) are analogous to the usual ones. If $x \in \partial M$ we may distinguish in $T_x M$ tangent vectors pointing into the interior, pointing into the exterior, and those in $T_x(\partial M)$.

8.9. Lemma. *Let M be a manifold with boundary of dimension m. Then M is a submanifold with boundary of an m-dimensional manifold $\tilde{M}$ without boundary.*

Proof. Using partitions of unity we construct a vector field X on M which points strictly into the interior of M. We may multiply X by a strictly positive function so that the flow Fl^X_t exists for all $0 \le t < 2\varepsilon$ for some $\varepsilon > 0$. Then $\mathrm{Fl}^X_\varepsilon : M \to M \setminus \partial M$ is a diffeomorphism onto its image which embeds M as a submanifold with boundary of $M \setminus \partial M$. $\square$

8.10. Lemma. *Let M be an oriented manifold with boundary. Then there is a canonical induced orientation on the boundary ∂M.*

Proof. Let (U_α, u_α) be an oriented atlas for M. Then $u_{\alpha\beta} : u_\beta(U_{\alpha\beta} \cap \partial M) \to u_\alpha(U_{\alpha\beta} \cap \partial M)$, thus for $x \in u_\beta(U_{\alpha\beta} \cap \partial M)$ we have $du_{\alpha\beta}(x) : 0 \times \mathbb{R}^{m-1} \to 0 \times \mathbb{R}^{m-1}$,

$$du_{\alpha\beta}(x) = \begin{pmatrix} \lambda & 0 & \dots & 0 \\ * & & * & \end{pmatrix},$$

where $\lambda > 0$ since $du_{\alpha\beta}(x)(-e_1)$ is again pointing downwards. So

$$\det du_{\alpha\beta}(x) = \lambda \det(du_{\alpha\beta}(x)|0 \times \mathbb{R}^{m-1}) > 0,$$

consequently $\det(du_{\alpha\beta}(x)|0 \times \mathbb{R}^{m-1}) > 0$ and the restriction of the atlas (U_α, u_α) is an oriented atlas for ∂M. $\square$

8.11. Theorem of Stokes. *Let M be an m-dimensional oriented manifold with boundary ∂M. Then for any $(m-1)$-form $\omega \in \Omega^{m-1}_c(M)$ with compact support on M we have*

$$\int_M d\omega = \int_{\partial M} i^*\omega = \int_{\partial M} \omega,$$

where $i : \partial M \to M$ is the embedding.

Proof. Clearly $d\omega$ has again compact support. Let (U_α, u_α) be an oriented smooth atlas for M and let (f_α) be a smooth partition of unity with $\mathrm{supp}(f_\alpha) \subset U_\alpha$. Then we have $\sum_\alpha f_\alpha \omega = \omega$ and $\sum_\alpha d(f_\alpha \omega) = d\omega$. Consequently $\int_M d\omega = \sum_\alpha \int_{U_\alpha} d(f_\alpha\omega)$ and $\int_{\partial M} \omega = \sum_\alpha \int_{\partial U_\alpha} f_\alpha \omega$. It suffices to show that for each α we have $\int_{U_\alpha} d(f_\alpha\omega) = \int_{\partial U_\alpha} f_\alpha\omega$. For simplicity's sake we now omit the index α. The form $f\omega$ has compact support in U and we have in turn

$$\begin{aligned} f\omega &= \sum_{k=1}^m \omega_k du^1 \wedge \dots \wedge \widehat{du^k} \dots \wedge du^m \\ d(f\omega) &= \sum_{k=1}^m \frac{\partial \omega_k}{\partial u^k} du^k \wedge du^1 \wedge \dots \wedge \widehat{du^k} \dots \wedge du^m \\ &= \sum_{k=1}^m (-1)^{k-1} \frac{\partial \omega_k}{\partial u^k} du^1 \wedge \dots \wedge du^m. \end{aligned}$$

Since $i^* du^1 = 0$ we have $f\omega|\partial U = i^*(f\omega) = \omega_1 du^2 \wedge \dots \wedge du^m$, where $i : \partial U \to U$

is the embedding. Finally we get

$$\begin{aligned}
\int_U d(f\omega) &= \int_U \sum_{k=1}^m (-1)^{k-1}\frac{\partial\omega_k}{\partial u^k} du^1\wedge\dots\wedge du^m \\
&= \sum_{k=1}^m (-1)^{k-1}\int_U \frac{\partial\omega_k}{\partial u^k} du^1\wedge\dots\wedge du^m \\
&= \sum_{k=1}^m (-1)^{k-1}\int_{u(U)} \frac{\partial\omega_k}{\partial x^k} dx^1\wedge\dots\wedge dx^m \\
&= \int_{\mathbb{R}^{m-1}} \left(\int_{-\infty}^0 \frac{\partial\omega_1}{\partial x^1}dx^1\right) dx^2\dots dx^m \\
&\quad + \sum_{k=2}^m (-1)^{k-1}\int_{(-\infty,0]\times\mathbb{R}^{m-2}} \left(\int_{-\infty}^\infty \frac{\partial\omega_k}{\partial x^k}dx^k\right) dx^1\dots\widehat{dx^k}\dots dx^m \\
&= \int_{\mathbb{R}^{m-1}} (\omega_1(0,x^2,\dots,x^m)-0)dx^2\dots dx^m \\
&= \int_{\partial U} (\omega_1|\partial U) du^2\dots du^m = \int_{\partial U} f\omega.
\end{aligned}$$

We used the fundamental theorem of calculus twice,

$$\int_{-\infty}^0 \frac{\partial\omega_1}{\partial x^1}dx^1 = \omega_1(0,x^2,\dots,x^m)-0, \qquad \int_{-\infty}^\infty \frac{\partial\omega_k}{\partial x^k}dx^k = 0,$$

which holds since $f\omega$ has compact support in U. $\square$

9. De Rham cohomology

9.1. De Rham cohomology. Let M be a smooth manifold which may have boundary. We consider the graded algebra $\Omega(M)=\bigoplus_{k=0}^{\dim M}\Omega^k(M)$ of all differential forms on M. The space $Z(M):=\{\omega\in\Omega(M):d\omega=0\}$ of *closed forms* is a graded subalgebra of Ω, i. e. it is a subalgebra and satisfies $Z(M)=\bigoplus_{k=0}^{\dim M}(\Omega^k(M)\cap Z(M))=\bigoplus_{k=0}^{\dim M}Z^k(M)$. The space $B(M):=\{d\varphi:\varphi\in\Omega(M)\}$ of *exact forms* is a graded ideal in $Z(M)$: $B(M)\wedge Z(M)\subset B(M)$. This follows directly from the derivation property $d(\varphi\wedge\psi)=d\varphi\wedge\psi+(-1)^{\deg\varphi}\varphi\wedge d\psi$ of the exterior derivative.

Definition. The algebra

$$H^*(M):=\frac{Z(M)}{B(M)}=\frac{\{\omega\in\Omega(M):d\omega=0\}}{\{d\varphi:\varphi\in\Omega(M)\}}$$

is called the *De Rham cohomology algebra* of the manifold M. It is graded by

$$H^*(M)=\bigoplus_{k=0}^{\dim M}H^k(M)=\bigoplus_{k=0}^{\dim M}\frac{\ker(d:\Omega^k(M)\to\Omega^{k+1}(M))}{\operatorname{im} d:\Omega^{k-1}(M)\to\Omega^k(M)}.$$

If $f : M \to N$ is a smooth mapping between manifolds then $f^* : \Omega(N) \to \Omega(M)$ is a homomorphism of graded algebras by (7.5) which satisfies $d \circ f^* = f^* \circ d$ by (7.9). Thus f^* induces an algebra homomorphism which we call again $f^* : H^*(N) \to H^*(M)$.

9.2. Remark. Since $\Omega^k(M) = 0$ for $k > \dim M =: m$ we have

$$\begin{aligned} H^m(M) &= \frac{\Omega^m(M)}{\{d\varphi : \varphi \in \Omega^{m-1}(M)\}}. \\ H^k(M) &= 0 \qquad \text{for } k > m. \\ H^0(M) &= \frac{\{f \in \Omega^0(M) = C^\infty(M) : df = 0\}}{0} \\ &= \text{ the space of locally constant functions on } M \\ &= \mathbb{R}^{b_0(M)}, \end{aligned}$$

where $b_0(M)$ is the number of arcwise connected components of M. We put $b_k(M) := \dim_{\mathbb{R}} H^k(M)$ and call it the k-th *Betti number* of M. If $b_k(M) < \infty$ for all k we put

$$f_M(t) := \sum_{k=0}^m b_k(M) t^k$$

and call it the *Poincaré polynomial* of M. The number

$$\chi_M := \sum_{k=0}^m b_k(M)(-1)^k = f_M(-1)$$

is called the *Euler Poincaré characteristic* of M, see also (11.7) below.

9.3. Examples. We have $H^0(\mathbb{R}^m) = \mathbb{R}$ since it has only one connected component. We have $H^k(\mathbb{R}^m) = 0$ for $k > 0$ by the proof of the lemma of Poincaré (7.10).

For the one dimensional sphere we have $H^0(S^1) = \mathbb{R}$ since it is connected, and clearly $H^k(S^1) = 0$ for $k > 1$ by reasons of dimension. And we have

$$\begin{aligned} H^1(S^1) &= \frac{\{\omega \in \Omega^1(S^1) : d\omega = 0\}}{\{d\varphi : \varphi \in \Omega^0(S^1)\}} \\ &= \frac{\Omega^1(S^1)}{\{df : f \in C^\infty(S^1)\}}, \\ \Omega^1(S^1) &= \{f\, d\theta : f \in C^\infty(S^1)\} \\ &\cong \{f \in C^\infty(\mathbb{R}) : f \text{ is periodic with period } 2\pi\}, \end{aligned}$$

where $d\theta$ denotes the global coframe of T^*S^1. If $f \in C^\infty(\mathbb{R})$ is periodic with period 2π then $f\, dt$ is exact if and only if $\int f\, dt$ is also 2π periodic, i. e. $\int_0^{2\pi} f(t)dt = 0$. So we have

$$\begin{aligned} H^1(S^1) &= \frac{\{f \in C^\infty(\mathbb{R}) : f \text{ is periodic with period } 2\pi\}}{\{f \in C^\infty(\mathbb{R}) : f \text{ is periodic with period } 2\pi, \int_0^{2\pi} f\, dt = 0\}} \\ &= \mathbb{R}, \end{aligned}$$

where $f \mapsto \int_0^{2\pi} f\, dt$ factors to the isomorphism.

9.4. Lemma. *Let f, $g : M \to N$ be smooth mappings between manifolds which are C^∞-homotopic: there exists $h \in C^\infty(\mathbb{R} \times M, N)$ with $h(0,x) = f(x)$ and $h(1,x) = g(x)$.*

Then f and g induce the same mapping in cohomology: $f^* = g^* : H(N) \to H(M)$.

Remark. f, $g \in C^\infty(M,N)$ are called homotopic if there exists a continuous mapping $h : [0,1] \times M \to N$ with with $h(0,x) = f(x)$ and $h(1,x) = g(x)$. This seemingly looser relation in fact coincides with the relation of C^∞-homotopy. We sketch a proof of this statement: let $\varphi : \mathbb{R} \to [0,1]$ be a smooth function with $\varphi((-\infty, 1/4]) = 0$, $\varphi([3/4,\infty)) = 1$, and φ monotone in between. Then consider $\bar h : \mathbb{R} \times M \to N$, given by $\bar h(t,x) = h(\varphi(t), x)$. Now we may approximate $\bar h$ by smooth functions $\tilde h : \mathbb{R} \times M \to N$ whithout changing it on $(-\infty, 1/8) \times M$ where it equals f, and on $(7/8, \infty) \times M$ where it equals g. This is done chartwise by convolution with a smooth function with small support on $\mathbb{R}^m$. See [Bröcker-Jänich, 1973] for a careful presentation of the approximation.

So we will use the equivalent concept of homotopic mappings below.

Proof. For $\omega \in \Omega^k(N)$ we have $h^*\omega \in \Omega^k(\mathbb{R} \times M)$. We consider the insertion operator $\operatorname{ins}_t : M \to \mathbb{R} \times M$, given by $\operatorname{ins}_t(x) = (t,x)$. For $\varphi \in \Omega^k(\mathbb{R} \times M)$ we then have a smooth curve $t \mapsto \operatorname{ins}_t^* h^*\varphi$ in $\Omega^k(M)$ (this can be made precise with the help of the calculus in infinite dimensions of [Frölicher-Kriegl, 1988]). We define the integral operator $I_0^1 : \Omega^k(\mathbb{R} \times M) \to \Omega^k(M)$ by $I_0^1(\varphi) := \int_0^1 \operatorname{ins}_t^* \varphi\, dt$. Let $T := \frac{\partial}{\partial t} \in \mathfrak{X}(\mathbb{R} \times M)$ be the unit vector field in direction $\mathbb{R}$.

We have $\operatorname{ins}_{t+s} = \operatorname{Fl}_t^T \circ \operatorname{ins}_s$ for s, $t \in \mathbb{R}$, so

$$\begin{aligned} \tfrac{\partial}{\partial s} \operatorname{ins}_s^* \varphi &= \tfrac{\partial}{\partial t}\big|_0 (\operatorname{Fl}_t^T \circ \operatorname{ins}_s)^*\varphi = \tfrac{\partial}{\partial t}\big|_0 \operatorname{ins}_s^*(\operatorname{Fl}_t^T)^*\varphi \\ &= \operatorname{ins}_s^* \tfrac{\partial}{\partial t}\big|_0 (\operatorname{Fl}_t^T)^*\varphi = (\operatorname{ins}_s)^* \mathcal{L}_T\varphi \qquad \text{by (7.6).} \end{aligned}$$

We have used that $(ins_s)^* : \Omega^k(\mathbb{R} \times M) \to \Omega^k(M)$ is linear and continuous and so one may differentiate through it by the chain rule. Then we have in turn

$$\begin{aligned} d\, I_0^1\, \varphi &= d \int_0^1 \operatorname{ins}_t^* \varphi\, dt = \int_0^1 d\, \operatorname{ins}_t^* \varphi\, dt \\ &= \int_0^1 \operatorname{ins}_t^* d\varphi\, dt = I_0^1\, d\,\varphi \qquad \text{by (7.9.4).} \\ (\operatorname{ins}_1^* - \operatorname{ins}_0^*)\varphi &= \int_0^1 \tfrac{\partial}{\partial t} \operatorname{ins}_t^* \varphi\, dt = \int_0^1 \operatorname{ins}_t^* \mathcal{L}_T\varphi\, dt \\ &= I_0^1\, \mathcal{L}_T\varphi = I_0^1(d\, i_T + i_T\, d)\varphi \qquad \text{by (7.9).} \end{aligned}$$

Now we define the *homotopy operator* $\bar h := I_0^1 \circ i_T \circ h^* : \Omega^k(N) \to \Omega^{k-1}(M)$. Then we get

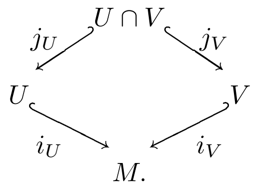
$$\begin{aligned} g^* - f^* &= (h \circ \operatorname{ins}_1)^* - (h \circ \operatorname{ins}_0)^* = (\operatorname{ins}_1^* - \operatorname{ins}_0^*) \circ h^* \\ &= (d \circ I_0^1 \circ i_T + I_0^1 \circ i_T \circ d) \circ h^* = d \circ \bar h - \bar h \circ d, \end{aligned}$$

which implies the desired result since for $\omega \in \Omega^k(M)$ with $d\omega = 0$ we have $g^*\omega - f^*\omega = \bar h d\omega + d\bar h\omega = d\bar h\omega$. □

9.5. Lemma. *If a manifold is decomposed into a disjoint union $M = \bigsqcup_\alpha M_\alpha$ of open submanifolds, then $H^k(M) = \prod_\alpha H^k(M_\alpha)$ for all k.*

Proof. $\Omega^k(M)$ is isomorphic to $\prod_\alpha \Omega^k(M_\alpha)$ via $\varphi \mapsto (\varphi|M_\alpha)_\alpha$. This isomorphism commutes with exterior differential d and induces the result. □

9.6. The setting for the Mayer-Vietoris Sequence. Let M be a smooth manifold, let U, $V \subset M$ be open subsets such that $M = U \cup V$. We consider the following embeddings:



Lemma. *In this situation the sequence*

$$0 \to \Omega(M) \xrightarrow{\alpha} \Omega(U) \oplus \Omega(V) \xrightarrow{\beta} \Omega(U \cap V) \to 0$$

is exact, where $\alpha(\omega) := (i_U^*\omega, i_V^*\omega)$ and $\beta(\varphi, \psi) = j_U^*\varphi - j_V^*\psi$. We also have $(d \oplus d) \circ \alpha = \alpha \circ d$ and $d \circ \beta = \beta \circ (d \oplus d)$.

Proof. We have to show that α is injective, $\ker \beta = \operatorname{im} \alpha$, and that β is surjective. The first two assertions are obvious and for the last one we we let $\{f_U, f_V\}$ be a partition of unity with $\operatorname{supp} f_U \subset U$ and $\operatorname{supp} f_V \subset V$. For $\varphi \in \Omega(U \cap V)$ we consider $f_V\varphi \in \Omega(U \cap V)$, note that $\operatorname{supp}(f_V\varphi)$ is closed in the set $U \cap V$ which is open in U, so we may extend $f_V\varphi$ by 0 to $\varphi_U \in \Omega(U)$. Likewise we extend $-f_U\varphi$ by 0 to $\varphi_V \in \Omega(V)$. Then we have $\beta(\varphi_U, \varphi_V) = (f_U + f_V)\varphi = \varphi$. □

Now we are in the situation where we may apply the main theorem of homological algebra, (9.8). So we deviate now to develop the basics of homological algebra.

9.7. The essentials of homological algebra. A *graded differential space* (GDS) $K = (K, d)$ is a sequence

$$\dots \to K^{n-1} \xrightarrow{d^{n-1}} K^n \xrightarrow{d^n} K^{n+1} \to \dots$$

of abelian groups K^n and group homomorphisms $d^n : K^n \to K^{n+1}$ such that $d^{n+1} \circ d^n = 0$. In our case these are the vector spaces $K^n = \Omega^n(M)$ and the exterior derivative. The group

$$H^n(K) := \frac{\ker(d^n : K^n \to K^{n+1})}{\operatorname{im}(d^{n-1} : K^{n-1} \to K^n)}$$

is called the n-th *cohomology group* of the GDS K. We consider also the direct sum

$$H^*(K) := \bigoplus_{n=-\infty}^{\infty} H^n(K)$$

as a graded group. A homomorphism $f : K \to L$ of graded differential spaces is a sequence of homomorphisms $f^n : K^n \to L^n$ such that $d^n \circ f^n = f^{n+1} \circ d^n$. It induces a homomorphism $f_* = H^*(f) : H^*(K) \to H^*(L)$ and H^* has clearly the properties of a functor from the category of graded differential spaces into the category of graded group: $H^*(Id_K) = Id_{H^*(K)}$ and $H^*(f \circ g) = H^*(f) \circ H^*(g)$.

A graded differential space (K, d) is called a graded differential algebra if $\bigoplus_n K^n$ is an associative algebra which is graded (so $K^n.K^m \subset K^{n+m}$), such that the differential d is a graded derivation: $d(x.y) = dx.y + (-1)^{\deg x} x.dy$. The cohomology group $H^*(K, d)$ of a graded differential algebra is a graded algebra, see (9.1).

By a *short exact sequence* of graded differential spaces we mean a sequence

$$0 \to K \xrightarrow{i} L \xrightarrow{p} M \to 0$$

of homomorphism of graded differential spaces which is degreewise exact: For each n the sequence $0 \to K^n \to L^n \to M^n \to 0$ is exact.

9.8. Theorem. *Let*

$$0 \to K \xrightarrow{i} L \xrightarrow{p} M \to 0$$

be an exact sequence of graded differential spaces. Then there exists a graded homomorphism $\delta = (\delta^n : H^n(M) \to H^{n+1}(K))_{n\in\mathbb{Z}}$ called the "connecting homomorphism" such that the following is an exact sequence of abelian groups:

$$\cdots \to H^{n-1}(M) \xrightarrow{\delta} H^n(K) \xrightarrow{i_*} H^n(L) \xrightarrow{p_*} H^n(M) \xrightarrow{\delta} H^{n+1}(K) \to \cdots$$

It is called the "long exact sequence in cohomology". δ is a natural transformation in the following sense: Let

$$\begin{array}{ccccccccc} 0 & \longrightarrow & K & \xrightarrow{\;i\;} & L & \xrightarrow{\;p\;} & M & \longrightarrow & 0 \\ & & \downarrow{\scriptstyle k} & & \downarrow{\scriptstyle \ell} & & \downarrow{\scriptstyle m} & & \\ 0 & \longrightarrow & K' & \xrightarrow[\;i'\;]{} & L' & \xrightarrow[\;p'\;]{} & M' & \longrightarrow & 0 \end{array}$$

be a commutative diagram of homomorphisms of graded differential spaces with exact lines. Then also the following diagram is commutative.

$$\begin{array}{ccccccccc} \cdots \longrightarrow & H^{n-1}(M) & \xrightarrow{\;\delta\;} & H^n(K) & \xrightarrow{\;i_*\;} & H^n(L) & \xrightarrow{\;p_*\;} & H^n(M) & \longrightarrow \cdots \\ & \downarrow{\scriptstyle m_*} & & \downarrow{\scriptstyle k_*} & & \downarrow{\scriptstyle \ell_*} & & \downarrow{\scriptstyle m_*} & \\ \cdots \longrightarrow & H^{n-1}(M') & \xrightarrow[\;\delta'\;]{} & H^n(K') & \xrightarrow[\;i'_*\;]{} & H^n(L') & \xrightarrow[\;p'_*\;]{} & H^n(M) & \longrightarrow \cdots \end{array}$$

The long exact sequence in cohomology can also be written in the following way:

$$\begin{array}{ccc} H^*(K) & \xrightarrow{\quad i_* \quad} & H^*(L) \\ {\scriptstyle \delta}\nwarrow & & \swarrow{\scriptstyle p_*} \\ & H^*(M) & \end{array}$$

Definition of δ. The connecting homomorphism is defined by '$\delta = i^{-1} \circ d \circ p^{-1}$' or $\delta[p\ell] = [i^{-1}d\ell]$. This is meant as follows.

$$\begin{array}{ccccccccc}
 & & & & L^{n-1} & \xrightarrow{p^{n-1}} & M^{n-1} & \longrightarrow & 0 \\
 & & & & \downarrow{\scriptstyle d^{n-1}} & & \downarrow{\scriptstyle d^{n-1}} & & \\
0 & \longrightarrow & K^n & \xrightarrow{i^n} & L^n & \xrightarrow{p^n} & M^n & \longrightarrow & 0 \\
 & & \downarrow{\scriptstyle d^n} & & \downarrow{\scriptstyle d^n} & & \downarrow{\scriptstyle d^n} & & \\
0 & \longrightarrow & K^{n+1} & \xrightarrow{i^{n+1}} & L^{n+1} & \xrightarrow{p^{n+1}} & M^{n+1} & \longrightarrow & 0 \\
 & & \downarrow{\scriptstyle d^{n+1}} & & \downarrow{\scriptstyle d^{n+1}} & & & & \\
0 & \longrightarrow & K^{n+2} & \xrightarrow{i^{n+2}} & L^{n+2} & & & &
\end{array}$$

The following argument is called a diagram chase. Let $[m] \in H^n(M)$. Then $m \in M^n$ with $dm = 0$. Since p is surjective there is $\ell \in L^n$ with $p\ell = m$. We consider $d\ell \in L^{n+1}$ for which we have $pd\ell = dp\ell = dm = 0$, so $d\ell \in \ker p = \operatorname{im} i$, thus there is an element $k \in K^{n+1}$ with $ik = d\ell$. We have $idk = dik = dd\ell = 0$. Since i is injective we have $dk = 0$, so $[k] \in H^{n+1}(K)$.

Now we put $\delta[m] := [k]$ or $\delta[p\ell] = [i^{-1}d\ell]$.

This method of diagram chasing can be used for the whole proof of the theorem. The reader is advised to do it at least once in his life with fingers on the diagram above. For the naturality imagine two copies of the diagram lying above each other with homomorphisms going up.

9.9. Five-Lemma. *Let*

$$\begin{array}{ccccccccc}
A_1 & \xrightarrow{\alpha_1} & A_2 & \xrightarrow{\alpha_2} & A_3 & \xrightarrow{\alpha_3} & A_4 & \xrightarrow{\alpha_4} & A_5 \\
\downarrow{\scriptstyle \varphi_1} & & \downarrow{\scriptstyle \varphi_2} & & \downarrow{\scriptstyle \varphi_3} & & \downarrow{\scriptstyle \varphi_4} & & \downarrow{\scriptstyle \varphi_5} \\
B_1 & \xrightarrow{\beta_1} & B_2 & \xrightarrow{\beta_2} & B_3 & \xrightarrow{\beta_3} & B_4 & \xrightarrow{\beta_4} & B_5
\end{array}$$

be a commutative diagram of abelian groups with exact lines. If φ_1, φ_2, φ_4, and φ_5 are isomorphisms then also the middle φ_3 is an isomorphism.

Proof. Diagram chasing in this diagram leads to the result. The chase becomes simpler if one first replaces the diagram by the following equivalent one with exact lines:

$$\begin{array}{ccccccccc}
0 & \longrightarrow & A_2/\operatorname{im}\alpha_1 & \xrightarrow{\alpha_2'} & A_3 & \xrightarrow{\alpha_3'} & \ker\alpha_4 & \longrightarrow & 0 \\
 & & \downarrow{\scriptstyle \varphi_2'}\,\cong & & \downarrow{\scriptstyle \varphi_3} & & \downarrow{\scriptstyle \varphi_4'}\,\cong & & \\
0 & \longrightarrow & B_2/\operatorname{im}\beta_2 & \xrightarrow{\beta_2'} & B_3 & \xrightarrow{\beta_3'} & \ker\beta_4 & \longrightarrow & 0.
\end{array}\qquad\square$$

9.10. Theorem. Mayer-Vietoris sequence. *Let U and V be open subsets in a manifold M such that $M = U \cup V$. Then there is an exact sequence*

$$\cdots \to H^k(M) \xrightarrow{\alpha_*} H^k(U) \oplus H^k(V) \xrightarrow{\beta_*} H^k(U \cap V) \xrightarrow{\delta} H^{k+1}(M) \to \cdots$$

It is natural in the triple (M, U, V) in the sense explained in (9.8)*. The homomorphisms α_* and β_* are algebra homomorphisms, but δ is not.*

Proof. This follows from (9.6) and theorem (9.8). □

Since we shall need it later we will give now a detailed description of the connecting homomorphism δ. Let $\{f_U, f_V\}$ be a partition of unity with $\operatorname{supp} f_U \subset U$ and $\operatorname{supp} f_V \subset V$. Let $\omega \in \Omega^k(U \cap V)$ with $d\omega = 0$ so that $[\omega] \in H^k(U \cap V)$. Then $(f_V.\omega, -f_U.\omega) \in \Omega^k(U) \oplus \Omega^k(V)$ is mapped to ω by β and so we have by the prescrition in (9.8)

$$\begin{aligned}\delta[\omega] &= [\alpha^{-1}\, d(f_V.\omega, -f_U.\omega)] = [\alpha^{-1}(df_V \wedge \omega, -df_U \wedge \omega)]\\ &= [df_V \wedge \omega] = -[df_U \wedge \omega)],\end{aligned}$$

where we have used the following fact: $f_U + f_V = 1$ implies that on $U \cap V$ we have $df_V = -df_U$ thus $df_V \wedge \omega = -df_U \wedge \omega$ and off $U \cap V$ both are 0.

9.11. Axioms for cohomology. The De Rham cohomology is uniquely determined by the following properties which we have already verified:

(1) $H^*(\quad)$ is a contravariant functor from the category of smooth manifolds and smooth mappings into the category of $\mathbb{Z}$-graded groups and graded homomorphisms.
(2) $H^k(\text{point}) = \mathbb{R}$ for $k = 0$ and $= 0$ for $k \neq 0$.
(3) If f and g are C^∞-homotopic then $H^*(f) = H^*(g)$.
(4) If $M = \bigsqcup_\alpha M_\alpha$ is a disjoint union of open subsets then $H^*(M) = \prod_\alpha H^*(M_\alpha)$.
(5) If U and V are open in M then there exists a connecting homomorphism $\delta : H^k(U \cap V) \to H^{k+1}(U \cup V)$ which is natural in the triple $(U \cup V, U, V)$ such that the following sequence is exact:

$$\cdots \to H^k(U \cup V) \to H^k(U) \oplus H^k(V) \to H^k(U \cap V) \xrightarrow{\delta} H^{k+1}(U \cup V) \to \cdots$$

There are lots of other cohomology theories for topological spaces like singular cohomology, Čech-cohomology, simplicial cohomology, Alexander-Spanier cohomology etc which satisfy the above axioms for manifolds when defined with real coefficients, so they all coincide with the De Rham cohomology on manifolds. See books on algebraic topology or sheaf theory for all this.

9.12. Example. If M is contractible (which is equivalent to the seemingly stronger concept of C^∞-contractibility, see the remark in (9.4)) then $H^0(M) = \mathbb{R}$ since M is connected, and $H^k(M) = 0$ for $k \neq 0$, because the constant mapping c :

$M \to$ point $\to M$ onto some fixed point of M is homotopic to Id_M, so $H^*(c) = H^*(Id_M) = Id_{H^*(M)}$ by (9.4). But we have

$$\begin{array}{ccc} H^k(M) & \xrightarrow{\quad H^k(c) \quad} & H^k(M) \\ & \searrow \qquad \nearrow & \\ & H^k(\text{point}) & \end{array}$$

More generally, two manifolds M and N are called to be smoothly homotopy equivalent if there exist smooth mappings $f : M \to N$ and $g : N \to M$ such that $g \circ f$ is homotopic to Id_M and $f \circ g$ is homotopic to Id_N. If this is the case both $H^*(f)$ and $H^*(g)$ are isomorphisms, since $H^*(g) \circ H^*(f) = Id_{H^*(M)}$ and $H^*(f) \circ H^*(g) = Id_{H^*(N)}$.

As an example consider a vector bundle (E, p, M) with zero section $0_E : M \to E$. Then $p \circ 0_E = Id_M$ whereas $0_E \circ p$ is homotopic to Id_E via $(t, u) \mapsto t.u$. Thus $H^*(E)$ is isomorphic to $H^*(M)$.

9.13. Example. The cohomology of spheres. *For $n \geq 1$ we have*

$$H^k(S^n) = \begin{cases} \mathbb{R} & \text{for } k = 0 \\ 0 & \text{for } 1 \leq k \leq n-1 \\ \mathbb{R} & \text{for } k = n \\ 0 & \text{for } k > n \end{cases} \qquad H^k(S^0) = \begin{cases} \mathbb{R}^2 & \text{for } k = 0 \\ 0 & \text{for } k > 0 \end{cases}$$

We may say: The cohomology of S^n has two generators as graded vector space, one in dimension 0 and one in dimension n. The Poincaré polynomial is given by $f_{S^n}(t) = 1 + t^n$.

Proof. The assertion for S^0 is obvious, and for S^1 it was proved in (9.3) so let $n \geq 2$. Then $H^0(S^n) = \mathbb{R}$ since it is connected, so let $k > 0$. Now fix a north pole $a \in S^n$, $0 < \varepsilon < 1$, and let

$$\begin{aligned} S^n &= \{x \in \mathbb{R}^{n+1} : |x|^2 = \langle x, x \rangle = 1\}, \\ U &= \{x \in S^n : \langle x, a \rangle > -\varepsilon\}, \\ V &= \{x \in S^n : \langle x, a \rangle < \varepsilon\}, \end{aligned}$$

so U and V are overlapping northern and southern hemispheres, respectively, which are diffeomorphic to an open ball and thus smoothly contractible. Their cohomology is thus described in (9.12). Clearly $U \cup V = S^n$ and $U \cap V \cong S^{n-1} \times (-\varepsilon, \varepsilon)$ which is obviously (smoothly) homotopy equivalent to S^{n-1}. By theorem (9.10) we have the following part of the Mayer-Vietoris sequence

$$\begin{array}{ccccccc} H^k(U) \oplus H^k(V) & \longrightarrow & H^k(U \cap V) & \xrightarrow{\ \delta\ } & H^{k+1}(S^n) & \longrightarrow & H^{k+1}(U) \oplus H^{k+1}(V) \\ \| & & \| & & & & \| \\ 0 & & H^k(S^{n-1}) & & & & 0, \end{array}$$

where the vertical isomorphisms are from (9.12). Thus $H^k(S^{n-1}) \cong H^{k+1}(S^n)$ for $k > 0$ and $n \geq 2$.

Next we look at the initial segment of the Mayer-Vietoris sequence:

$$\begin{array}{ccccccccc} 0 \longrightarrow & H^0(S^n) & \longrightarrow & H^0(U \sqcup V) & \xrightarrow{\beta} & H^0(U \cap V) & \xrightarrow{\delta} H^1(S^n) \longrightarrow & H^1(U \sqcup V) \\ & \| & & \| & & \| & & \| \\ 0 \longrightarrow & \mathbb{R} & \xrightarrow{\alpha} & \mathbb{R}^2 & \longrightarrow & \mathbb{R} & & 0 \end{array}$$

From exactness we have: in the lower line α is injective, so $\dim(\ker\beta) = 1$, so β is surjective and thus $\delta = 0$. This implies that $H^1(S^n) = 0$ for $n \geq 2$. Starting from $H^k(S^1)$ for $k > 0$ the result now follows by induction on n.

By looking more closely on on the initial segment of the Mayer-Vietoris sequence for $n = 1$ and taking into account the form of $\delta : H^0(S^0) \to H^1(S^1)$ we could even derive the result for S^1 without using (9.3). The reader is advised to try this. □

9.14. Example. The Poincaré polynomial of the Stiefel manifold $V(k, n; \mathbb{R})$ of oriented orthonormal k-frames in $\mathbb{R}^n$ (see (21.5)) is given by:

For:	$f_{V(k,n)} =$
$n = 2m,\ k = 2l + 1,\ l \geq 0:$	$(1 + t^{2m-1}) \prod_{i=1}^{l} (1 + t^{4m-4i-1})$
$n = 2m + 1,\ k = 2l,\ l \geq 1:$	$\prod_{i=1}^{l} (1 + t^{4m-4i+3})$
$n = 2m,\ k = 2l,\ m > l \geq 1:$	$(1 + t^{2m-2l})(1 + t^{2m-1}) \prod_{i=1}^{l-1} (1 + t^{4m-4i-1})$
$n = 2m + 1, k = 2l + 1,$ $m > l \geq 0:$	$(1 + t^{2m-2l}) \prod_{i=1}^{l-1} (1 + t^{4m-4i+3})$

Since $V(n - 1, n; \mathbb{R}) = SO(n; \mathbb{R})$ we get

$$f_{SO(2m;\mathbb{R})}(t) = (1 + t^{2m-1}) \prod_{i=1}^{m-1} (1 + t^{4i-1}),$$

$$f_{SO(2m+1,\mathbb{R})}(t) = \prod_{i=1}^{m} (1 + t^{4i-1}).$$

So the cohomology can be quite complicated. For a proof of these formulas using the Gysin sequence for sphere bundles see [Greub-Halperin-Vanstone II, 1973].

9.15. Relative De Rham cohomology. Let $N \subset M$ be a closed submanifold and let

$$\Omega^k(M, N) := \{\omega \in \Omega^k(M) : i^*\omega = 0\},$$

where $i : N \to M$ is the embedding. Since $i^* \circ d = d \circ i^*$ we get a graded differential subalgebra $(\Omega^*(M, N), d)$ of $(\Omega^*(M), d)$. Its cohomology, denoted by $H^*(M, N)$, is called the *relative De Rham cohomology* of the *manifold pair* (M, N).

9.16. Lemma. *In the setting of* (9.15),

$$0 \to \Omega^*(M,N) \hookrightarrow \Omega^*(M) \xrightarrow{i^*} \Omega^*(N) \to 0$$

is an exact sequence of differential graded algebras. Thus by (9.8) *we have the following long exact sequence in cohmology*

$$\dots \to H^k(M,N) \to H^k(M) \to H^k(N) \xrightarrow{\delta} H^{k+1}(M,N) \to \dots$$

which is natural in the manifold pair (M,N)*. It is called the long exact cohomology sequence of the pair* (M,N)*.*

Proof. We only have to show that $i^* : \Omega^*(M) \to \Omega^*(N)$ is surjective. So we have to extend each $\omega \in \Omega^k(N)$ to the whole of M. We cover N by submanifold charts of M with respect to N. These and $M \setminus N$ cover M. On each of the submanifold charts one can easily extend the restriction of ω and one can glue all these extensions by a partition of unity which is subordinated to the cover of M. □

10. Cohomology with compact supports and Poincaré duality

10.1. Cohomology with compact supports. Let $\Omega^k_c(M)$ denote the space of all k-forms with compact support on the manifold M. Since $\operatorname{supp}(d\omega) \subset \operatorname{supp}(\omega)$, $\operatorname{supp}(\mathcal{L}_X\omega) \subset \operatorname{supp}(X) \cap \operatorname{supp}(\omega)$, and $\operatorname{supp}(i_X\omega) \subset \operatorname{supp}(X) \cap \operatorname{supp}(\omega)$, all formulas of section (7) are also valid in $\Omega^*_c(M) = \bigoplus_{k=0}^{\dim M} \Omega^k_c(M)$. So $\Omega^*_c(M)$ is an ideal and a differential graded subalgebra of $\Omega^*(M)$. The cohomology of $\Omega^*_c(M)$

$$H^k_c(M) := \frac{\ker(d : \Omega^k_c(M) \to \Omega^{k+1}_c(M))}{\operatorname{im} d : \Omega^{k-1}_c(M) \to \Omega^k_c(M)},$$

$$H^*_c(M) := \bigoplus_{k=0}^{\dim M} H^k_c(M)$$

is called the *De Rham cohomology algebra with compact supports* of the manifold M. It has no unit if M is not compact.

10.2. Mappings. If $f : M \to N$ is a smooth mapping between manifolds and if $\omega \in \Omega^k_c(N)$ is a form with compact support, then $f^*\omega$ is a k-form on M, in general with noncompact support. So Ω^*_c is not a functor on the category of all smooth manifolds and all smooth mappings. But if we restrict the morphisms suitably, then Ω^*_c becomes a functor. There are two ways to do this:

(1) Ω^*_c is a contravariant functor on the category of all smooth manifolds and *proper smooth mappings* (f is called proper if f^{-1}(compact set) is a compact set) by the usual pullback operation.

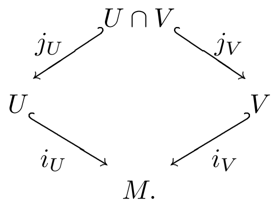
(2) Ω^*_c is a covariant functor on the category of all smooth manifolds and embeddings of open submanifolds: for $i : U \hookrightarrow M$ and $\omega \in \Omega^k_c(U)$ just extend ω by 0 off U to get $i_*\omega \in \Omega^k_c(M)$. Clearly $i_* \circ d = d \circ i_*$.

10.3. Remark. 1. If a manifold M is a disjoint union, $M = \bigsqcup_\alpha M_\alpha$, then we have obviously $H_c^k(M) = \bigoplus_\alpha H_c^k(M_\alpha)$.

2. $H_c^0(M)$ is a direct sum of copies of $\mathbb{R}$, one for each compact connected component of M.

3. If M is compact, then $H_c^k(M) = H^k(M)$.

10.4. The Mayer-Vietoris sequence with compact supports. Let M be a smooth manifold, let $U, V \subset M$ be open subsets such that $M = U \cup V$. We consider the following embeddings:



Theorem. *The following sequence of graded differential algebras is exact:*

$$0 \to \Omega_c^*(U \cap V) \xrightarrow{\beta_c} \Omega_c^*(U) \oplus \Omega_c^*(V) \xrightarrow{\alpha_c} \Omega_c^*(M) \to 0,$$

where $\beta_c(\omega) := ((j_U)_*\omega, (j_V)_*\omega)$ and $\alpha_c(\varphi, \psi) = (i_U)_*\varphi - (i_V)_*\psi$. So by (9.8) *we have the following long exact sequence*

$$\to H_c^{k-1}(M) \xrightarrow{\delta_c} H_c^k(U \cap V) \to H_c^k(U) \oplus H_c^k(V) \to H_c^k(M) \xrightarrow{\delta_c} H_c^{k+1}(U \cap V) \to$$

which is natural in the triple (M, U, V). It is called the Mayer Vietoris sequence with compact supports.

The connecting homomorphism $\delta_c : H_c^k(M) \to H_c^{k+1}(U \cap V)$ is given by

$$\begin{aligned}\delta_c[\varphi] &= [\beta_c^{-1}\, d\, \alpha_c^{-1}(\varphi)] = [\beta_c^{-1}\, d(f_U\varphi, -f_V\varphi)]\\ &= [df_U \wedge \varphi \restriction U \cap V] = -[df_V \wedge \varphi \restriction U \cap V].\end{aligned}$$

Proof. The only part that is not completely obvious is that α_c is surjective. Let $\{f_U, f_V\}$ be a partition of unity with $\operatorname{supp}(f_U) \subset U$ and $\operatorname{supp}(f_V) \subset V$, and let $\varphi \in \Omega_c^k(M)$. Then $f_U\varphi \in \Omega_c^k(U)$ and $-f_V\varphi \in \Omega_c^k(V)$ satisfy $\alpha_c(f_U\varphi, -f_V\varphi) = (f_U + f_V)\varphi = \varphi$. $\square$

10.5. Proper homotopies. A smooth mapping $h : \mathbb{R} \times M \to N$ is called a *proper homotopy* if $h^{-1}(\text{ compact set }) \cap ([0,1] \times M)$ is compact. A continuous homotopy $h : [0,1] \times M \to N$ is a proper homotopy if and only if it is a proper mapping.

Lemma. *Let $f, g : M \to N$ be proper and proper homotopic, then $f^* = g^* : H^k_c(N) \to H^k_c(M)$ for all k.*

Proof. Recall the proof of lemma (9.4).
Claim. In the proof of (9.4) we have furthermore $\bar{h} : \Omega^k_c(N) \to \Omega^{k-1}_c(M)$.
Let $\omega \in \Omega^k_c(N)$ and let $K_1 := \operatorname{supp}(\omega)$, a compact set in N. Then $K_2 := h^{-1}(K_1) \cap ([0,1] \times M)$ is compact in $\mathbb{R} \times M$, and finally $K_3 := pr_2(K_2)$ is compact in M. If $x \notin K_3$ then we have

$$(\bar{h}\omega)_x = ((I_0^1 \circ i_T \circ h^*)\omega)_x = \int_0^1 (\operatorname{ins}_t^*(i_T h^*\omega))_x \, dt) = 0.$$

The rest of the proof is then again as in (9.4). □

10.6. Lemma.

$$H^k_c(\mathbb{R}^n) = \begin{cases} \mathbb{R} & \text{for } k = n \\ 0 & \text{else.} \end{cases}$$

Proof. We embed $\mathbb{R}^n$ into its one point compactification $\mathbb{R}^n \cup \{\infty\}$ which is diffeomorphic to S^n, see (1.2). The embedding induces the exact sequence of complexes

$$0 \to \Omega_c(\mathbb{R}^n) \to \Omega(S^n) \to \Omega(S^n)_\infty \to 0,$$

where $\Omega(S^n)_\infty$ denotes the space of germs at the point $\infty \in S^n$. For germs at a point the lemma of Poincaré (7.10) is valid, so we have $H^0(\Omega(S^n)_\infty) = \mathbb{R}$ and $H^k(\Omega(S^n)_\infty) = 0$ for $k > 0$. By theorem (9.8) there is a long exact sequence in cohomology whose beginning is:

$$\begin{array}{cccccccccc} H^0_c(\mathbb{R}^n) & \longrightarrow & H^0(S^n) & \longrightarrow & H^0(\Omega(S^n)_\infty) & \xrightarrow{\delta} & H^1_c(\mathbb{R}^n) \longrightarrow H^1(S^n) & \longrightarrow & H^1(\Omega(S^n)_\infty) \\ \| & & \| & & \| & & & & \| \\ 0 & & \mathbb{R} & & \mathbb{R} & & & & 0 \end{array}$$

From this we see that $\delta = 0$ and consequently $H^1_c(\mathbb{R}^n) \cong H^1(S^n)$. Another part of this sequence for $k \geq 2$ is:

$$\begin{array}{ccccccc} H^{k-1}(\Omega(S^n)_\infty) & \xrightarrow{\delta} & H^k_c(\mathbb{R}^n) & \longrightarrow & H^k(S^n) & \longrightarrow & H^k(\Omega(S^n)_\infty) \\ \| & & & & & & \| \\ 0 & & & & & & 0 \end{array}$$

It implies $H^k_c(\mathbb{R}^n) \cong H^k(S^n)$ for all k. □

10.7. Fiber integration. Let M be a manifold, $pr_1 : M \times \mathbb{R} \to M$. We define an operator called fiber integration

$$\int_{\text{fiber}} : \Omega^k_c(M \times \mathbb{R}) \to \Omega^{k-1}_c(M)$$

as follows. Let t be the coordinate function on $\mathbb{R}$. A differential form with compact support on $M \times \mathbb{R}$ is a finite linear combination of two types of forms:

(1) $pr_1^*\varphi.f(x,t)$, shorter $\varphi.f$.
(2) $pr_1^*\varphi \wedge f(x,t)dt$, shorter $\varphi \wedge f dt$.

where $\varphi \in \Omega(M)$ and $f \in C_c^\infty(M \times \mathbb{R}, \mathbb{R})$. We then put

(1) $\int_{\text{fiber}} pr_1^*\varphi f := 0$.
(2) $\int_{\text{fiber}} pr_1^*\varphi \wedge f dt := \varphi \int_{-\infty}^{\infty} f(\quad, t)dt$

This is well defined since the only relation which we have to satisfy is $\text{pr}_1^*(\varphi g) \wedge f(x,t)dt = \text{pr}_1^* \varphi g(x) \wedge f(x,t)dt$.

Lemma. *We have* $d \circ \int_{\text{fiber}} = \int_{\text{fiber}} \circ d$. *Thus* $\int_{\text{fiber}}$ *induces a mapping in cohomology*

$$\left(\int_{\text{fiber}}\right)_* : H_c^k(M \times \mathbb{R}) \to H_c^{k-1}(M),$$

which however is not an algebra homomorphism.

Proof. In case (1) we have

$$\begin{aligned}\int_{\text{fiber}} d(\varphi.f) &= \int_{\text{fiber}} d\varphi.f + (-1)^k \int_{\text{fiber}} \varphi.d_M f + (-1)^k \int_{\text{fiber}} \varphi.\tfrac{\partial f}{\partial t} dt \\ &= (-1)^k \varphi \int_{-\infty}^{\infty} \tfrac{\partial f}{\partial t} dt = 0 \quad \text{ since } f \text{ has compact support} \\ &= d \int_{\text{fiber}} \varphi.f.\end{aligned}$$

In case (2) we get

$$\begin{aligned}\int_{\text{fiber}} d(\varphi \wedge f dt) &= \int_{\text{fiber}} d\varphi \wedge f dt + (-1)^k \int_{\text{fiber}} \varphi \wedge d_M f \wedge dt \\ &= d\varphi \int_{-\infty}^{\infty} f(\quad, t)dt + (-1)^k \varphi \int_{-\infty}^{\infty} d_M f(\quad, t)dt \\ &= d\left(\varphi \int_{-\infty}^{\infty} f(\quad, t)dt\right) = d \int_{\text{fiber}} \varphi \wedge f dt. \quad \square\end{aligned}$$

In order to find a mapping in the converse direction we let $e = e(t)dt$ be a compactly supported 1-form on $\mathbb{R}$ with $\int_{-\infty}^{\infty} e(t)dt = 1$. We define $e_* : \Omega_c^k(M) \to \Omega_c^{k+1}(M \times \mathbb{R})$ by $e_*(\varphi) = \varphi \wedge e$. Then $de_*(\varphi) = d(\varphi \wedge e) = d\varphi \wedge e + 0 = e_*(d\varphi)$, so we have an induced mapping in cohomology $e_* : H_c^k(M) \to H_c^{k+1}(M \times \mathbb{R})$.

We have $\int_{\text{fiber}} \circ e_* = Id_{\Omega_c^k(M)}$, since

$$\int_{\text{fiber}} e_*(\varphi) = \int_{\text{fiber}} \varphi \wedge e(\quad)dt = \varphi \int_{-\infty}^{\infty} e(t)dt = \varphi.$$

Next we define $K : \Omega_c^k(M \times \mathbb{R}) \to \Omega_c^{k-1}(M \times \mathbb{R})$ by

(1) $K(\varphi.f) := 0$
(2) $K(\varphi \wedge f dt) = \varphi \int_{-\infty}^{t} f dt - \varphi.A(t) \int_{-\infty}^{\infty} f dt$, where $A(t) := \int_{-\infty}^{t} e(t)dt$.

Lemma. *Then we have*

$$Id_{\Omega^k_c(M\times\mathbb{R})} - e_* \circ \int_{\text{fiber}} = (-1)^{k-1}(d\circ K - K\circ d) \tag{3}$$

Proof. We have to check the two cases. In case (1) we have

$$\begin{aligned}
(Id - e_* \circ \int_{\text{fiber}})(\varphi.f) &= \varphi.f - 0,\\
(d\circ K - K\circ d)(\varphi.f) &= 0 - K(d\varphi.f + (-1)^k\varphi\wedge d_1 f + (-1)^k\varphi\wedge \tfrac{\partial f}{\partial t}dt)\\
&= -(-1)^k\left(\varphi\int_{-\infty}^t \tfrac{\partial f}{\partial t}dt - \varphi.A(t)\int_{-\infty}^{\infty}\tfrac{\partial f}{\partial t}dt\right)\\
&= (-1)^{k-1}\varphi.f + 0.
\end{aligned}$$

In case (2) we get

$$\begin{aligned}
(Id - e_* \circ \int_{\text{fiber}})(\varphi\wedge f dt) &= \varphi\wedge f dt - \varphi\int_{-\infty}^{\infty} f dt\wedge e,\\
(d\circ K - K\circ d)(\varphi\wedge f dt) &= d\left(\varphi\int_{-\infty}^t f dt - \varphi.A(t)\int_{-\infty}^{\infty} f dt\right)\\
&\quad - K(d\varphi\wedge f dt + (-1)^{k-1}\varphi\wedge d_1 f\wedge dt)\\
&= (-1)^{k-1}\left(\varphi\wedge f dt - \varphi\wedge e\int_{-\infty}^{\infty} f dt\right) \qquad \square
\end{aligned}$$

Corollary. *The induced mappings* $\left(\int_{\text{fiber}}\right)_*$ *and* e_* *are inverse to each other, and thus isomorphism between* $H^k_c(M\times\mathbb{R})$ *and* $H^{k-1}_c(M)$.

Proof. This is clear from the chain homotopy (3). $\square$

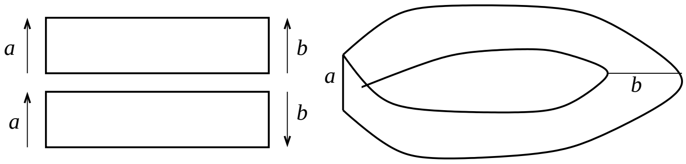
10.8. Second Proof of (10.6)**.** For $k \le n$ we have

$$\begin{aligned}
H^k_c(\mathbb{R}^n) &\cong H^{k-1}_c(\mathbb{R}^{n-1}) \cong \cdots \cong H^0_c(\mathbb{R}^{n-k})\\
&= \begin{cases} 0 & \text{for } k < n\\ H^0_c(\mathbb{R}^0) = \mathbb{R} & \text{for } k = n.\end{cases}
\end{aligned}$$

Note that the isomorphism $H^n_c(\mathbb{R}^n) \cong \mathbb{R}$ is given by integrating the differential form with compact support with respect to the standard orientation. This is well defined since by Stokes' theorem (8.11) we have $\int_{\mathbb{R}^n} d\omega = \int_\emptyset \omega = 0$, so the integral induces a mapping $\int_* : H^n_c(\mathbb{R}^n) \to \mathbb{R}$. $\square$

10.9. Example. We consider the open Möbius strip M in $\mathbb{R}^3$, see (1.20). Open means without boundary. Then M is contractible onto S^1, in fact M is the total space of a real line bundle over S^1. So from (9.12) we see that $H^k(M) \cong H^k(S^1) = \mathbb{R}$ for $k = 0, 1$ and $= 0$ for $k > 1$.

Now we claim that $H_c^k(M) = 0$ for all k. For that we cut the Möbius strip in two pieces which are glued at the end with one turn,



so that $M = U \cup V$ where $U \cong \mathbb{R}^2$, $V \cong \mathbb{R}^2$, and $U \cap V \cong \mathbb{R}^2 \sqcup \mathbb{R}^2$, the disjoint union. We also know that $H_c^0(M) = 0$ since M is not compact and connected. Then the Mayer-Vietoris sequence (see (10.4)) is given by

$$\underbrace{H_c^1(U) \oplus H_c^1(V)}_{=0} \longrightarrow H_c^1(M) \xrightarrow{\delta} \underbrace{H_c^2(U \cap V)}_{=\mathbb{R}\oplus\mathbb{R}} \xrightarrow{\beta_c}$$

$$\xrightarrow{\beta_c} \underbrace{H_c^2(U) \oplus H_c^2(V)}_{=\mathbb{R}\oplus\mathbb{R}} \longrightarrow H_c^2(M) \longrightarrow \underbrace{H_c^3(U \cap V)}_{=0}$$

We shall show that the linear mapping β_c has rank 2. So we read from the sequence that $H_c^1(M) = 0$ and $H_c^2(M) = 0$. By dimension reasons $H^k(M) = 0$ for $k > 2$.

Let φ, $\psi \in \Omega_c^2(U \cap V)$ be two forms, supported in the two connected components, respectively, with integral 1 in the orientation induced from one on U. Then $\int_U \varphi = 1$, $\int_U \psi = 1$, but for some orientation on V we have $\int_V \varphi = 1$ and $\int_V \psi = -1$. So the matrix of the mapping β_c in these bases is $\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$, which has rank 2.

10.10. Mapping degree for proper mappings. Let $f : \mathbb{R}^n \to \mathbb{R}^n$ be a smooth proper mapping, then $f^* : \Omega_c^k(\mathbb{R}^n) \to \Omega_c^k(\mathbb{R}^n)$ is defined and is an algebra homomorphism. So also the induced mapping in cohomology with compact supports makes sense and by

$$\begin{array}{ccc} H_c^n(\mathbb{R}^n) & \xrightarrow{f^*} & H_c^n(\mathbb{R}^n) \\ {\scriptstyle \int_*}\downarrow{\scriptstyle \cong} & & {\scriptstyle \cong}\downarrow{\scriptstyle \int_*} \\ \mathbb{R} & \xrightarrow{\deg f} & \mathbb{R} \end{array}$$

a linear mapping $\mathbb{R} \to \mathbb{R}$, i. e. multiplication by a real number, is defined. This number $\deg f$ is called the *"mapping degree"* of f.

10.11. Lemma. *The mapping degree of proper mappings has the following properties:*

(1) *If* f, $g : \mathbb{R}^n \to \mathbb{R}^n$ *are proper, then* $\deg(f \circ g) = \deg(f). \deg(g)$.
(2) *If* f *and* $g : \mathbb{R}^n \to \mathbb{R}^n$ *are proper homotopic (see* (10.5)*) then* $\deg(f) = \deg(g)$.
(3) $\deg(Id_{\mathbb{R}^n}) = 1$.
(4) *If* $f : \mathbb{R}^n \to \mathbb{R}^n$ *is proper and not surjective then* $\deg(f) = 0$.

Proof. Only statement (4) needs a proof. Since f is proper, $f(\mathbb{R}^n)$ is closed in $\mathbb{R}^n$: for K compact in $\mathbb{R}^n$ the inverse image $K_1 = f^{-1}(K)$ is compact, so $f(K_1) = f(\mathbb{R}^n) \cap K$ is compact, thus closed. By local compactness $f(\mathbb{R}^n)$ is closed.

Suppose that there exists $x \in \mathbb{R}^n \setminus f(\mathbb{R}^n)$, then there is an open neighborhood $U \subset \mathbb{R}^n \setminus f(\mathbb{R}^n)$. We choose a bump n-form α on $\mathbb{R}^n$ with support in U and $\int \alpha = 1$. Then $f^*\alpha = 0$, so $\deg(f) = 0$ since $[\alpha]$ is a generator of $H^n_c(\mathbb{R}^n)$. □

10.13. Lemma. *For a proper smooth mapping $f : \mathbb{R}^n \to \mathbb{R}^n$ the mapping degree is an integer, in fact for any regular value y of f we have*

$$\deg(f) = \sum_{x \in f^{-1}(y)} \operatorname{sign}(\det(df(x))) \in \mathbb{Z}.$$

Proof. By the Morse-Sard theorem, see (10.12), there exists a regular value y of f. If $f^{-1}(y) = \emptyset$ then f is not surjective, so $\deg(f) = 0$ by (10.11.4) and the formula holds. If $f^{-1}(y) \neq \emptyset$, then for all $x \in f^{-1}(y)$ the tangent mapping $T_x f$ is surjective, thus an isomorphism. By the inverse mapping theorem f is locally a diffeomorphism from an open neighborhood of x onto a neighborhood of y. Thus $f^{-1}(y)$ is a discrete and compact set, say $f^{-1}(y) = \{x_1, \dots, x_k\} \subset \mathbb{R}^n$.

Now we choose pairwise disjoint open neighborhoods U_i of x_i and an open neighborhood V of y such that $f : U_i \to V$ is a diffeomorphism for each i. We choose an n-form α on $\mathbb{R}^n$ with support in V and $\int \alpha = 1$. So $f^*\alpha = \sum_i (f|U_i)^*\alpha$ and moreover

$$\int_{U_i} (f|U_i)^*\alpha = \operatorname{sign}(\det(df(x_i))) \int_V \alpha = \operatorname{sign}(\det(df(x_i)))$$

$$\deg(f) = \int_{\mathbb{R}^n} f^*\alpha = \sum_i \int_{U_i} (f|U_i)^*\alpha = \sum_i^k \operatorname{sign}(\det(df(x_i))) \in \mathbb{Z}. \quad \square$$

10.14. Example. The last result for a proper smooth mapping $f : \mathbb{R} \to \mathbb{R}$ can be interpreted as follows: think of f as parametrizing the path of a car on an (infinite) street. A regular value of f is then a position on the street where the car never stops. Wait there and count the directions of the passes of the car: the sum is the mapping degree, the number of journeys from $-\infty$ to ∞. In dimension 1 it can be only -1, 0, or $+1$ (why?).

10.15. Poincaré duality. Let M be an oriented smooth manifold of dimension m without boundary. By Stokes' theorem the integral $\int : \Omega^m_c(M) \to \mathbb{R}$ vanishes on exact forms and induces the *"cohomological integral"*

(1) $$\int_* : \; H^m_c(M) \to \mathbb{R}.$$

It is surjective (use a bump m-form with small support). The *'Poincaré product'* is the bilinear form

(2) $$P^k_M : H^k(M) \times H^{m-k}_c(M) \to \mathbb{R},$$
$$P^k_M([\alpha], [\beta]) = \int_* [\alpha] \wedge [\beta] = \int_M \alpha \wedge \beta.$$

It is well defined since for β closed $d\gamma \wedge \beta = d(\gamma \wedge \beta)$, etc. If $j : U \to M$ is an orientation preserving embedding of an open submanifold then for $[\alpha] \in H^k(M)$ and for $[\beta] \in H_c^{m-k}(U)$ we may compute as follows:

$$
\begin{aligned}
\text{(3)} \qquad P_U^k(j^*[\alpha],[\beta]) &= \int_* (j^*[\alpha]) \wedge [\beta] = \int_U j^*\alpha \wedge \beta \\
&= \int_U j^*(\alpha \wedge j_*\beta) = \int_{j(U)} \alpha \wedge j_*\beta \\
&= \int_M \alpha \wedge j_*\beta = P_M^k([\alpha], j_*[\beta]).
\end{aligned}
$$

Now we define the *Poincaré duality operator*

$$
\begin{aligned}
\text{(4)} \qquad D_M^k &: H^k(M) \to (H_c^{m-k}(M))^*, \\
\langle [\beta], D_M^k[\alpha] \rangle &= P_M^k([\alpha],[\beta]).
\end{aligned}
$$

For example we have $D^0_{\mathbb{R}^n}(1) = (\int_{\mathbb{R}^n})_* \in (H_c^n(\mathbb{R}^n))^*$.

Let $M = U \cup V$ with U, V open in M, then we have the two Mayer Vietoris sequences from (9.10) and from (10.4)

$$
\cdots \to H^k(M) \xrightarrow{\alpha_*} H^k(U) \oplus H^k(V) \xrightarrow{\beta_*} H^k(U \cap V) \xrightarrow{\delta} H^{k+1}(M) \to \cdots
$$

$$
\leftarrow H_c^{m-k}(M) \leftarrow H_c^{m-k}(U) \oplus H_c^{m-k}(V) \leftarrow H_c^{m-k}(U \cap V) \xleftarrow{\delta_c} H_c^{m-(k+1)}(M) \leftarrow
$$

We take dual spaces and dual mappings in the second sequence and we replace δ in the first sequence by $(-1)^{k-1}\delta$ and get the following diagram which is commutative as we will see in a moment.

$$
\text{(5)} \qquad
\begin{array}{ccc}
\vdots & & \vdots \\
{\scriptstyle (-1)^{k-2}\delta}\downarrow & & \downarrow{\scriptstyle \delta_c^*} \\
H^k(M) & \xrightarrow{\quad D_M^k \quad} & H_c^{m-k}(M)^* \\
{\scriptstyle (i_U^*, i_V^*)}\downarrow & & \downarrow{\scriptstyle ((i_U)_*, (i_V)_*)^*} \\
H^k(U) \oplus H^k(V) & \xrightarrow{D_U^k \oplus D_V^k} & H_c^{m-k}(U)^* \oplus H_c^{m-k}(V)^* \\
{\scriptstyle j_U^* - j_V^*}\downarrow & & \downarrow{\scriptstyle ((j_U)_* - (j_V)_*)^*} \\
H^k(U \cap V) & \xrightarrow{\quad D_{U \cap V} \quad} & H_c^{m-k}(U \cap V)^* \\
{\scriptstyle (-1)^{k-1}\delta}\downarrow & & \downarrow{\scriptstyle \delta_c^*} \\
H^{k+1}(M) & \xrightarrow{\quad D_M^{k+1} \quad} & H_c^{m-(k+1)}(M)^* \\
\downarrow & & \downarrow \\
\vdots & & \vdots
\end{array}
$$

10.16. Lemma. *The diagram (5) in* (10.15) *commutes.*

Proof. The first and the second square from the top commute by (10.15.3). So we have to check that the bottom one commutes. Let $[\alpha] \in H^k(U \cap V)$ and $[\beta] \in H_c^{m-(k+1)}(M)$, and let (f_U, f_V) be a partition of unity which is subordinated to the open cover (U, V) of M. Then we have

$$\begin{aligned}
\langle[\beta], D_M^{k+1}(-1)^{k-1}\delta[\alpha]\rangle &= P_M^{k+1}((-1)^{k-1}\delta[\alpha], [\beta]) \\
&= P_M^{k+1}((-1)^{k-1}[df_V \wedge \alpha], [\beta]) \quad \text{ by (9.10)} \\
&= (-1)^{k-1}\int_M df_V \wedge \alpha \wedge \beta. \\
\langle[\beta], \delta_c^* D_{U\cap V}^k[\alpha]\rangle &= \langle\delta_c[\beta], D_{U\cap V}^k[\alpha]\rangle = P_{U\cap V}^k([\alpha], \delta_c[\beta]) \\
&= P_{U\cap V}^k([\alpha], [df_U \wedge \beta] = -[df_V \wedge \beta]) \quad \text{ by (10.4)} \\
&= -\int_{U\cap V} \alpha \wedge df_V \wedge \beta = -(-1)^k \int_M df_V \wedge \alpha \wedge \beta. \quad \square
\end{aligned}$$

10.17. Theorem. Poincaré Duality. *If M is an oriented manifold of dimension m without boundary then the Poincaré duality mapping*

$$D_M^k : H^k(M) \to H_c^{m-k}(M)^*$$

is a linear isomomorphism for each k.

Proof. Step 1. Let $\mathcal{O}$ be an i-base for the open sets of M, i. e. $\mathcal{O}$ is a basis containing all finite intersections of sets in $\mathcal{O}$. Let $\mathcal{O}_f$ be the the set of all open sets in M which are finite unions of sets in $\mathcal{O}$. Let $\mathcal{O}_s$ be the set of all open sets in M which are at most countable disjoint unions of sets in $\mathcal{O}$. Then obviously $\mathcal{O}_f$ and $\mathcal{O}_s$ are again i-bases.

Step 2. Let $\mathcal{O}$ be an i-base for M. If $D_O : H(O) \to H_c(O)^*$ is an isomorphism for all $O \in \mathcal{O}$, then also for all $O \in \mathcal{O}_f$.

Let $U \in \mathcal{O}_f$, $U = O_1 \cup \dots \cup O_k$ for $O_i \in \mathcal{O}$. We consider O_1 and $V = O_2 \cup \dots \cup O_k$. Then $O_1 \cap V = (O_1 \cap O_2) \cup \dots \cup (O_1 \cap O_k)$ is again a union of elements of $\mathcal{O}$ since it is an i-base. Now we prove the claim by induction on k. The case $k = 1$ is trivial. By induction D_{O_1}, D_V, and $D_{O_1 \cap V}$ are isomorphisms, so D_U is also an isomorphism by the five-lemma (9.9) applied to the diagram (10.15.5).

Step 3. If $\mathcal{O}$ is a basis of open sets in M such that D_O is an isomorphism for all $O \in \mathcal{O}$, then also for all $O \in \mathcal{O}_s$.

If $U \in \mathcal{O}_s$ we have $U = O_1 \sqcup O_2 \sqcup \ldots = \bigsqcup_{i=1}^\infty O_i$ for $O_i \in \mathcal{O}$. But then the diagram

$$\begin{array}{ccccc}
H(U) & = & & = & \prod_{i=1}^\infty H(O_i) \\
\Big\downarrow D_U & & & & \Big\downarrow \prod D_{O_i} \\
H_c(U)^* & = & (\bigoplus_{i=1}^\infty H_c(O_i))^* & = & \prod_{i=1}^\infty H_c(O_i)^*
\end{array}$$

commutes and implies that D_U is an isomorphism.

Step 4. If D_O is an isomorphism for each $O \in \mathcal{O}$ where $\mathcal{O}$ is an i-base for the open sets of M then D_U is an isomorphism for each open set $U \subset M$.

For $((\mathcal{O}_f)_s)_f$ contains all open sets of M. This is a consequence of the proof that each manifold admits a finite atlas. Then the result follows from steps 2 and 3.

Step 5. $D_{\mathbb{R}^m} : H(\mathbb{R}^m) \to H_c(\mathbb{R}^m)^*$ is an isomorphism.

We have

$$H^k(\mathbb{R}^m) = \begin{cases} \mathbb{R} & \text{for } k = 0 \\ 0 & \text{for } k > 0 \end{cases} \qquad H^k_c(\mathbb{R}^m) = \begin{cases} \mathbb{R} & \text{for } k = m \\ 0 & \text{for } k \neq m \end{cases}$$

The class $[1]$ is a generator for $H^0(\mathbb{R}^m)$, and $[\alpha]$ is a generator for $H^m_c(\mathbb{R}^m)$ where α is any m-form with compact support and $\int_M \alpha = 1$. But then $P^0_{\mathbb{R}^m}([1],[\alpha]) = \int_{\mathbb{R}^m} 1.\alpha = 1$.

Step 6. For each open subset $U \subset \mathbb{R}^m$ the mapping D_U is an isomorphism.

The set $\{\{x \in \mathbb{R}^m : a^i < x^i < b^i \text{ for all } i\} : a^i < b^i\}$ is an i-base of $\mathbb{R}^m$. Each element O in it is diffeomorphic (with orientation preserved) to $\mathbb{R}^m$, so D_O is an isomorphism by step 5. From step 4 the result follows.

Step 7. D_M is an isomorphism for each oriented manifold M.

Let $\mathcal{O}$ be the the set of all open subsets of M which are diffeomorphic to an open subset of $\mathbb{R}^m$, i. e. all charts of a maximal atlas. Then $\mathcal{O}$ is an i-base for M, and D_O is an isomorphism for each $O \in \mathcal{O}$. By step 4 D_U is an isomorphism for each open U in M, thus also D_U. $\square$

10.18. Corollary. *For each oriented manifold M without boundary the bilinear pairings*

$$P_M : H^*(M) \times H^*_c(M) \to \mathbb{R},$$
$$P^k_M : H^k(M) \times H^{m-k}_c(M) \to \mathbb{R}$$

are not degenerate.

10.19. Corollary. *Let $j : U \to M$ be the embedding of an open submanifold of an oriented manifold M of dimension m without boundary. Then of the following two mappings one is an isomorphism if and only if the other one is:*

$$j^* : H^k(U) \leftarrow H^k(M),$$
$$j_* : H^{m-k}_c(U) \to H^{m-k}_c(M).$$

Proof. Use (10.15.3), $P^k_U(j^*[\alpha],[\beta]) = P^k_M([\alpha], j_*[\beta])$. $\square$

10.20. Theorem. *Let M be an oriented connected manifold of dimension m without boundary. Then the integral*

$$\int_* : H_c^m(M) \to \mathbb{R}$$

is an isomorphism. So $\ker \int_M = d(\Omega_c^{m-1}(M)) \subset \Omega_c^m(M)$.

Proof. Considering m-forms with small support shows that the integral is surjective. By Poincaré duality (10.17) $\dim_{\mathbb{R}} H_c^m(M)^* = \dim_{\mathbb{R}} H^0(M) = 1$ since M is connected. $\square$

Definition. The uniquely defined cohomology class $\omega_M \in H_c^m(M)$ with integral $\int_M \omega_M = 1$ is called the *orientation class* of the manifold M.

10.21. Relative cohomology with compact supports. Let M be a smooth manifold and let N be a closed submanifold. Then the injection $i : N \to M$ is a proper smooth mapping. We consider the spaces

$$\Omega_c^k(M, N) := \{\omega \in \Omega_c^k(M) : \omega|N = i^*\omega = 0\}$$

whose direct sum is a graded differential subalgebra $(\Omega_c^*(M, N), d)$ of $(\Omega_c^*(M), d)$. Its cohomology, denoted by $H_c^*(M, N)$, is called the *relative De Rham cohomology with compact supports* of the *manifold pair* (M, N).

$$0 \to \Omega_c^*(M, N) \hookrightarrow \Omega_c^*(M) \xrightarrow{i^*} \Omega_c^*(N) \to 0$$

is an exact sequence of differential graded algebras. This is seen by the same proof as of (9.16) with some obvious changes. Thus by (9.8) we have the following long exact sequence in cohomology

$$\cdots \to H_c^k(M, N) \to H_c^k(M) \to H_c^k(N) \xrightarrow{\delta} H_c^{k+1}(M, N) \to \dots$$

which is natural in the manifold pair (M, N). It is called the *long exact cohomology sequence with compact supports of the pair* (M, N).

10.22. Now let M be an oriented smooth manifold of dimension m with boundary ∂M. Then ∂M is a closed submanifold of M. Since for $\omega \in \Omega_c^{m-1}(M, \partial M)$ we have $\int_M d\omega = \int_{\partial M} \omega = \int_{\partial M} 0 = 0$, the integral of m-forms factors as follows

$$\begin{array}{ccccc} \Omega_c^m(M, \partial M) & \hookrightarrow & \Omega_c^m(M) & \xrightarrow{\int_M} & \mathbb{R} \\ \downarrow & & & \overset{\int_*}{\nearrow} & \\ H_c^m(M, \partial M) & & & & \end{array}$$

to the *cohomological integral* $\int_* : H_c^m(M, \partial M) \to \mathbb{R}$.

Example. Let $I = [a,b]$ be a compact intervall, then $\partial I = \{a,b\}$. We have $H^1(I) = 0$ since $fdt = d\int_a^t f(s)ds$. The long exact sequence in cohomology of the pair $(I, \partial I)$ is

$$\begin{array}{ccccccccccc} 0 \longrightarrow & H^0(I,\partial I) & \longrightarrow & H^0(I) & \longrightarrow & H^0(\partial I) & \xrightarrow{\delta} & H^1(I,\partial I) & \longrightarrow & H^1(I) & \longrightarrow & H^1(\partial I) \\ & \| & & \| & & \| & & {\scriptstyle\int_*}\downarrow{\scriptstyle\cong} & & \| & & \| \\ & 0 & & \mathbb{R} & & \mathbb{R}^2 & & \mathbb{R} & & 0 & & 0 \end{array}$$

The connecting homomorphism $\delta : H^0(\partial I) \to H^1(I, \partial I)$ is given by the following procedure: Let $(f(a), f(b)) \in H^0(\partial I)$, where $f \in C^\infty(I)$. Then

$$\delta(f(a), f(b)) = [df] = \int_* [df] = \int_a^b df = \int_a^b f'(t)dt = f(b) - f(a).$$

So the fundamental theorem of calculus can be interpreted as the connecting homomorphism for the long exact sequence of the relative cohomology for the pair $(I, \partial I)$.

The general situation. Let M be an oriented smooth manifold with boundary ∂M. We consider the following piece of the long exact sequence in cohomology with compact supports of the pair $(M, \partial M)$:

$$\begin{array}{ccccccccc} H_c^{m-1}(M) & \longrightarrow & H_c^{m-1}(\partial M) & \xrightarrow{\delta} & H_c^m(M, \partial M) & \longrightarrow & H_c^m(M) & \longrightarrow & 0 \\ & & {\scriptstyle\int_*}\downarrow & & \downarrow{\scriptstyle\int_*} & & & & \\ & & \mathbb{R} & = & \mathbb{R} & & & & \end{array}$$

The connecting homomorphism is given by

$$\delta[\omega|\partial M] = [d\omega]_{H_c^m(M,\partial M)}, \quad \omega \in \Omega_c^{m-1}(M),$$

so commutation of the diagram above is equivalent to the validity of Stokes' theorem.

11. De Rham cohomology of compact manifolds

11.1. The oriented double cover. Let M be a manifold. We consider the orientation bundle $\operatorname{Or}(M)$ of M which we dicussed in (8.6), and we consider the subset $\operatorname{or}(M) := \{v \in \operatorname{Or}(M) : |v| = 1\}$, see (8.7) for the modulus. We shall see shortly that it is a submanifold of the total space $\operatorname{Or}(M)$, that it is orientable, and that $\pi_M : \operatorname{or}(M) \to M$ is a double cover of M. The manifold $\operatorname{or}(M)$ is called the *orientable double cover* of M.

We first check that the total space $\operatorname{Or}(M)$ of the orientation bundle is orientable. Let (U_α, u_α) be an atlas for M. Then the orientation bundle is given by the cocycle of transition functions

$$\tau_{\alpha\beta}(x) = \operatorname{sign}\varphi_{\alpha\beta}(x) = \operatorname{sign}\det d(u_\beta \circ u_\alpha^{-1})(u_\alpha(x)).$$

Let (U_α, τ_α) be the induced vector bundle atlas for $\operatorname{Or}(M)$, see (6.3). We consider the mappings

$$\begin{array}{ccccc}
\operatorname{Or}(M)|U_\alpha & \xrightarrow{\tau_\alpha} & U_\alpha \times \mathbb{R} & \xrightarrow{u_\alpha \times Id} & u_\alpha(U_\alpha) \times \mathbb{R} \subset \mathbb{R}^{m+1} \\
& {\scriptstyle \pi_M} \searrow & & \swarrow {\scriptstyle pr_1} & \\
& & U_\alpha & &
\end{array}$$

and we use them as charts for $\operatorname{Or}(M)$. The chart changes $u_\beta(U_{\alpha\beta}) \times \mathbb{R} \to u_\alpha(U_{\alpha\beta}) \times \mathbb{R}$ are then given by

$$\begin{aligned}
(y, t) &\mapsto (u_\alpha \circ u_\beta^{-1}(y), \tau_{\alpha\beta}(u_\beta^{-1}(y))t) \\
&= (u_\alpha \circ u_\beta^{-1}(y), \operatorname{sign}\det d(u_\beta \circ u_\alpha^{-1})((u_\alpha \circ u_\beta^{-1})(y))t) \\
&= (u_\alpha \circ u_\beta^{-1}(y), \operatorname{sign}\det d(u_\alpha \circ u_\beta^{-1})(y)t)
\end{aligned}$$

The Jacobi matrix of this mapping is

$$\begin{pmatrix} d(u_\alpha \circ u_\beta^{-1})(y) & * \\ 0 & \operatorname{sign}\det d(u_\alpha \circ u_\beta^{-1})(y) \end{pmatrix}$$

which has positive determinant.

Now we let $Z := \{v \in \operatorname{Or}(M) : |v| \le 1\}$ which is a submanifold with boundary in $\operatorname{Or}(M)$ of the same dimension and thus orientable. Its boundary ∂Z coincides with $\operatorname{or}(M)$, which is thus orientable.

Next we consider the diffeomorphism $\varphi : \operatorname{or}(M) \to \operatorname{or}(M)$ which is induced by the multiplication with -1 in $\operatorname{Or}(M)$. We have $\varphi \circ \varphi = Id$ and $\pi_M^{-1}(x) = \{z, \varphi(z)\}$ for $z \in \operatorname{or}(M)$ and $\pi_M(z) = x$.

Suppose that the manifold M is connected. Then the oriented double cover $\operatorname{or}(M)$ has at most two connected components, since π_M is a two sheeted convering map. If $\operatorname{or}(M)$ has two components, then φ restricts to a diffeomorphism between them. The projection π_M, if restricted to one of the components, becomes invertible, so $\operatorname{Or}(M)$ admits a section which vanishes nowhere, thus M is orientable. So we see that $\operatorname{or}(M)$ is connected if and only if M is not orientable.

The pullback mapping $\varphi^* : \Omega(\operatorname{or}(M)) \to \Omega(\operatorname{or}(M))$ also satisfies $\varphi^* \circ \varphi^* = Id$. We put

$$\begin{aligned}
\Omega_+(\operatorname{or}(M)) &: = \{\omega \in \Omega(\operatorname{or}(M)) : \varphi^*\omega = \omega\}, \\
\Omega_-(\operatorname{or}(M)) &: = \{\omega \in \Omega(\operatorname{or}(M)) : \varphi^*\omega = -\omega\}.
\end{aligned}$$

For each $\omega \in \Omega(\operatorname{or}(M))$ we have $\omega = \frac{1}{2}(\omega + \varphi^*\omega) + \frac{1}{2}(\omega - \varphi^*\omega) \in \Omega_+(\operatorname{or}(M)) \oplus \Omega_-(\operatorname{or}(M))$, so $\Omega(\operatorname{or}(M)) = \Omega_+(\operatorname{or}(M)) \oplus \Omega_-(\operatorname{or}(M))$. Since $d \circ \varphi^* = \varphi^* \circ d$ these two subspaces are invariant under d, thus we conclude that

$$H^k(\operatorname{or}(M)) = H^k(\Omega_+(\operatorname{or}(M))) \oplus H^k(\Omega_-(\operatorname{or}(M))). \tag{1}$$

Since $\pi_M^* : \Omega(M) \to \Omega(\operatorname{or}(M))$ is an embedding with image $\Omega_+(\operatorname{or}(M))$ we see that the induced mapping $\pi_M^* : H^k(M) \to H^k(\operatorname{or}(M))$ is also an embedding with image $H^k(\Omega_+(\operatorname{or}(M)))$.

11.2. Theorem. *For a compact manifold M we have* $\dim_{\mathbb{R}} H^*(M) < \infty$.

Proof. Step 1. If M is orientable we have by Poincaré duality (10.17)

$$H^k(M) \xrightarrow[\cong]{D^k_M} (H^{m-k}_c(M))^* = (H^{m-k}(M))^* \xleftarrow[\cong]{(D^{m-k}_M)^*} (H^k_c(M))^{**},$$

so $H^k(M)$ is finite dimensional since otherwise $\dim(H^k(M))^* > \dim H^k(M)$.

Step 2. Let M be not orientable. Then from (11.1) we see that the oriented double cover $\operatorname{or}(M)$ of M is compact, oriented, and connected, and we have $\dim H^k(M) = \dim H^k(\Omega_+(\operatorname{or}(M))) \le \dim H^k(\operatorname{or}(M)) < \infty$. □

11.3. Theorem. *Let M be a connected manifold of dimension m. Then*

$$H^m(M) \cong \begin{cases} \mathbb{R} & \text{if } M \text{ is compact and orientable,} \\ 0 & \text{else.} \end{cases}$$

Proof. If M is compact and orientable by (10.20) we the integral $\int_* : H^m(M) \to \mathbb{R}$ is an isomorphism.

Next let M be compact but not orientable. Then the oriented double cover $\operatorname{or}(M)$ is connected, compact and oriented. Let $\omega \in \Omega^m(\operatorname{or}(M))$ be an m-form which vanishes nowhere. Then also $\varphi^*\omega$ is nowhere zero where $\varphi : \operatorname{or}(M) \to \operatorname{or}(M)$ is the covering transformation from (11.1). So $\varphi^*\omega = f\omega$ for a function $f \in C^\infty(\operatorname{or}(M))$ which vanishes nowhere. So $f > 0$ or $f < 0$. If $f > 0$ then $\alpha := \omega + \varphi^*\omega = (1+f)\omega$ is again nowhere 0 and $\varphi^*\alpha = \alpha$, so $\alpha = \pi_M^*\beta$ for an m-form β on M without zeros. So M is orientable, a contradiction. Thus $f < 0$ and φ changes the orientation.

The m-form $\gamma := \omega - \varphi^*\omega = (1-f)\omega$ has no zeros, so $\int_{\operatorname{or}(M)} \gamma > 0$ if we orient $\operatorname{or}(M)$ using ω, thus the cohomology class $[\gamma] \in H^m(\operatorname{or}(M))$ is not zero. But $\varphi^*\gamma = -\gamma$ so $\gamma \in \Omega_-(\operatorname{or}(M))$, thus $H^m(\Omega_-(\operatorname{or}(M))) \ne 0$. By the first part of the proof we have $H^m(\operatorname{or}(M)) = \mathbb{R}$ and from (11.1) we get $H^m(\operatorname{or}(M)) = H^m(\Omega_-(\operatorname{or}(M)))$, so $H^m(M) = H^m(\Omega_+(\operatorname{or}(M))) = 0$.

Finally let us suppose that M is not compact. If M is orientable we have by Poincaré duality (10.17) and by (10.3.1) that $H^m(M) \cong H^0_c(M)^* = 0$.

If M is not orientable then $\operatorname{or}(M)$ is connected by (11.1) and not compact, so $H^m(M) = H^m(\Omega_+(\operatorname{or}(M))) \subset H^m(\operatorname{or}(M)) = 0$. □

11.4. Corollary. *Let M be a connected manifold which is not orientable. Then* $\operatorname{or}(M)$ *is orientable and the Poincaré duality pairing of* $\operatorname{or}(M)$ *satisfies*

$$\begin{aligned}
&P^k_{\operatorname{or}(M)}(H^k_+(\operatorname{or}(M)), (H^{m-k}_c)_+(\operatorname{or}(M))) = 0 \\
&P^k_{\operatorname{or}(M)}(H^k_-(\operatorname{or}(M)), (H^{m-k}_c)_-(\operatorname{or}(M))) = 0 \\
&H^k_+(\operatorname{or}(M)) \cong (H^{m-k}_c)_-(\operatorname{or}(M))^* \\
&H^k_-(\operatorname{or}(M)) \cong (H^{m-k}_c)_+(\operatorname{or}(M))^*
\end{aligned}$$

Proof. From (11.1) we know that $\operatorname{or}(M)$ is connected and orientable. So $\mathbb{R} = H^0(\operatorname{or}(M)) \cong H_c^m(\operatorname{or}(M))^*$.

Now we orient $\operatorname{or}(M)$ and choose a positive bump m-form ω with compact support on $\operatorname{or}(M)$ so that $\int_{\operatorname{or}(M)} \omega > 0$. From the proof of (11.3) we know that the covering transformation $\varphi : \operatorname{or}(M) \to \operatorname{or}(M)$ changes the orientation, so $\varphi^*\omega$ is negatively oriented, $\int_{\operatorname{or}(M)} \varphi^*\omega < 0$. Then $\omega - \varphi^*\omega \in \Omega_-^m(\operatorname{or}(M))$ and $\int_{\operatorname{or}(M)}(\omega - \varphi^*\omega) > 0$, so $(H_c^m)_-(\operatorname{or}(M)) = \mathbb{R}$ and $(H_c^m)_+(\operatorname{or}(M)) = 0$.

Since φ^* is an algebra homomorphism we have

$$\begin{aligned}
&\Omega_+^k(\operatorname{or}(M)) \wedge (\Omega_c^{m-k})_+(\operatorname{or}(M)) \subset (\Omega_c^m)_+(\operatorname{or}(M)),\\
&\Omega_-^k(\operatorname{or}(M)) \wedge (\Omega_c^{m-k})_-(\operatorname{or}(M)) \subset (\Omega_c^m)_+(\operatorname{or}(M)).
\end{aligned}$$

From $(H_c^m)_+(\operatorname{or}(M)) = 0$ the first two results follows. The last two assertions then follow from this and $H^k(\operatorname{or}(M)) = H_+^k(\operatorname{or}(M)) \oplus H_-^k(\operatorname{or}(M))$ and the analogous decomposition of $H_c^k(\operatorname{or}(M))$. □

11.5. Theorem. *For the real projective spaces we have*

$$\begin{aligned}
&H^0(\mathbb{RP}^n) = \mathbb{R}\\
&H^k(\mathbb{RP}^n) = 0 \qquad \textit{for } 1 \le k < n,\\
&H^n(\mathbb{RP}^n) = \begin{cases} \mathbb{R} & \textit{for odd } n,\\ 0 & \textit{for even } n. \end{cases}
\end{aligned}$$

Proof. The projection $\pi : S^n \to \mathbb{RP}^n$ is a smooth covering mapping with 2 sheets, the covering transformation is the antipodal mapping $A : S^n \to S^n$, $x \mapsto -x$. We put $\Omega_+(S^n) = \{\omega \in \Omega(S^n) : A^*\omega = \omega\}$ and $\Omega_-(S^n) = \{\omega \in \Omega(S^n) : A^*\omega = -\omega\}$. The pullback $\pi^* : \Omega(\mathbb{RP}^n) \to \Omega(S^n)$ is an embedding onto $\Omega_+(S^n)$.

Let Δ be the determinant function on the oriented Euclidean space $\mathbb{R}^{n+1}$. We identify T_xS^n with $\{x\}^\perp$ in $\mathbb{R}^{n+1}$ and we consider the n-form $\omega_{S^n} \in \Omega^n(S^n)$ which is given by $(\omega_{S^n})_x(X_1, \dots, X_n) = \Delta(x, X_1, \dots, X_n)$. Then we have

$$\begin{aligned}
(A^*\omega_{S^n})_x(X_1, \dots, X_n) &= (\omega_{S^n})_{A(x)}(T_xA.X_1, \dots, T_xA.X_n)\\
&= (\omega_{S^n})_{-x}(-X_1, \dots, -X_n)\\
&= \Delta(-x, -X_1, \dots, -X_n)\\
&= (-1)^{n+1}\Delta(x, X_1, \dots, X_n)\\
&= (-1)^{n+1}(\omega_{S^n})_x(X_1, \dots, X_n)
\end{aligned}$$

Since ω_{S^n} is invariant under the action of the group $SO(n+1, \mathbb{R})$ it must be the Riemannian volume form, so

$$\int_{S^n} \omega_{S^n} = \operatorname{vol}(S^n) = \frac{(n+1)\pi^{\frac{n+1}{2}}}{\Gamma(\frac{n+3}{2})} = \begin{cases} \frac{2\pi^k}{(k-1)!} & \text{for } n = 2k-1\\ \frac{2^k\pi^{k-1}}{1\cdot 3\cdot 5 \dots (2k-3)} & \text{for } n = 2k-2 \end{cases}$$

Thus $[\omega_{S^n}] \in H^n(S^n)$ is a generator for the cohomology. We have $A^*\omega_{S^n} = (-1)^{n+1}\omega_{S^n}$, so

$$\omega_{S^n} \in \begin{cases} \Omega^n_+(S^n) & \text{for odd } n, \\ \Omega^n_-(S^n) & \text{for even } n. \end{cases}$$

Thus $H^n(\mathbb{RP}^n) = H^n(\Omega_+(S^n))$ equals $H^n(S^n) = \mathbb{R}$ for odd n and equals 0 for even n.

Since $\mathbb{RP}^n$ is connected we have $H^0(\mathbb{RP}^n) = \mathbb{R}$. For $1 \le k < n$ we have $H^k(\mathbb{RP}^n) = H^k(\Omega_+(S^n)) \subset H^k(S^n) = 0$. □

11.6. Corollary. *Let M be a compact manifold. Then for all Betti numbers we have $b_k(M) := \dim_\mathbb{R} H^k(M) < \infty$. If M is compact and orientable of dimension m we have $b_k(M) = b_{m-k}(M)$.*

Proof. This follows from (11.2) and from Poincaré duality (10.17). □

11.7. Euler-Poincaré characteristic. If M is compact then all Betti numbers are finite, so the Euler Poincaré characteristic (see also (9.2))

$$\chi_M = \sum_{k=0}^{\dim M} (-1)^k b_k(M) = f_M(-1)$$

is defined.

Theorem. *Let M be a compact and orientable manifold of dimension m. Then we have:*

(1) *If m is odd then $\chi_M = 0$.*
(2) *If $m = 2n$ for odd n then $\chi_M \equiv b_n(M) \equiv 0 \mod (2)$.*
(3) *If $m = 4k$ then $\chi_M \equiv b_{2k}(M) \equiv$ signature$(P^{2k}_M) \mod (2)$.*

Proof. From (11.6) we have $b_q(M) = b_{m-q}(M)$. Thus the Euler Poincaré characteristic is given by $\chi_M = \sum_{q=0}^m (-1)^q b_q = \sum_{q=0}^m (-1)^q b_{m-q} = (-1)^m \chi_M$ which implies (1).

If $m = 2n$ we have $\chi_M = \sum_{q=0}^{2n} (-1)^q b_q = 2\sum_{q=0}^{n-1}(-1)^q b_q + (-1)^n b_n$, so $\chi_M \equiv b_n($ mod 2). In general we have for a compact oriented manifold

$$P^q_M([\alpha],[\beta]) = \int_M \alpha\wedge\beta = (-1)^{q(m-q)}\int_M \beta\wedge\alpha = (-1)^{q(m-q)} P^{m-q}_M([\beta],[\alpha]).$$

For odd n and $m = 2n$ we see that P^n_M is a skew symmetric non degenerate bilinear form on $H^n(M)$, so b_n must be even (see (4.7) or (25.4) below) which implies (2).

(3). If $m = 4k$ then P^{2k}_M is a non degenerate symmetric bilinear form on $H^{2k}(M)$, an inner product. By the *signature* of a non degenerate symmetric inner product one means the number of positive eigenvalues minus the number of negative eigenvalues, so the number $\dim H^{2k}(M)_+ - \dim H^{2k}(M)_- =: a_+ - a_-$, but since $H^{2k}(M)_+ \oplus H^{2k}(M)_- = H^{2k}(M)$ we have $a_+ + a_- = b_{2k}$, so $a_+ - a_- = b_{2k} - 2a_- \equiv b_{2k}($ mod 2). □

11.8. The mapping degree. Let M and N be smooth compact oriented manifolds, both of the same dimension m. Then for any smooth mapping $f : M \to N$ there is a real number $\deg f$, called the *degree* of f, which is given in the bottom row of the diagram

$$\begin{array}{ccc} H^m(M) & \xleftarrow{H^m(f)} & H^m(N) \\ {\scriptstyle\int_*}\Big\downarrow{\scriptstyle\cong} & & {\scriptstyle\int_*}\Big\downarrow{\scriptstyle\cong} \\ \mathbb{R} & \xleftarrow{\deg f} & \mathbb{R} \end{array}$$

where the vertical arrows are isomorphisms by (10.20), and where $\deg f$ is the linear mapping given by multiplication with that number. So we also have the defining relation

$$\int_M f^*\omega = \deg f \int_N \omega \qquad \text{for all } \omega \in \Omega^m(N).$$

11.9. Lemma. *The mapping degree* deg *has the following properties:*

(1) $\deg(f \circ g) = \deg f \cdot \deg g$, $\deg(Id_M) = 1$.
(2) *If* f, $g : M \to N$ *are (smoothly) homotopic then* $\deg f = \deg g$.
(3) *If* $\deg f \neq 0$ *then* f *is surjective.*
(4) *If* $f : M \to M$ *is a diffeomorphism then* $\deg f = 1$ *if* f *respects the orientation and* $\deg f = -1$ *if* f *reverses the orientation.*

Proof. (1) and (2) are clear. (3) If $f(M) \neq N$ we choose a bump m-form ω on N with support in the open set $N \setminus f(M)$. Then $f^*\omega = 0$ so we have $0 = \int_M f^*\omega = \deg f \int_N \omega$. Since $\int_N \omega \neq 0$ we get $\deg f = 0$.

(4) follows either directly from the definition of the integral (8.7) of from (11.11) below. □

11.10. Examples on spheres. Let $f \in O(n+1, \mathbb{R})$ and restrict it to a mapping $f : S^n \to S^n$. Then $\deg f = \det f$. This follows from the description of the volume form on S^n given in the proof of (11.5).

Let f, $g : S^n \to S^n$ be smooth mappings. If $f(x) \neq -g(x)$ for all $x \in S^n$ then the mappings f and g are smoothly homotopic: The homotopy moves $f(x)$ along the shorter arc of the geodesic (big circle) to $g(x)$. So $\deg f = \deg g$.

If $f(x) \neq -x$ for all $x \in S^n$ then f is homotopic to Id_{S^n}, so $\deg f = 1$.

If $f(x) \neq x$ for all $x \in S^n$ then f is homotopic to $-Id_{S^n}$, so $\deg f = (-1)^{n+1}$.

The *hairy ball theorem* says that on S^n for even n each vector field vanishes somewhere. This can be seen as follows. The tangent bundle of the sphere is

$$TS^n = \{(x, y) \in \mathbb{R}^{n+1} \times \mathbb{R}^{n+1} : |x|^2 = 1, \langle x, y\rangle = 0\},$$

so a vector field without zeros is a mapping $x \mapsto (x, g(x))$ with $g(x) \perp x$; then $f(x) := g(x)/|g(x)|$ defines a smooth mapping $f : S^n \to S^n$ with $f(x) \perp x$ for all x. So $f(x) \neq x$ for all x, thus $\deg f = (-1)^{n+1} = -1$. But also $f(x) \neq -x$ for all x, so $\deg f = 1$, a contradiction.

Finally we consider the unit circle $S^1 \xrightarrow{i} \mathbb{C} = \mathbb{R}^2$. Its volume form is given by $\omega := i^*(x\,dy - y\,dx) = i^*\frac{x\,dy - y\,dx}{x^2+y^2}$; obviously we have $\int_{S^1} xdy - ydx = 2\pi$. Now let $f : S^1 \to S^1$ be smooth, $f(t) = (x(t), y(t))$ for $0 \le t \le 2\pi$. Then

$$\deg f = \frac{1}{2\pi}\int_{S^1} f^*(xdy - ydx)$$

is the winding number about 0 from compex analysis.

11.11. The mapping degree is an integer. Let $f : M \to N$ be a smooth mapping between compact oriented manifolds of dimension m. Let $b \in N$ be a regular value for f which exists by Sard's theorem, see (10.12). Then for each $x \in f^{-1}(b)$ the tangent mapping $T_x f$ mapping is invertible, so f is diffeomorphism near x. Thus $f^{-1}(b)$ is a finite set, since M is compact. We define the mapping $\varepsilon : M \to \{-1, 0, 1\}$ by

$$\varepsilon(x) = \begin{cases} 0 & \text{if } T_x f \text{ is not invertible} \\ 1 & \text{if } T_x f \text{ is invertible and respects orientations} \\ -1 & \text{if } T_x f \text{ is invertible and changes orientations.} \end{cases}$$

11.12. Theorem. *In the setting of* (11.11)*, if* $b \in N$ *is a regular value for* f*, then*

$$\deg f = \sum_{x \in f^{-1}(b)} \varepsilon(x).$$

In particular $\deg f$ *is always an integer.*

Proof. The proof is the same as for lemma (10.13) with obvious changes. □

12. Lie groups III. Analysis on Lie groups

Invariant integration on Lie groups

12.1. Invariant differential forms on Lie groups. Let G be a real Lie group of dimension n with Lie algebra $\mathfrak{g}$. Then the tangent bundle of G is a trivial vector bundle, see (5.17), so G is orientable. Recall from section (4) the notation: $\mu : G \times G \to G$ is the multiplication, $\mu_x : G \to G$ is left translation by x, and $\mu^y : G \to G$ is right translation. $\nu : G \to G$ is the inversion.

A differential form $\omega \in \Omega^n(G)$ is called *left invariant* if $\mu_x^*\omega = \omega$ for all $x \in G$. Then ω is uniquely determined by its value $\omega_e \in \Lambda^n T^*G = \Lambda^n \mathfrak{g}^*$. For each determinant function Δ on $\mathfrak{g}$ there is a unique left invariant n-form L_Δ on G which is given by

(1)
$$(L_\Delta)_x(X_1, \dots, X_n) := \Delta(T_x(\mu_{x^{-1}}).X_1, \dots, T_x(\mu_{x^{-1}}).X_n),$$
$$(L_\Delta)_x = T_x(\mu_{x^{-1}})^*\Delta.$$

Likewise there is a unique right invariant n-form R_Δ which is given by

(2)
$$(R_\Delta)_x(X_1, \dots, X_n) := \Delta(T_x(\mu^{x^{-1}}).X_1, \dots, T_x(\mu^{x^{-1}}).X_n).$$

12.2. Lemma. *We have for all $a \in G$*

$$(\mu^a)^* L_\Delta = \det(Ad(a^{-1}))L_\Delta, \tag{1}$$

$$(\mu_a)^* R_\Delta = \det(Ad(a))R_\Delta, \tag{2}$$

$$(R_\Delta)_a = \det(Ad(a))(L_\Delta)_a. \tag{3}$$

Proof. We compute as follows:

$$\begin{aligned}
((\mu^a)^*L_\Delta)_x(X_1,\dots,X_n) &= (L_\Delta)_{xa}(T_x(\mu^a).X_1,\dots,T_x(\mu^a).X_n)\\
&= \Delta(T_{xa}(\mu_{(xa)^{-1}}).T_x(\mu^a).X_1,\dots,T_{xa}(\mu_{(xa)^{-1}}).T_x(\mu^a).X_n)\\
&= \Delta(T_a(\mu_{a^{-1}}).T_{xa}(\mu_{x^{-1}}).T_x(\mu^a).X_1,\dots,T_a(\mu_{a^{-1}}).T_{xa}(\mu_{x^{-1}}).T_x(\mu^a).X_n)\\
&= \Delta(T_a(\mu_{a^{-1}}).T_e(\mu^a).T_x(\mu_{x^{-1}}).X_1,\dots,T_a(\mu_{a^{-1}}).T_e(\mu^a).T_x(\mu_{x^{-1}}).X_n)\\
&= \Delta(Ad(a^{-1}).T_x(\mu_{x^{-1}}).X_1,\dots,Ad(a^{-1}).T_x(\mu_{x^{-1}}).X_n)\\
&= \det(Ad(a^{-1}))\Delta(T_x(\mu_{x^{-1}}).X_1,\dots,T_x(\mu_{x^{-1}}).X_n)\\
&= \det(Ad(a^{-1}))(L_\Delta)_x(X_1,\dots,X_n).\\
((\mu_a)^*R_\Delta)_x(X_1,\dots,X_n) &= (R_\Delta)_{ax}(T_x(\mu_a).X_1,\dots,T_x(\mu_a).X_n)\\
&= \Delta(T_{ax}(\mu^{(ax)^{-1}}).T_x(\mu_a).X_1,\dots,T_{ax}(\mu^{(ax)^{-1}}).T_x(\mu_a).X_n)\\
&= \Delta(T_a(\mu^{a^{-1}}).T_{ax}(\mu^{x^{-1}}).T_x(\mu_a).X_1,\dots,T_a(\mu^{a^{-1}}).T_{ax}(\mu^{x^{-1}}).T_x(\mu_a).X_n)\\
&= \Delta(T_a(\mu^{a^{-1}}).T_e(\mu_a).T_x(\mu^{x^{-1}}).X_1,\dots,T_a(\mu^{a^{-1}}).T_e(\mu_a).T_x(\mu^{x^{-1}}).X_n)\\
&= \Delta(Ad(a).T_x(\mu^{x^{-1}}).X_1,\dots,Ad(a).T_x(\mu^{x^{-1}}).X_n)\\
&= \det(Ad(a))\Delta(T_x(\mu^{x^{-1}}).X_1,\dots,T_x(\mu^{x^{-1}}).X_n)\\
&= \det(Ad(a))(R_\Delta)_x(X_1,\dots,X_n).
\end{aligned}$$

$$\begin{aligned}
\det(Ad(a))(L_\Delta)_a(X_1,\dots,X_n)\\
&= \det(Ad(a))\Delta(T_a(\mu_{a^{-1}}).X_1,\dots,T_a(\mu_{a^{-1}}).X_n)\\
&= \Delta(Ad(a).T_a(\mu_{a^{-1}}).X_1,\dots,Ad(a).T_a(\mu_{a^{-1}}).X_n)\\
&= \Delta(T_a(\mu^{a^{-1}}).T_e(\mu_a).T_a(\mu_{a^{-1}}).X_1,\dots,T_a(\mu^{a^{-1}}).T_e(\mu_a).T_a(\mu_{a^{-1}}).X_n)\\
&= \Delta(T_a(\mu^{a^{-1}}).X_1,\dots,T_a(\mu^{a^{-1}}).X_n) = (R_\Delta)_a(X_1,\dots,X_n). \quad \square
\end{aligned}$$

12.3. Corollary and Definition. *The Lie group G admits a bi-invariant (i.e. left and right invariant) n-form if and only if* $\det(Ad(a)) = 1$ *for all $a \in G$.*

The Lie group G is called unimodular if $|\det(Ad(a))| = 1$ *for all $a \in G$.*

Note that $\det(\mathrm{Ad}(a)) > 0$ if G is connected.

Proof. This is obvious from lemma (12.2). □

12.4. Haar measure. We orient the Lie group G by a left invariant n-form L_Δ. If $f \in C_c^\infty(G,\mathbb{R})$ is a smooth function with compact support on G then the integral $\int_G fL_\Delta$ is defined and we have

$$\int_G (\mu_a^* f)L_\Delta = \int_G \mu_a^*(fL_\Delta) = \int_G fL_\Delta,$$

because $\mu_a : G \to G$ is an orientation preserving diffeomorphism of G. Thus $f \mapsto \int_G f L_\Delta$ is a left invariant integration on G, which is also denoted by $\int_G f(x) d_L x$, and which gives rise to a left invariant measure on G, the so called *Haar measure*. It is unique up to a multiplicative constant, since $\dim(\Lambda^n \mathfrak{g}^*) = 1$. In the other notation the left invariance looks like

$$\int_G f(ax) d_L x = \int_G f(x) d_L x \text{ for all } f \in C_c^\infty(G, \mathbb{R}), a \in G.$$

From lemma (12.2.1) we have

$$\begin{aligned}\int_G ((\mu^a)^* f) L_\Delta &= \det(Ad(a)) \int_G (\mu^a)^* (f L_\Delta) \\ &= |\det(Ad(a))| \int_G f L_\Delta,\end{aligned}$$

since the mapping μ^a is orientation preserving if and only if $\det(Ad(a)) > 0$. So a left Haar measure is also a right invariant one if and only if the Lie group G is unimodular.

12.5. Lemma. *Each compact Lie group is unimodular.*

Proof. The mapping $\det \circ Ad : G \to GL(1, \mathbb{R})$ is a homomorphism of Lie groups, so its image is a compact subgroup of $GL(1, \mathbb{R})$. Thus $\det(Ad(G))$ equals $\{1\}$ or $\{1, -1\}$. In both cases we have $|\det(Ad(a))| = 1$ for all $a \in G$. $\square$

Analysis for mappings between Lie groups

12.6. Definition. Let G and H be Lie groups with Lie algebras $\mathfrak{g}$ and $\mathfrak{h}$, respectively, and let $f : G \to H$ be a smooth mapping. Then we define the mapping $Df : G \to L(\mathfrak{g}, \mathfrak{h})$ by

$$Df(x) := T_{f(x)}((\mu^{f(x)})^{-1}).T_x f.T_e(\mu^x) = \delta f(x).T_e(\mu^x),$$

and we call it the *right trivialized derivative* of f.

12.7. Lemma. *The chain rule: For smooth $g : K \to G$ and $f : G \to H$ we have*

$$D(f \circ g)(x) = Df(g(x)) \circ Dg(x).$$

The product rule: For $f, h \in C^\infty(G, H)$ we have

$$D(fh)(x) = Df(x) + Ad(f(x))Dh(x).$$

Proof. We compute as follows:

$$D(f \circ g)(x) = T(\mu^{f(g(x))^{-1}}).T_x(f \circ g).T_e(\mu^x)$$

$$
\begin{aligned}
&= T(\mu^{f(g(x))^{-1}}).T_{g(x)}(f).T_e(\mu^{g(x)}).T(\mu^{g(x)^{-1}}).T_x(g).T_e(\mu^x)\\
&= Df(g(x)).Dg(x).\\
D(fh)(x) &= T(\mu^{(f(x)h(x))^{-1}}).T_x(\mu\circ(f,h)).T_e(\mu^x)\\
&= T(\mu^{(f(x)^{-1}}).T(\mu^{h(x))^{-1}}).T_{f(x),h(x)}\mu.(T_xf.T_e(\mu^x),T_xh.T_e(\mu^x))\\
&= T(\mu^{(f(x)^{-1}}).T(\mu^{h(x))^{-1}}).\Big(T(\mu^{h(x)}).T_xf.T_e(\mu^x)+T(\mu_{f(x)}).T_xh.T_e(\mu^x)\Big)\\
&= T(\mu^{(f(x)^{-1}}).T_xf.T_e(\mu^x)+T(\mu^{(f(x)^{-1}}).T(\mu_{f(x)}).T(\mu^{h(x))^{-1}}).T_xh.T_e(\mu^x)\\
&= Df(x)+Ad(f(x)).Dh(x). \quad\square
\end{aligned}
$$

12.8. Inverse function theorem. *Let $f : G \to H$ be smooth and for some $x \in G$ let $Df(x) : \mathfrak{g} \to \mathfrak{h}$ be invertible. Then f is a diffeomorphism from a suitable neighborhood of x in G onto a neighborhood of $f(x)$ in H, and for the derivative we have $D(f^{-1})(f(x)) = (Df(x))^{-1}$.*

Proof. This follows from the usual inverse function theorem. □

12.9. Lemma. *Let $f \in C^\infty(G,G)$ and let $\Delta \in \Lambda^{\dim G}\mathfrak{g}^*$ be a determinant function on $\mathfrak{g}$. Then we have for all $x \in G$,*

$$(f^*R_\Delta)_x = \det(Df(x))(R_\Delta)_x.$$

Proof. Let $\dim G = n$. We compute as follows

$$
\begin{aligned}
(f^*R_\Delta)_x(X_1,\dots,X_n) &= (R_\Delta)_{f(x)}(T_xf.X_1,\dots,T_xf.X_n)\\
&= \Delta(T(\mu^{f(x)^{-1}}).T_xf.X_1,\dots)\\
&= \Delta(T(\mu^{f(x)^{-1}}).T_xf.T(\mu^x).T(\mu^{x^{-1}}).X_1,\dots)\\
&= \Delta(Df(x).T(\mu^{x^{-1}}).X_1,\dots)\\
&= \det(Df(x))\Delta(T(\mu^{x^{-1}}).X_1,\dots)\\
&= \det(Df(x))(R_\Delta)_x(X_1,\dots,X_n). \quad\square
\end{aligned}
$$

12.10. Theorem. Transformation formula for multiple integrals. *Let $f : G \to G$ be a diffeomorphism, let $\Delta \in \Lambda^{\dim G}\mathfrak{g}^*$. Then for any $g \in C_c^\infty(G,\mathbb{R})$ we have*

$$\int_G g(f(x))|\det(Df(x))|d_Rx = \int_G g(y)d_Ry,$$

where d_Rx is the right Haar measure, given by R_Δ.

Proof. We consider the locally constant function $\varepsilon(x) = \operatorname{sign}\det(Df(x))$ which is 1 on those connected components where f respects the orientation and is -1 on the other components. Then the integral is the sum of all integrals over the connected components and we may investigate each one separately, so let us restrict attention to the component G_0 of the identity. By a right translation (which does not change the integrals) we may assume that $f(G_0) = G_0$. So finally let us assume without loss of generality that G is connected, so that ε is constant. Then by lemma (12.9) we have

$$\begin{aligned}\int_G gR_\Delta &= \varepsilon \int_G f^*(gR_\Delta) = \varepsilon \int_G f^*(g) f^*(R_\Delta)\\ &= \int_G (g\circ f)\varepsilon \det(Df) R_\Delta = \int_G (g\circ f)|\det(Df)|R_\Delta. \quad \square\end{aligned}$$

12.11. Theorem. *Let G be a compact and connected Lie group, let $f \in C^\infty(G,G)$ and $\Delta \in \Lambda^{\dim G}\mathfrak{g}^*$. Then we have for $g \in C^\infty(G)$,*

$$\begin{aligned}\deg f \int_G gR_\Delta &= \int_G (g\circ f)\det(Df)R_\Delta, \quad \textit{or}\\ \deg f \int_G g(y)d_R y &= \int_G g(f(x))\det(Df(x))d_R x.\end{aligned}$$

Here $\deg f$, the mapping degree of f, see (11.8)*, is an integer.*

Proof. From lemma (12.9) we have $f^* R_\Delta = \det(Df)R_\Delta$. Using this and the defining relation from (11.8) for $\deg f$ we may compute as follows:

$$\begin{aligned}\deg f \int_G gR_\Delta &= \int_G f^*(gR_\Delta) = \int_G f^*(g)f^*(R_\Delta)\\ &= \int_G (g\circ f)\det(Df)R_\Delta. \quad \square\end{aligned}$$

12.12. Examples. Let G be a compact connected Lie group.

1. If $f = \mu^a : G \to G$ then $D(\mu^a)(x) = Id_{\mathfrak{g}}$. From theorem (12.11) we get $\int_G gR_\Delta = \int_G (g\circ\mu^a)R_\Delta$, the right invariance of the right Haar measure.

2. If $f = \mu_a : G \to G$ then $D(\mu_a)(x) = T(\mu^{(ax)^{-1}}).T_x(\mu_a).T_e(\mu^x) = Ad(a)$. So the last two results give $\int_G gR_\Delta = \int_G (g\circ\mu_a)|\det Ad(a)|R_\Delta$ which we already know from (12.4).

3. If $f(x) = x^2 = \mu(x,x)$ we have

$$\begin{aligned}Df(x) &= T_{x^2}(\mu^{x^{-2}}).T_{(x,x)}\mu.(T_e(\mu^x), T_e(\mu^x))\\ &= T_x(\mu^{x^{-1}}).T_{x^2}(\mu^{x^{-1}})\,(T_x(\mu_x).T_e(\mu^x) + T_x(\mu^x).T_e(\mu^x))\\ &= Ad(x) + Id_{\mathfrak{g}}.\end{aligned}$$

Let us now suppose that $\int_G R_\Delta = 1$, then we get

$$\deg((\quad)^2) = \deg((\quad)^2)\int_G R_\Delta = \int_G \det(Id_{\mathfrak{g}} + Ad(x))d_R x$$

$$\int_G g(x^2)\det(Id_{\mathfrak{g}} + Ad(x))d_R x = \int_G \det(Id_{\mathfrak{g}} + Ad(x))d_R x \int_G g(x)d_R x.$$

4. Let $f(x) = x^k$ for $k \in \mathbb{N}$, $\int_G d_R x = 1$. Then we claim that

$$D((\quad)^k)(x) = \sum_{i=0}^{k-1} Ad(x^i).$$

This follows from induction, starting from example 3 above, since

$$\begin{aligned} D((\quad)^k)(x) &= D(Id_G(\quad)^{k-1})(x) \\ &= D(Id_G)(x) + Ad(x).D((\quad)^{k-1})(x) \quad \text{by (12.7)} \\ &= Id_{\mathfrak{g}} + Ad(x)(\sum_{i=0}^{k-2} Ad(x^i)) = \sum_{i=0}^{k-1} Ad(x^i). \end{aligned}$$

We conclude that

$$\deg(\quad)^k = \int_G \det\left(\sum_{i=0}^{k-1} Ad(x^i)\right) d_R x.$$

If G is abelian we have $\deg(\quad)^k = k$ since then $Ad(x) = Id_{\mathfrak{g}}$.

5. Let $f(x) = \nu(x) = x^{-1}$. Then we have $D\nu(x) = T\mu^{\nu(x)^{-1}}.T_x\nu.T_e\mu^x = -Ad(x^{-1})$. Using this we see that the result in 4. holds also for negative k, if the summation is interpreted in the right way:

$$D((\quad)^{-k})(x) = \sum_{i=-k+1}^{0} Ad(x^i) = -\sum_{i=0}^{k-1} Ad(x^{-i}).$$

Cohomology of compact connected Lie groups

12.13. Let G be a connected Lie group with Lie algebra $\mathfrak{g}$. The De Rham cohomology of G is the cohomology of the graded differential algebra $(\Omega(G), d)$. We will investigate now what is contributed by the subcomplex of the left invariant differential forms.

Definition. A differential form $\omega \in \Omega(G)$ is called *left invariant* if $\mu_a^*\omega = \omega$ for all $a \in G$. We denote by $\Omega_L(G)$ the subspace of all left invariant forms. Clearly the mapping

$$\begin{gathered} L : \Lambda\mathfrak{g}^* \to \Omega_L(G), \\ (L_\omega)_x(X_1, \dots, X_k) = \omega(T(\mu_{x^{-1}}).X_1, \dots, T(\mu_{x^{-1}}).X_k), \end{gathered}$$

is a linear isomorphism. Since $\mu_a^* \circ d = d \circ \mu_a^*$ the space $(\Omega_L(G), d)$ is a graded differential subalgebra of $(\Omega(G), d)$.

We shall also need the representation $\widetilde{Ad} : G \to GL(\Lambda\mathfrak{g}^*)$ which is given by $\widetilde{Ad}(a) = \Lambda(Ad(a^{-1})^*)$ or

$$(\widetilde{Ad}(a)\omega)(X_1, \dots, X_k) = \omega(Ad(a^{-1}).X_1, \dots, Ad(a^{-1}).X_k).$$

12.14. Lemma.

(1) *Via the isomorphism* $L : \Lambda\mathfrak{g}^* \to \Omega_L(G)$ *the exterior differential* d *has the following form on* $\Lambda\mathfrak{g}^*$*:*

$$d\omega(X_0,\dots,X_k) = \sum_{0\le i<j\le k} (-1)^{i+j}\omega([X_i,X_j],X_0,\dots,\widehat{X_i},\dots\widehat{X_j},\dots,X_k),$$

where $\omega \in \Lambda^k\mathfrak{g}^*$ *and* $X_i \in \mathfrak{g}$.

(2) *For* $X \in \mathfrak{g}$ *we have* $i(L_X)\Omega_L(G) \subset \Omega_L(G)$ *and* $\mathcal{L}_{L_X}\Omega_L(G) \subset \Omega_L(G)$. *Thus we have induced mappings*

$$\begin{aligned} i_X &: \Lambda^k\mathfrak{g}^* \to \Lambda^{k-1}\mathfrak{g}^*,\\ (i_X\omega)(X_1,\dots,X_{k-1}) &= \omega(X,X_1,\dots,X_{k-1});\\ \mathcal{L}_X &: \Lambda^k\mathfrak{g}^* \to \Lambda^k\mathfrak{g}^*,\\ (\mathcal{L}_X\omega)(X_1,\dots,X_k) &= \sum_{i=1}^k (-1)^i\omega([X,X_i],X_1,\dots,\widehat{X_i},\dots X_k). \end{aligned}$$

(3) *These mappings satisfy all the properties from section* (7), *in particular*

$$\begin{aligned} &\mathcal{L}_X = i_X\circ d + d\circ i_X, && \text{see } (7.9.2),\\ &\mathcal{L}_X\circ d = d\circ\mathcal{L}_X, && \text{see } (7.9.5),\\ &[\mathcal{L}_X,\mathcal{L}_Y] = \mathcal{L}_{[X,Y]}, && \text{see } (7.6.3).\\ &[\mathcal{L}_X,i_Y] = i_{[X,Y]}, && \text{see } (7.7.3). \end{aligned}$$

(4) *The representation* $\widetilde{Ad} : G \to GL(\Lambda\mathfrak{g}^*)$ *has derivative* $T_e\widetilde{Ad}.X = \mathcal{L}_X$.

Proof. For $\omega \in \Lambda^k\mathfrak{g}^*$ and $X_i \in \mathfrak{g}$ the function

$$\begin{aligned} (L_\omega)_x(L_{X_0}(x),\dots,L_{X_k}(x)) &= \omega(T(\mu_{x^{-1}}).L_{X_1}(x),\dots)\\ &= \omega(T(\mu_{x^{-1}}).T(\mu_x).X_1,\dots)\\ &= \omega(X_1,\dots,X_k) \end{aligned}$$

is constant in x. This implies already that $i(L_X)\Omega_L(G) \subset \Omega_L(G)$ and the form of i_X in 2. Then by (7.8.2) we have

$$\begin{aligned} (d\omega)(X_0,\dots,X_k) &= (dL_\omega)(L_{X_0},\dots,L_{X_k})(e)\\ &= \sum_{i=0}^k (-1)^i L_{X_i}(e)(\omega(X_0,\dots\widehat{X_i},\dots X_k))\\ &\quad + \sum_{0\le i<j\le k} (-1)^{i+j}\omega([X_i,X_j],X_0,\dots,\widehat{X_i},\dots,\widehat{X_j},\dots X_k), \end{aligned}$$

from which assertion (1) follows since the first summand is 0. Similarly we have

$$\begin{aligned} (\mathcal{L}_X\omega)(X_1,\dots,X_k) &= (\mathcal{L}_{L_X}L_\omega)(L_{X_1},\dots,L_{X_k})(e)\\ &= L_X(e)(\omega(X_1,\dots,X_k)) + \sum_{i=1}^k (-1)^i\omega([X,X_i],X_1,\dots,\widehat{X_i},\dots X_k). \end{aligned}$$

Again the first summand is 0 and the second result of (2) follows.

(3) This is obvious.

(4) For X and $X_i \in \mathfrak{g}$ and for $\omega \in \Lambda^k \mathfrak{g}^*$ we have

$$\begin{aligned}
((T_e\widetilde{Ad}.X)\omega)(X_1,\dots,X_k) &= \tfrac{\partial}{\partial t}\big|_0 (\widetilde{Ad}(\exp(tX))\omega)(X_1,\dots,X_k)\\
&= \tfrac{\partial}{\partial t}\big|_0 \omega(Ad(\exp(-tX)).X_1,\dots,Ad(\exp(-tX)).X_k)\\
&= \sum_{i=1}^k \omega(X_1,\dots,X_{i-1},-ad(X)X_i,X_{i+1},\dots X_k)\\
&= \sum_{i=1}^k (-1)^i\omega([X,X_i],X_1,\dots,\widehat{X}_i,\dots X_k)\\
&= (\mathcal{L}_X\omega)(X_1,\dots,X_k). \quad \square
\end{aligned}$$

12.15. Lemma of Maschke. *Let G be a compact Lie group, let*

$$(0\to)V_1 \xrightarrow{i} V_2 \xrightarrow{p} V_3 \to 0$$

be an exact sequence of G-modules and homomorphisms such that each V_i is a complete locally convex vector space and the representation of G on each V_i consists of continuous linear mappings with $g \mapsto g.v$ continuous $G \to V_i$ for each $v \in V_i$. Then also the sequence

$$(0\to)V_1^G \xrightarrow{i} V_2^G \xrightarrow{p^G} V_3^G \to 0$$

is exact, where $V_i^G := \{v \in V_i : g.v = v \text{ for all } g \in G\}$.

Proof. We prove first that p^G is surjective. Let $v_3 \in V_3^G \subset V_3$. Since $p : V_2 \to V_3$ is surjective there is an $v_2 \in V_2$ with $p(v_2) = v_3$. We consider the element $\tilde v_2 := \int_G x.v_2 d_L x$; the integral makes sense since $x \mapsto x.v_2$ is a continuous mapping $G \to V_2$, G is compact, and Riemann sums converge in the locally convex topology of V_2. We assume that $\int_G d_L x = 1$. Then we have $a.\tilde v_2 = a.\int_G x.v_2 d_L x = \int_G (ax).v_2 d_L x = \int_G x.v_2 d_L x = \tilde v_2$ by the left invariance of the integral, see (12.4), where one uses continuous linear functionals to reduce to the scalar valued case. So $\tilde v_2 \in V_2^G$ and since p is a G-homomorphism we get

$$\begin{aligned}
p^G(\tilde v_2) = p(\tilde v_2) &= p(\int_G x.v_2 d_L x)\\
&= \int_G p(x.v_2) d_L x = \int_G x.p(v_2) d_L x\\
&= \int x.v_3 d_L x = \int_G v_3 d_L x = v_3.
\end{aligned}$$

So p^G is surjective.

Now we prove that the sequence is exact at V_2^G. Clearly $p^G \circ i^G = (p\circ i)|V_1^G = 0$. Suppose conversely that $v_2 \in V_2^G$ with $p^G(v_2) = p(v_2) = 0$. Then there is an $v_1 \in V_1$ with $i(v_1) = v_2$. Consider $\tilde v_1 := \int_G x.v_1 d_L x$. As above we see that $\tilde v_1 \in V_1^G$ and that $i^G(\tilde v_1) = v_2$. $\square$

12.16. Theorem (Chevalley, Eilenberg). *Let G be a compact connected Lie group with Lie algebra $\mathfrak{g}$. Then we have:*

(1) $H^*(G) = H^*(\Lambda\mathfrak{g}^*, d) := H^*(\mathfrak{g})$.

(2) $H^*(\mathfrak{g}) = H^*(\Lambda\mathfrak{g}^*, d) = (\Lambda\mathfrak{g}^*)^{\mathfrak{g}} = \{\omega \in \Lambda\mathfrak{g}^* : \mathcal{L}_X\omega = 0$ *for all* $X \in \mathfrak{g}\}$, *the space of all* $\mathfrak{g}$*-invariant forms on* $\mathfrak{g}$.

The algebra $H^*(\mathfrak{g}) = H(\Lambda\mathfrak{g}^*, d)$ is called the *Chevalley cohomology of the Lie algebra* $\mathfrak{g}$.

Proof. (Following [Pitie, 1976].)

(1) Let $Z^k(G) = \ker(d : \Omega^k(G) \to \Omega^{k+1}(G))$, and let us consider the following exact sequence of vector spaces:

$$\Omega^{k-1}(G) \xrightarrow{d} Z^k(G) \to H^k(G) \to 0 \tag{3}$$

The group G acts on $\Omega(G)$ by $a \mapsto \mu^*_{a^{-1}}$, this action commutes with d and induces thus an action of G of $Z^k(G)$ and also on $H^k(G)$. On the space $\Omega(G)$ we may consider the compact C^∞-topology (uniform convergence on the compact G, in all derivatives separately, in a fixed set of charts). In this topology d is continuous, $Z^k(G)$ is closed, and the action of G is pointwise continuous. So the assumptions of the lemma of Maschke (12.15) are satisfied and we conclude that the following sequence is also exact:

$$\Omega^{p-1}_L(G) \xrightarrow{d} Z^k(G)^G \to H^k(G)^G \to 0 \tag{4}$$

Since G is connected, for each $a \in G$ we may find a smooth curve $c : [0,1] \to G$ with $c(0) = e$ and $c(1) = a$. Then $(t, x) \mapsto \mu_{c(t)^{-1}}(x) = c(t)^{-1}x$ is a smooth homotopy between Id_G and $\mu_{a^{-1}}$, so by (9.4) the two mappings induce the same mapping in homology; we have $\mu^*_{a^{-1}} = Id : H^k(G) \to H^k(G)$ for each $a \in G$. Thus $H^k(G)^G = H^k(G)$. Furthermore $Z^k(G)^G = \ker(d : \Omega^k_L(G) \to \Omega^{k+1}_L(G))$, so from the exact sequence (4) we may conclude that

$$H^k(G) = H^k(G)^G = \frac{\ker(d : \Omega^k_L(G) \to \Omega^{k+1}_L(G))}{\operatorname{im}(d : \Omega^{k-1}_L(G) \to \Omega^k_L(G))} = H^k(\Lambda\mathfrak{g}^*, d).$$

(2) From (12.14.3) we have $\mathcal{L}_X \circ d = d \circ \mathcal{L}_X$, so by (12.14.4) we conclude that $\widetilde{Ad}(a) \circ d = d \circ \widetilde{Ad}(a) : \Lambda\mathfrak{g}^* \to \Lambda\mathfrak{g}^*$ since G is connected. Thus the the sequence

$$\Lambda^{k-1}\mathfrak{g}^* \xrightarrow{d} Z^k(\mathfrak{g}^*) \to H^k(\Lambda\mathfrak{g}^*, d) \to 0, \tag{5}$$

is an exact sequence of G-modules and G-homomorphisms, where $Z^k(\mathfrak{g}^*) = \ker(d : \Lambda^k\mathfrak{g}^* \to \Lambda^{k+1}\mathfrak{g}^*)$. All spaces are finite dimensional, so the lemma of Maschke (12.15) is applicable and we may conclude that also the following sequence is exact:

$$(\Lambda^{k-1}\mathfrak{g}^*)^G \xrightarrow{d} Z^k(\mathfrak{g}^*)^G \to H^k(\Lambda\mathfrak{g}^*, d)^G \to 0, \tag{6}$$

The space $H^k(\Lambda\mathfrak{g}^*, d)^G$ consist of all cohomology classes α with $\widetilde{Ad}(a)\alpha = \alpha$ for all $a \in G$. Since G is connected, by (12.14.4) these are exactly the α with $\mathcal{L}_X\alpha = 0$ for all $X \in \mathfrak{g}$. For $\omega \in \Lambda\mathfrak{g}^*$ with $d\omega = 0$ we have by (12.14.3) that $\mathcal{L}_X\omega = i_X d\omega + di_X\omega = di_X\omega$, so that $\mathcal{L}_X\alpha = 0$ for all $\alpha \in H^k(\Lambda\mathfrak{g}^*, d)$. Thus we get $H^k(\Lambda\mathfrak{g}^*, d) = H^k(\Lambda\mathfrak{g}^*, d)^G$. Also we have $(\Lambda\mathfrak{g}^*)^G = (\Lambda\mathfrak{g}^*)^{\mathfrak{g}}$ so that the exact sequence (6) tranlates to

$$H^k(\mathfrak{g}) = H^k(\Lambda\mathfrak{g}^*, d) = H^k((\Lambda\mathfrak{g}^*)^{\mathfrak{g}}, d). \tag{7}$$

Now let $\omega \in (\Lambda^k\mathfrak{g}^*)^{\mathfrak{g}} = \{\varphi : \mathcal{L}_X\varphi = 0 \text{ for all } X \in \mathfrak{g}\}$ and consider the inversion $\nu : G \to G$. Then we have for $\omega \in \Lambda^k\mathfrak{g}^*$ and $X_i \in \mathfrak{g}$:

$$\begin{aligned}
&(\nu^* L_\omega)_a(T_e(\mu_a).X_1, \dots, T_e(\mu_a).X_k) = \\
&\quad = (L_\omega)_{a^{-1}}(T_a\nu.T_e(\mu_a).X_1, \dots, T_a\nu.T_e(\mu_a).X_k) \\
&\quad = (L_\omega)_{a^{-1}}(-T(\mu^{a^{-1}}).T(\mu_{a^{-1}}).T_e(\mu_a).X_1, \dots) \\
&\quad = (L_\omega)_{a^{-1}}(-T_e(\mu^{a^{-1}}).X_1, \dots, -T_e(\mu^{a^{-1}}).X_k) \\
&\quad = (-1)^k\omega(T\mu_a.T\mu^{a^{-1}}.X_1, \dots, T\mu_a.T\mu^{a^{-1}}.X_k) \\
&\quad = (-1)^k\omega(Ad(a).X_1, \dots, Ad(a).X_k) \\
&\quad = (-1)^k(\widetilde{Ad}(a^{-1})\omega)(X_1, \dots, X_k) \\
&\quad = (-1)^k\omega(X_1, \dots, X_k) \qquad \text{since } \omega \in (\Lambda^k\mathfrak{g}^*)^{\mathfrak{g}} \\
&\quad = (-1)^k(L_\omega)_a(T_e(\mu_a).X_1, \dots, T_e(\mu_a).X_k).
\end{aligned}$$

So for $\omega \in (\Lambda^k\mathfrak{g}^*)^{\mathfrak{g}}$ we have $\nu^*L_\omega = (-1)^k L_\omega$ and thus also $(-1)^{k+1}L_{d\omega} = \nu^* dL_\omega = d\nu^* L_\omega = (-1)^k dL_\omega = (-1)^k L_{d\omega}$ which implies $d\omega = 0$. Hence we have $d|(\Lambda\mathfrak{g}^*)^{\mathfrak{g}} = 0$.

From (7) we now get $H^k(\mathfrak{g}) = H^k((\Lambda\mathfrak{g}^*)^{\mathfrak{g}}, 0) = (\Lambda^k\mathfrak{g}^*)^{\mathfrak{g}}$ as required. □

12.17. Corollary. *Let G be a compact connected Lie group. Then its Poincaré polynomial is given by*

$$f_G(t) = \int_G \det(Ad(x) + tId_{\mathfrak{g}})d_L x.$$

Proof. Let $\dim G = n$. By definition (9.2) and by Poincaré duality (11.6) we have

$$f_G(t) = \sum_{k=0}^n b_k(G)t^k = \sum_{k=0}^n b_k(G)t^{n-k} = \sum_{k=0}^n \dim_{\mathbb{R}} H^k(G)t^{n-k}.$$

On the other hand we hand we have

$$\begin{aligned}
\int_G \det(Ad(x) + tId_{\mathfrak{g}})d_L x &= \int_G \det(Ad(x^{-1})^* + tId_{\mathfrak{g}^*})d_L x \\
&= \int_G \sum_{k=0}^n \operatorname{Trace}(\Lambda^k Ad(x^{-1})^*)\, t^{n-k} d_L x \qquad \text{by (12.19) below} \\
&= \sum_{k=0}^n \int_G \operatorname{Trace}(\widetilde{Ad}(x)|\Lambda^k\mathfrak{g}^*)d_L x\; t^{n-k}.
\end{aligned}$$

If $\rho : G \to GL(V)$ is a finite dimensional representation of G then the operator $\int_G \rho(x) d_L x : V \to V$ is just a projection onto V^G, the space of fixed points of the representation, see the proof of the lemma of Maschke (12.14). The trace of a projection is the dimension of the image. So

$$\begin{aligned}\int_G \operatorname{Trace}(\widetilde{Ad}(a)|\Lambda^k\mathfrak{g}^*) d_L x &= \operatorname{Trace}\left(\int_G (\widetilde{Ad}(a)|\Lambda^k\mathfrak{g}^*) d_L x\right)\\ &= \dim(\Lambda^k\mathfrak{g}^*)^G = \dim H^k(G). \quad \square\end{aligned}$$

12.18. Let $\mathbb{T}^n = (S^1)^n$ be the n-dimensional torus, let $\mathfrak{t}^n$ be its Lie algebra. The bracket is zero since the torus is an abelian group. From theorem (12.16) we have then that $H^*(\mathbb{T}^n) = (\Lambda(\mathfrak{t}^n)^*)^{\mathfrak{t}^n} = \Lambda(\mathfrak{t}^n)^*$, so the Poincaré Polynomial is $f_{\mathbb{T}^n}(t) = (1+t)^n$.

12.19. Lemma. *Let V be an n-dimensional vector space and let $A : V \to V$ be a linear mapping. Then we have*

$$\det(A + tId_V) = \sum_{k=0}^n t^{n-k} \operatorname{Trace}(\Lambda^k A).$$

Proof. By $\Lambda^k A : \Lambda^k V \to \Lambda^k V$ we mean the mapping $v_1 \wedge \dots \wedge v_k \mapsto Av_1 \wedge \dots \wedge Av_k$. Let $e_1, \dots, e_n$ be a basis of V. By the definition of the determinant we have

$$\begin{aligned}\det(A + tId_V)(e_1 \wedge \dots \wedge e_n) &= (Ae_1 + te_1) \wedge \dots \wedge (Ae_n + te_n)\\ &= \sum_{k=0}^n t^{n-k} \sum_{i_1 < \dots < i_k} e_1 \wedge \dots \wedge Ae_{i_1} \wedge \dots \wedge Ae_{i_k} \wedge \dots \wedge e_n.\end{aligned}$$

The multivectors $(e_{i_1} \wedge \dots \wedge e_{i_k})_{i_1 < \dots < i_k}$ are a basis of $\Lambda^k V$ and we can thus write

$$(\Lambda^k A)(e_{i_1} \wedge \dots \wedge e_{i_k}) = Ae_{i_1} \wedge \dots \wedge Ae_{i_k} = \sum_{j_1 < \dots < j_k} A^{j_1 \dots j_k}_{i_1 \dots i_k} e_{j_1} \wedge \dots \wedge e_{j_k},$$

where $(A^{j_1 \dots j_k}_{i_1 \dots i_k})$ is the matrix of $\Lambda^k A$ in this basis. We see that

$$e_1 \wedge \dots \wedge Ae_{i_1} \wedge \dots \wedge Ae_{i_k} \wedge \dots \wedge e_n = A^{i_1 \dots i_k}_{i_1 \dots i_k} e_1 \wedge \dots \wedge e_n.$$

Consequently we have

$$\begin{aligned}\det(A + tId_V) e_1 \wedge \dots \wedge e_n &= \sum_{k=0}^n t^{n-k} \sum_{i_1 < \dots < i_k} A^{i_1 \dots i_k}_{i_1 \dots i_k} e_1 \wedge \dots \wedge e_n\\ &= \sum_{k=0}^n t^{n-k} \operatorname{Trace}(\Lambda^{\mathrm{k}}\mathrm{A})\, e_1 \wedge \dots \wedge e_n,\end{aligned}$$

which implies the result. $\square$

CHAPTER IV
Riemannian Geometry

13. Pseudo Riemann metrics and the Levi Civita covariant derivative

13.1. Riemann metrics. Let M be a smooth manifold of dimension m. A *Riemann metric* g on M is a symmetric $\binom{0}{2}$ tensor field such that $g_x : T_xM \times T_xM \to \mathbb{R}$ is a positively defined inner product for each $x \in M$. A *pseudo Riemann metric* g on M is a symmetric $\binom{0}{2}$ tensor field such that g_x is non degenerate, i.e. $\check{g}_x : TxM \to T_x^*M$ is bijective for each $x \in M$. If (U, u) is a chart on M then we have

$$g|U = \sum_{i,j=0}^{m} g(\tfrac{\partial}{\partial u^i}, \tfrac{\partial}{\partial u^j})\, du^i \otimes du^j =: \sum_{i,j} g_{ij} du^i \otimes du^j.$$

Here $(g_{ij}(x))$ is a symmetric invertible $(m \times m)$-matrix for each $x \in M$, positively defined in the case of a Riemann metric, thus $(g_{ij}) : U \to \mathrm{Mat}_{\mathrm{sym}}(m \times m)$. In the case of a pseudo Riemann metric, the matrix (g_{ij}) has p positive eigenvalues and q negative ones; (p, q) is called the *signature of the metric* and $q = m - p$ is called the *index of the metric*; both are locally constant on M and we shall always assume that it is constant on M.

Lemma. *One each manifold M there exist many Riemann metrics. But there need not exist a pseudo Riemann metric of any given signature.*

Proof. Let (U_α, u_α) be an atlas on M with a subordinated partition of unity (f_α). Choose smooth mappings (g^α_{ij}) from U_α to the convex cone of all positively defined symmetric $(m \times m)$-matrices for each α and put $g = \sum_\alpha f_\alpha \sum_{ij} g^\alpha_{ij}\, du^i_\alpha \otimes d^j_\alpha$.

For example, on any even dimensional sphere S^{2n} there does not exist a pseudo Riemann metric g of signature $(1, 2n - 1)$: Otherwise there would exist a line subbundle $L \subset TS^2$ with $g(v, v) > 0$ for $0 \neq v \in L$. But since the Euler characteristic $\chi(S^{2n}) = 2$ such a line subbundle of the tangent bundle cannot exist, see ???. $\square$

13.2. Length and energy of a curve. Let $c : [a, b] \to M$ be a smooth curve. In the Riemann case the *length* of the curve c is then given by

$$L_a^b(c) := \int_a^b g(c'(t), c'(t))^{1/2} dt = \int_a^b |c'(t)|_g\, dt.$$

In both cases the *energy* of the curve c is given by

$$E_a^b(c) := \tfrac{1}{2}\int_a^b g(c'(t),c'(t))dt.$$

For piecewise smooth curves the length and the energy are defined by taking it for the smooth pieces and then by summing up over all the pieces. In the pseudo Riemann case for the length one has to distinguish different classes of curves according to to the sign of $g(c'(t),c'(t))$ (the sign then should be assumed constant), and by taking an appropriate sign before taking the root. These leads to the concept of 'time-like' curves (with speed less than the speed of light) and 'space-like' curves.

The length is invariant under reparameterizations of the curve:

$$\begin{aligned}
L_a^b(c\circ f) &= \int_a^b g((c\circ f)'(t),(c\circ f)'(t))^{1/2}dt\\
&= \int_a^b g(f'(t)c'(f(t)),f'(t)c'(f(t)))^{1/2}dt\\
&= \int_a^b g(c'(f(t)),c'(f(t)))^{1/2}|f'(t)|dt = \int_a^b g(c'(t),c'(t))^{1/2}dt = L_a^b(c).
\end{aligned}$$

The energy is not invariant under reparametrizations.

13.3. Theorem. *(First variational formula) Let g be a pseudo Riemann metric on an open subset $U\subseteq\mathbb{R}^m$. Let $\gamma:[a,b]\times(-\varepsilon,\varepsilon)\to U$ be a smooth variation of the curve $c=\gamma(\quad,0):[a,b]\to U$. Let $r(t)=\frac{\partial}{\partial s}|_0\gamma(t,s)=T_{(t,0)}\gamma.(0,1)\in T_{c(t)}U$ be the variational vector field along c.*

Then we have:

$$\begin{aligned}
\tfrac{\partial}{\partial s}|_0(E_a^b(\gamma(\quad,s))) = \int_a^b\Big(&-g(c(t))(c''(t),r(t)) - dg(c(t))(c'(t))(c'(t),r(t))+\\
&+\tfrac{1}{2}dg(c(t))(r(t))(c'(t),c'(t))\Big)\,dt+\\
&+g(c(b))(c'(b),r(b)) - g(c(a))(c'(a),r(a)).
\end{aligned}$$

Proof. We have the Taylor expansion $\gamma(t,s)=\gamma(t,0)+s\,\gamma_s(t,0)+O(s^2)=c(t)+sr(t)+O(s^2)$ where the remainder $O(s^2)=s^2R(s,t)$ is smooth and uniformly bounded in t. We plug this into the energy and take also the Taylor expansion of g as follows

$$\begin{aligned}
&E_a^b(\gamma(\quad,s)) = \tfrac{1}{2}\int_a^b g(\gamma(t,s))\big(\gamma_t(t,s),\gamma_t(t,s)\big)\,dt\\
&= \tfrac{1}{2}\int_a^b g(c(t)+sr(t)+O(s^2))\Big(c'(t)+sr'(t)+O(s^2),c'(t)+sr'(t)+O(s^2)\Big)\,dt\\
&= \tfrac{1}{2}\int_a^b\Big(g(c(t))+sg'(c(t))(r(t))+O(s^2)\Big)\Big(\dots,\dots\Big)\,dt
\end{aligned}$$

$$= \tfrac{1}{2}\int_a^b \Big(g(c(t))(c'(t),c'(t)) + 2sg(c(t))(c'(t),r'(t)) + {} + sg'(c(t))(r(t))(c'(t),c'(t))\Big)\,dt + O(s^2)$$

$$= E_a^b(c) + s\int_a^b g(c(t))(c'(t),r'(t))\,dt + \tfrac{1}{2}s\int_a^b g'(c(t))(r(t))(c'(t),c'(t))\,dt + O(s^2).$$

Thus for the derivative we get, using partial integration:

$$\begin{aligned}
\tfrac{\partial}{\partial s}|_0 E_a^b(\gamma(\quad,s)) &= \lim_{s\to 0}\tfrac{1}{s}\Big(E_a^b(\gamma(\quad,s)) - E_a^b(\gamma(\quad,0))\Big)\\
&= \tfrac{1}{2}\int_a^b g'(c(t))(r(t))(c'(t),c'(t))\,dt + \int_a^b g(c(t))(c'(t),r'(t))\,dt\\
&= \tfrac{1}{2}\int_a^b g'(c(t))(r(t))(c'(t),c'(t))\,dt + g(c(t))(c'(t),r(t))|_{t=a}^{t=b} -\\
&\quad - \int_a^b \Big(g'(c(t))(c'(t))(c'(t),r(t)) + g(c(t))(c''(t),r(t))\Big)\,dt\\
&= \int_a^b \Big(-g(c(t))(c''(t),r(t)) - g'(c(t))(c'(t))(c'(t),r(t)) +\\
&\qquad + \tfrac{1}{2}g'(c(t))(r(t))(c'(t),c'(t))\Big)\,dt +\\
&\quad + g(c(b))(c'(b),r(b)) - g(c(a))(c'(a),r(a)) \quad \square
\end{aligned}$$

13.4. Christoffel symbols and geodesics. On a pseudo Riemann manifold (M,g), by theorem (13.3), we have $\frac{\partial}{\partial s}|_0 E_a^b(\gamma(\quad,s)) = 0$ for all variations γ of the curve c with fixed end points ($r(a) = r(b) = 0$) in a chart (U,u), if and only if the integral in theorem (13.3) vanishes. This is the case if and only if we have in $u(U)\subset\mathbb{R}^m$:

$$\begin{aligned}
g(c(t))(c''(t),\quad) &= \tfrac{1}{2}g'(c(t))(\quad)(c'(t),c'(t))\\
&\quad - \tfrac{1}{2}g'(c(t))(c'(t))(c'(t),\quad)\\
&\quad - \tfrac{1}{2}g'(c(t))(c'(t))(\quad,c'(t))
\end{aligned}$$

For $x\in u(U)$ and $X,Y,Z\in\mathbb{R}^m$ we consider the polarized version of the last equation:

(1) $g(x)(\Gamma_x(X,Y),Z) = \tfrac{1}{2}g'(x)(Z)(X,Y) - \tfrac{1}{2}g'(x)(X)(Y,Z) - \tfrac{1}{2}g'(x)(Y)(Z,X)$

which is a well defined smooth mapping

$$\Gamma : u(U)\to L^2_{\text{sym}}(\mathbb{R}^m;\mathbb{R}^m).$$

Back on $U\subset M$ we have in coordinates

$$\begin{aligned}
\Gamma_x(X,Y) &= \Gamma_x\Big(\sum_i X^i\tfrac{\partial}{\partial u^i},\sum_j Y^j\tfrac{\partial}{\partial u^j}\Big) = \sum_{i,j}\Gamma_x\Big(\tfrac{\partial}{\partial u^i},\tfrac{\partial}{\partial u^j}\Big)X^iY^j\\
&=: \sum_{i,j}\Gamma_{ij}(x)X^iY^j =: \sum_{i,j,k}\Gamma_{ij}^k(x)X^iY^j\tfrac{\partial}{\partial u^k},
\end{aligned}$$

where the $\Gamma_{ij}^k : U\to\mathbb{R}$ are smooth functions, which are called the *Christoffel symbols* in the chart (U,u). Attention: Most of the literature uses the negative of the Christoffel symbols.

Lemma. *If $g|U = \sum_{i,j} g_{ij} du^i \otimes du^j$ and if $(g_{ij})^{-1} = (g^{ij})$ denotes the inverse matrix then we have*

$$\Gamma^k_{ij} = \frac{1}{2}\sum_l g^{kl}\Big(\frac{\partial\, g_{ij}}{\partial\, u^l} - \frac{\partial\, g_{lj}}{\partial\, u^i} - \frac{\partial\, g_{il}}{\partial\, u^j}\Big). \tag{2}$$

Proof. We have

$$\begin{aligned}\sum_k \Gamma^k_{ij} g_{kl} &= \sum_k \Gamma^k_{ij} g(\tfrac{\partial}{\partial u^k}, \tfrac{\partial}{\partial u^l}) = g\Big(\sum_k \Gamma^k_{ij}\tfrac{\partial}{\partial u^k}, \tfrac{\partial}{\partial u^l}\Big) = g(\Gamma(\tfrac{\partial}{\partial u^i}, \tfrac{\partial}{\partial u^j}), \tfrac{\partial}{\partial u^l})\\ &= \tfrac{1}{2}g'(\tfrac{\partial}{\partial u^l})(\tfrac{\partial}{\partial u^i}, \tfrac{\partial}{\partial u^j}) - \tfrac{1}{2}g'(\tfrac{\partial}{\partial u^i})(\tfrac{\partial}{\partial u^j}, \tfrac{\partial}{\partial u^l}) - \tfrac{1}{2}g'(\tfrac{\partial}{\partial u^j})(\tfrac{\partial}{\partial u^l}, \tfrac{\partial}{\partial u^i})\\ &= \tfrac{1}{2}\tfrac{\partial\, g_{ij}}{\partial\, u^l} - \tfrac{1}{2}\tfrac{\partial\, g_{lj}}{\partial\, u^i} - \tfrac{1}{2}\tfrac{\partial\, g_{il}}{\partial\, u^j}. \quad \square\end{aligned}$$

Let $c : [a, b] \to M$ be a smooth curve in the pseudo Riemann manifold (M, g). The curve c is called a *geodesic* on M if in each chart (U, u) for the Christoffel symbols of this chart we have

$$c''(t) = \Gamma_{c(t)}(c'(t), c'(t)). \tag{3}$$

The reason for this name is: If the energy E^b_a of (each piece of) the curve is minimal under all variations with fixed end points, then by (13.3) the integral

$$\int_a^b g_{c(t)}(c''(t) - \Gamma_{c(t)}(c'(t), c'(t)), r(t))\, dt = 0$$

for each vector field r along c with $r(a) = r(b) = 0$. This implies (3). Thus (local) infima of the energy functional E^b_a are geodesics, and we call geodesic any curve on which the energy functional E^b_a has vanishing derivative (with repect to local variations with constant ends).

Finally we should compute how the Christoffel symbols react to a chart change. Since this is easily done, and since we will see soon that the Christoffel symbols indeed are coordinate expressions of an entity which belongs into the second tangent bundle TTM, we leave this exercise to the interested reader.

13.5. Covariant derivatives. Let (M, g) be a pseudo Riemann manifold. A *covariant derivative* on M is a mapping $\nabla : \mathfrak{X}(M) \times \mathfrak{X}(M) \to \mathfrak{X}(M)$, denoted by $(X, Y) \mapsto \nabla_X Y$, which satisfies the following conditions:

(1) $\nabla_X Y$ is $C^\infty(N)$-linear in $X \in \mathfrak{X}(M)$, i.e. $\nabla_{f_1 X_1 + f_2 X_2} Y = f_1 \nabla_{X_1} Y + f_2 \nabla_{X_2} Y$. So for a tangent vector $X_x \in T_x M$ the mapping $\nabla_{X_x} : \mathfrak{X}(M) \to T_x M$ makes sense and we have $(\nabla_X s)(x) = \nabla_{X(x)} s$.
(2) $\nabla_X Y$ is $\mathbb{R}$-linear in $Y \in \mathfrak{X}(M)$.
(3) $\nabla_X (f.Y) = df(X).Y + f.\nabla_X Y$ for $f \in C^\infty(M)$, the derivation property of ∇_X.

The covariant derivative ∇ is called *symmetric* or *torsion free* if moreover the following holds:

(4) $\nabla_X Y - \nabla_Y X = [X, Y]$.

The covariant derivative ∇ is called *compatible with the pseudo Riemann metric* if we have:

(5) $X(g(Y,Z)) = g(\nabla_X Y, Z) + g(Y, \nabla_X Z)$ for all $X, Y, Z \in \mathfrak{X}(M)$.

Compare with (22.12) where we treat the covariant derivative on vector bundles.

Theorem. *On each pseudo Riemann manifold (M, g) there exists a unique torsion free covariant derivative $\nabla = \nabla^g$ which is compatible with the pseudo Riemann metric g. In a chart (U, u) we have*

$$\nabla_{\frac{\partial}{\partial u^i}} \frac{\partial}{\partial u^j} = -\sum_k \Gamma^k_{ij} \frac{\partial}{\partial u^k}, \tag{6}$$

where the Γ^k_{ij} are the Christoffel symbols from (13.4).

This unique covariant derivative is called *Levi Civita covariant derivative.*

Proof. We write the cyclic permutations of property (5) equipped with the signs $+, +, -$:

$$\begin{aligned} X(g(Y,Z)) &= g(\nabla_X Y, Z) + g(Y, \nabla_X Z) \\ Y(g(Z,X)) &= g(\nabla_Y Z, X) + g(Z, \nabla_Y X) \\ -Z(g(X,Y)) &= -g(\nabla_Z X, Y) - g(X, \nabla_Z Y) \end{aligned}$$

We add these three equations and use the torsion free property (4) to get

$$\begin{aligned} &X(g(Y,Z)) + Y(g(Z,X)) - Z(g(X,Y)) = \\ &= g(\nabla_X Y + \nabla_Y X, Z) + g(\nabla_X Z - \nabla_Z X, Y) + g(\nabla_Y Z - \nabla_Z Y, X) \\ &= g(2\nabla_X Y - [X,Y], Z) - g([Z,X], Y) + g([Y,Z], X), \end{aligned}$$

which we rewrite as implicit defining equation for $\nabla_X Y$:

$$\begin{aligned} 2g(\nabla_X Y, Z) &= X(g(Y,Z)) + Y(g(Z,X)) - Z(g(X,Y)) \\ &\quad - g(X, [Y,Z]) + g(Y, [Z,X]) + g(Z, [X,Y]) \end{aligned} \tag{7}$$

This by (7) uniquely determined bilinear mapping $(X, Y) \mapsto \nabla_X Y$ indeed satisfies (1)–(5), which is tedious but easy to check. The final assertion of the theorem follows by using (7) once more:

$$\begin{aligned} 2g(\nabla_{\frac{\partial}{\partial u^i}} \tfrac{\partial}{\partial u^j}, \tfrac{\partial}{\partial u^l}) &= \tfrac{\partial}{\partial u^i}(g(\tfrac{\partial}{\partial u^j}, \tfrac{\partial}{\partial u^l})) + \tfrac{\partial}{\partial u^j}(g(\tfrac{\partial}{\partial u^l}, \tfrac{\partial}{\partial u^i})) - \tfrac{\partial}{\partial u^l}(g(\tfrac{\partial}{\partial u^i}, \tfrac{\partial}{\partial u^j})) \\ &= -2\sum_k \Gamma^k_{ij} g_{kl}, \qquad \text{by (13.4.2).} \quad \square \end{aligned}$$

13.6. Geodesic structures and sprays. By (13.5.6) and (13.4.3) we see that a smooth curve $c:(a,b)\to(M,g)$ is a geodesic in a pseudo Riemann manifold if $\nabla_{\partial_t}c'=0$, in a sense which we will make precise later in (13.9.6) when we discuss how we can apply ∇ to vector fields which are only defined along curves or mappings. In each chart (U,u) this is an ordinary differential equation

$$c''(t)=\Gamma_{c(t)}(c'(t),c'(t)),$$
$$\frac{d^2}{dt^2}c^k(t)=\sum_{i,j}\Gamma^k_{ij}(c(t))\,\frac{d}{dt}c^i(t)\,\frac{d}{dt}c^j(t),\qquad c=(c^1,\dots,c^m)$$

which is of second order, linear in the second derivative, quadratic in the first derivative, and in general completely non-linear in $c(t)$ itself. By the theorem of Picard-Lindelöf for ordinary differential eqations there exists a unique solution for each given initial condition $c(t_0),c'(t_0)$, depending smoothly on the initial conditions. Thus we may piece together the local solutions and get a geodesic structure in the following sense:

A *geodesic structure on a manifold* M is a smooth mapping $\operatorname{geo}:TM\times\mathbb{R}\supset U\to M$, where U is an open neighborhood of $TM\times\{0\}$ in $TM\times\mathbb{R}$, which satisfies:

(1) $\operatorname{geo}(X_x)(0)=x$ and $\frac{\partial}{\partial t}\big|_0\operatorname{geo}(X_x)(t)=X_x$.
(2) $\operatorname{geo}(t.X_x)(s)=\operatorname{geo}(X_x)(t.s)$.
(3) $\operatorname{geo}(\operatorname{geo}(X_x)'(s))(t)=\operatorname{geo}(X_x)(t+s)$.
(4) $U\cap(X_x\times\mathbb{R})=\{X_x\}\times$ intervall .

One could also require that U is maximal with respect to all this properties. But we shall not elaborate on this since we will reduce everything to the geodesic vector field shortly.

If we are given a geodesic structure $\operatorname{geo}:U\to M$ as above, then the mapping $(X,t)\mapsto\operatorname{geo}(X)'(t)=\frac{\partial}{\partial t}\operatorname{geo}(X)(t)\in TM$ is the flow for the vector field $S\in\mathfrak{X}(TM)$ which is given by $S(X)=\frac{\partial}{\partial t}\big|_0\frac{\partial}{\partial t}\operatorname{geo}(X)(t)\in T^2M$, since

$$\begin{aligned}\tfrac{\partial}{\partial t}\tfrac{\partial}{\partial t}\operatorname{geo}(X)(t)&=\tfrac{\partial}{\partial s}|_0\tfrac{\partial}{\partial s}\operatorname{geo}(X)(t+s)=\tfrac{\partial}{\partial s}|_0\tfrac{\partial}{\partial s}\operatorname{geo}(\tfrac{\partial}{\partial t}\operatorname{geo}(X)(t))(s)\qquad\text{by (3)}\\&=S(\tfrac{\partial}{\partial t}\operatorname{geo}(X)(t))\\ \operatorname{geo}(X)'(0)&=X.\end{aligned}$$

The smooth vector field $S\in\mathfrak{X}(TM)$ is called the *geodesic spray* of the geodesic structure.

Recall now the chart structure on the second tangent bundle T^2M and the canonical flip mapping $\kappa_M:T^2M\to T^2M$ from (6.12) and (6.13). Let (U,u) be a chart on M and let $c_{(x,y)}(t)=u(\operatorname{geo}(Tu^{-1}(x,y))(t))\in U$. Then we have

$$\begin{aligned}Tu(\operatorname{geo}(Tu^{-1}(x,y))'(t))&=(c_{(x,y)}(t),c'_{(x,y)}(t))\\T^2u(\operatorname{geo}(Tu^{-1}(x,y))''(t))&=(c_{(x,y)}(t),c'_{(x,y)}(t);c'_{(x,y)}(t),c''_{(x,y)}(t)\\T^2u.S(Tu^{-1}(x,y))&=T^2u(\operatorname{geo}(Tu^{-1}(x,y))''(0))\\&=(c_{(x,y)}(0),c'_{(x,y)}(0);c'_{(x,y)}(0),c''_{(x,y)}(0)\\&=(x,y;y,\bar S(x,y))\end{aligned}\tag{5}$$

Property (2) of the geodesic structure implies in turn

$$c_{(x,ty)}(s) = c_{(x,y)}(ts) \qquad c'_{(x,ty)}(s) = t.c'_{(x,y)}(ts)$$
$$c''_{(x,ty)}(0) = t^2.c''_{(x,y)}(0) \qquad \bar{S}(x,ty) = t^2\bar{S}(x,y)$$

so that $\bar{S}(x,\quad): \mathbb{R}^m \to \mathbb{R}^m$ is homogenous of degree 2. By polarizing or taking the second derivative with respect to y we get

$$\bar{S}(x,y) = \Gamma_x(y,y), \quad \text{for} \quad \Gamma : u(U) \to L^2_{\text{sym}}(\mathbb{R}^m;\mathbb{R}^m),$$
$$\Gamma_x(y,z) = \tfrac{1}{2}(\bar{S}(x,y+z) - \bar{S}(x,y) - \bar{S}(x,z)).$$

If the geodesic structure is induced by a pseudo Riemann metric on M, then we have seen that $c''_{(x,y)}(t) = \Gamma_{c_{(x,y)}(t)}(c'_{(x,y)}(t), c'_{(x,y)}(t))$ for the Christoffel symbols in the chart (U,u). Thus the geodesic spray is given in terms of the Christoffel symbols by

$$T^2u(S(Tu^{-1}(x,y))) = (x,y;y,\Gamma_x(y,y)). \tag{6}$$

13.7. The geodesic exponential mapping. Let M be a smooth manifold and let $S \in \mathfrak{X}(TM)$ be a vector field with the following properties:

(1) $\pi_{TM} \circ S = \text{Id}_{TM}$; S is a vector field.
(2) $T(\pi_M) \circ S = \text{Id}_{TM}$; S is a 'differential equation of second order'.
(3) Let $m_t^M : TM \to TM$ and $m_t^{TM} : T^2M \to T^2M$ be the scalar multiplications. Then $S \circ m_t^M = T(m_t^M).m_t^{TM}.S$

A vector field with these properties is called a *spray.*

Theorem. *If $S \in \mathfrak{X}(TM)$ is a spray on a manifold M, let us put* $\text{geo}(X)(t) := \pi_M(\text{Fl}^S_t(X))$. *Then this is a geodesic structure on M in the sense on* (13.6).

If we put $\exp(X) := \pi_M(\text{Fl}^S_1(X)) = \text{geo}(X)(1)$, *then* $\exp : TM \supset V \to M$ *is a smooth mapping, defined on an open neighborhood V of the zero section in TM, which is called the exponential mapping of the spray S and which has the following properties:*

(4) $T_{0_x}(\exp|T_xM) = \text{Id}_{T_xM}$ *(via $T_{0_x}(T_xM) = T_xM$). Thus by the inverse function theorem* $\exp_x := \exp|T_xM : V_x \to W_x$ *is a diffeomorphism from an open neighborhood V_x of 0_x in TM onto an open neighborhood W_x of x in M. The chart $(W_x, \exp_x^{-1})$ is called a Riemann normal coordinate system at x.*
(5) $\text{geo}(X)(t) = \exp(t.X)$.
(6) $(\pi_M, \exp) : TM \supset \tilde{V} \to M \times M$ *is a diffeomorphism from an open neighboorhood $\tilde{V}$ of the zero section in TM onto an open neighboorhood of the diagonal in $M \times M$.*

Proof. By properties (1) and (2) the local expression the spray S is given by $(x,y) \mapsto (x,y;y,\bar{S}(x,y))$, as in (13.6.5). By (3) we have $(x,ty;ty,\bar{S}(x,ty)) =$

$T(m_t^M).m_t^{TM}.(x,y;y,\bar S(x,y)) = (x,ty;ty,t^2\bar S(x,y))$, so that $\bar S(x,ty) = t^2\bar S(x,y)$ as in (13.6).

(7) We have $\operatorname{Fl}^S_t(s.X) = s.\operatorname{Fl}^S_{s.t}(X)$ if one side exists, by uniqueness of solutions of differential equations:

$$\begin{aligned}
\tfrac{\partial}{\partial t} s.\operatorname{Fl}^S_{s.t}(X) &= \tfrac{\partial}{\partial t} m^M_s \operatorname{Fl}^S_{s.t}(X) = T(m^M_s)\tfrac{\partial}{\partial t}\operatorname{Fl}^S_{s.t}(X)\\
&= T(m^M_s).m^{TM}_s S(\operatorname{Fl}^S_{s.t}(X)) \overset{(3)}{=} S(s.\operatorname{Fl}^S_{s.t}(X))\\
s.\operatorname{Fl}^S_{s.0}(X) &= s.X, \qquad \text{thus} \qquad s.\operatorname{Fl}^S_{s.t}(X) = \operatorname{Fl}^S_t(s.X).
\end{aligned}$$

We check that $\operatorname{geo} = \pi_M\circ\operatorname{Fl}^S$ is a geodesic structure, i.e., (13.6.1)-(13.6.4) holds:

$$\begin{aligned}
\operatorname{geo}(X_x)(0) &= \pi_M(\operatorname{Fl}^S_0(X_x)) = \pi_M(X_x) = x.\\
\tfrac{\partial}{\partial t}\big|_0 \operatorname{geo}(X_x)(t) &= \tfrac{\partial}{\partial t}\big|_0 \pi_M(\operatorname{Fl}^S_t(X_x)) = T(\pi_M)\ \tfrac{\partial}{\partial t}\big|_0 \operatorname{Fl}^S_t(X_x)\\
&= T(\pi_M)S(X_x) \overset{(2)}{=} X_x\\
\operatorname{geo}(s.X_x)(t) &= \pi_M(\operatorname{Fl}^S_t(s.X_x)) = \pi_M(s.\operatorname{Fl}^S_{s.t}(X_x)), \quad \text{see above},\\
&= \operatorname{geo}(X_x)(s.t).\\
\operatorname{geo}(\tfrac{\partial}{\partial s}\operatorname{geo}(X_x)(s))(t) &= \pi_M(\operatorname{Fl}^S_t(\tfrac{\partial}{\partial s}\pi_M\operatorname{Fl}^S_s(X_x)))\\
&= \pi_M(\operatorname{Fl}^S_t(T(\pi_M)S(\operatorname{Fl}^S_s(X_x)))) = \pi_M(\operatorname{Fl}^S_t(\operatorname{Fl}^S_s(X_x))) \quad \text{by (2)}\\
&= \pi_M(\operatorname{Fl}^S_{t+s}(X_x)) = \operatorname{geo}(X_x)(t+s).
\end{aligned}$$

Let us investigate the exponential mapping. For $\varepsilon > 0$ let X_x be so small that $(\frac{1}{\varepsilon}X_x,\varepsilon)$ is in the domain of definition of the flow Fl^S. Then

$$\begin{aligned}
\exp_x(X_x) &= \pi_M(\operatorname{Fl}^S_1(X_x)) = \pi_M(\operatorname{Fl}^S_1(\varepsilon.\tfrac{1}{\varepsilon}.X_x))\\
&= \pi_M(\varepsilon.\operatorname{Fl}^S_\varepsilon(\tfrac{1}{\varepsilon}.X_x)) = \pi_M(\operatorname{Fl}^S_\varepsilon(\tfrac{1}{\varepsilon}.X_x)), \quad \text{by (7)}.
\end{aligned}$$

We check the properties of the exponential mapping.

$$\begin{aligned}
(4)\qquad T_{0_x}(\exp_x).X_x &= \tfrac{\partial}{\partial t}\big|_0 \exp_x(0_x + t.X_x) = \tfrac{\partial}{\partial t}\big|_0 \pi_M(\operatorname{Fl}^S_1(t.X_x))\\
&= \tfrac{\partial}{\partial t}\big|_0 \pi_M(t.\operatorname{Fl}^S_t(X_x)) = \tfrac{\partial}{\partial t}\big|_0 \pi_M(\operatorname{Fl}^S_t(X_x)), \quad \text{by (7)}\\
&= T(\pi_M)\ \tfrac{\partial}{\partial t}\big|_0 (\operatorname{Fl}^S_t(X_x)) = T(\pi_M)(S(X_x)) = X_x.\\
(5)\qquad \exp_x(t.X_x) &= \pi_M(\operatorname{Fl}^S_1(t.X_x)) = \pi_M(t.\operatorname{Fl}^S_t(X_x))\\
&= \pi_M(\operatorname{Fl}^S_t(X_x)) = \operatorname{geo}(X_x)(t)
\end{aligned}$$

(6) By (4) we have $T_{0_x}(\pi_M,\exp) = \left(\begin{smallmatrix}\mathbb{I} & 0\\ * & \mathbb{I}\end{smallmatrix}\right)$, thus $(\pi_M,\exp)$ is a local diffeomorphism. Again by (4) the mapping $(\pi_M,\exp)$ is injective on a small neighborhood of the zero section. □

13.8. Linear connections and connectors. Let M be a smooth manifold. A smooth mapping $C : TM\times_M TM \to T^2M$ is called a *linear connection* or *horizontal lift* on M if it has the following properties:

(1) $(T(\pi_M),\pi_{TM})\circ C = \operatorname{Id}_{TM\times_M TM}$.

(2) $C(\quad, X_x) : T_xM \to T_{X_x}(TM)$ is linear; this is the first vector bundle structure on T^2M treated in (6.13).
(3) $C(X_x, \quad) : T_xM \to T(\pi_M)^{-1}(X_x)$ is linear; this is the second vector bundle structure on T^2M treated in (6.13).

The connection C is called *symmetric* or *torsion free* if moreover the following property holds:

(4) $\kappa_M \circ C = C \circ \text{flip} : TM \times_M TM \to T^2M$, where $\kappa_M : T^2M \to T^2M$ is the canonical flip mapping treated in (6.13).

From the properties (1)-(3) it follows that for a chart (U_α, u_α) on M the mapping C is given by

(5) $$T^2(u_\alpha) \circ C \circ (T(u_\alpha)^{-1} \times_M T(u_\alpha)^{-1})((x,y),(x,z)) = (x, z; y, \Gamma^\alpha_x(y,z)),$$

where the *Christoffel symbol* $\Gamma^\alpha_x(y,z) \in \mathbb{R}^m$ ($m = \dim(M)$) is smooth in $x \in u_\alpha(U_\alpha)$ and is bilinear in $(y,z) \in \mathbb{R}^m \times \mathbb{R}^m$. For the sake of completeness let us also note the tranformation rule of the Christoffel symbols which follows now directly from the chart change of the second tangent bundle in (6.12) and (6.13). For the chart change $u_{\alpha\beta} = u_\alpha \circ u_\beta^{-1} : u_\beta(U_\alpha \cap U_\beta) \to u_\alpha(U_\alpha \cap U_\beta)$ we have

(6) $$\Gamma^\alpha_{u_{\alpha\beta}(x)}(d(u_{\alpha\beta})(x)y, d(u_{\alpha\beta})(x)z) = d(u_{\alpha\beta})(x)\Gamma^\beta_x(y,z) + d^2(u_{\alpha\beta})(x)(y,z).$$

We have seen in (13.6.6) that a spray S on a manifold determines symmetric Christoffel symbols and thus a symmetric connection C. If the spray S is induced by a pseudo Riemann metric g on M then the Christoffel symbols are the same as we found by determining the singular curves of the energy in (13.4). The promised geometric description of the Christoffel symbols is (5) which also explains their transformation behavior under chart changes: They belong into the vertical part of the second tangent bundle.

Consider now a linear connection $C : TM \times_M TM \to T^2M$. For $\xi \in T^2M$ we have $\xi - C(T(\pi_M).\xi, \pi_{TM}(\xi)) \in V(TM) = T(\pi_M)^{-1}(0)$, an element of the vertical bundle, since $T(\pi_M)(\xi - C(T(\pi_M).\xi, \pi_{TM}(\xi))) = T(\pi_M).\xi - T(\pi_M).\xi = 0$ by (1). Thus we may define the *connector* $K : T^2M \to TM$ by

(7) $$K(\xi) = \text{vpr}_{TM}(\xi - C(T(\pi_M).\xi, \pi_{TM}(\xi))), \quad \text{where } \xi \in T^2M,$$

where the vertical projection vpr_{TM} was defined in (6.12). In coordinates induced by a chart on M we have

(8) $$K(x,y;a,b) = \text{vpr}(x,y;0,b - \Gamma_x(a,y)) = (x, b - \Gamma_x(a,y)).$$

Obviously the connector K has the following properties:

(9) $K \circ \text{vl}_{TM} = \text{pr}_2 : TM \times_M TM \to TM$, where the vertical lift $\text{vl}_{TM}(X_x, Y_x) = \frac{\partial}{\partial t}\big|_0 (X_x + tY_x)$ was introduced in (6.12).
(10) $K : TTM \to TM$ is linear for the (first) π_{TM} vector bundle structure.
(11) $K : TTM \to TM$ is linear for the (second) $T(\pi_M)$ vector bundle structure.

A connector, defined as a mapping satisfying (9)-(11), is equivalent to a connection, since one can reconstruct it (which is most easily checked in a chart) by

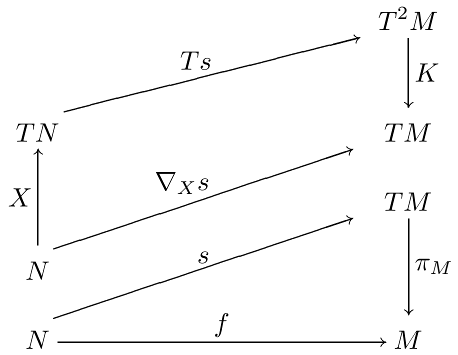
$$C(\quad, X_x) = (T(\pi_M)|\ker(K : T_{X_x}(TM) \to T_xM))^{-1}.$$

The connecter K is associated to a symmetric connetion if and only if $K \circ \kappa_M = K$. The connector treated here is a special case of of the one in (22.11).

13.9. Covariant derivatives, revisited. We describe here the passage from a linear connection $C : TM \times_M TM \to T^2M$ and its associated connector $K : T^2M \to TM$ to the covariant derivative. In the more general setting of vector bundles this is treated in (22.12). Namely, for any manifold N, a smooth mapping $s : N \to TM$ (a vector field along $f := \pi_M \circ s$) and a vector field $X \in \mathfrak{X}(N)$ we define

$$\nabla_X s := K \circ Ts \circ X : N \to TN \to T^2M \to TM \tag{1}$$

which is again a vector field along f.



If $f : N \to M$ is a fixed smooth mapping, let us denote by $C^\infty_f(N, TM) \cong \Gamma(f^*TM)$ the vector space of all smooth mappings $s : N \to TM$ with $\pi_M \circ s = f$ – vector fields along f. Then the covariant derivative may be viewed as a bilinear mapping

$$\nabla : \mathfrak{X}(N) \times C^\infty_f(N, TM) \to C^\infty_f(N, TM). \tag{2}$$

In particular for $f = Id_M$ we have $\nabla : \mathfrak{X}(M) \times \mathfrak{X}(M) \to \mathfrak{X}(M)$ as in (13.5).

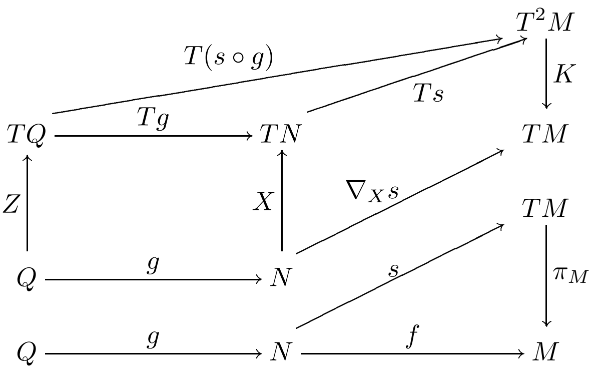
Lemma. *This covariant derivative has the following properties:*

(3) $\nabla_X s$ *is* $C^\infty(N)$*-linear in* $X \in \mathfrak{X}(N)$*. So for a tangent vector* $X_x \in T_xN$ *the mapping* $\nabla_{X_x} : C^\infty_f(N, TM) \to T_{f(x)}M$ *makes sense and we have* $(\nabla_X s)(x) = \nabla_{X(x)} s$.

(4) $\nabla_X s$ *is* $\mathbb{R}$*-linear in* $s \in C^\infty_f(N, TM)$.

(5) $\nabla_X(h.s) = dh(X).s + h.\nabla_X s$ *for* $h \in C^\infty(N)$*, the derivation property of* ∇_X.

(6) *For any manifold Q and smooth mapping $g : Q \to N$ and $Z_y \in T_yQ$ we have $\nabla_{Tg.Z_y} s = \nabla_{Z_y}(s \circ g)$. If $Z \in \mathfrak{X}(Q)$ and $X \in \mathfrak{X}(N)$ are g-related, then we have $\nabla_Z(s \circ g) = (\nabla_X s) \circ g$.*



(7) *In charts on N and M, for $s(x) = (\bar f(x), \bar s(x))$ and $X(x) = (x, \bar X(x))$ we have $(\nabla_X s)(x) = (\bar f(x), d\bar s(x).\bar X(x) - \Gamma_{\bar f(x)}(\bar s(x), d\bar f(x)\bar X(x)))$.*

(8) *The connection is symmetric if and only if $\nabla_X Y - \nabla_Y X = [X,Y]$.*

Proof. All these properties follow easily from the definition (1). $\square$

Remark. Property (6) is not well understood in some differential geometric literature. It is the reason why in the beginning of (13.6) we wrote $\nabla_{\partial_t} c' = 0$ for the geodesic equation and not $\nabla_{c'} c' = 0$ which one finds in the literature.

13.10. Torsion. Let ∇ be a general covariant derivative on a manifold M. Then the *torsion* is given by

$$\text{(1)}\qquad \operatorname{Tor}(X,Y) := \nabla_X Y - \nabla_Y X - [X,Y]. \quad X, Y \in \mathfrak{X}(M)$$

It is skew symmetric and $C^\infty(M)$-linear in $X, Y \in \mathfrak{X}(M)$ and is thus a 2-form with values in TM: $\operatorname{Tor} \in \Omega^2(M;TM) = \Gamma(\Lambda^2 T^*M \otimes TM)$, since we have

$$\begin{aligned} \operatorname{Tor}(f.X, Y) &= \nabla_{f.X} Y - \nabla_Y (f.X) - [f.X, Y] \\ &= f.\nabla_X Y - Y(f).X - f.\nabla_Y(X) - f.[X,Y] + Y(f).X \\ &= f.\operatorname{Tor}(X,Y). \end{aligned}$$

Locally on a chart (U,u) we have

$$\begin{aligned} \text{(2)}\qquad \operatorname{Tor}|U &= \sum_{i,j} \operatorname{Tor}\Big(\tfrac{\partial}{\partial u^i}, \tfrac{\partial}{\partial u^j}\Big) \otimes du^i \otimes du^j \\ &= \sum_{i,j} \Big(\nabla_{\frac{\partial}{\partial u^i}} \tfrac{\partial}{\partial u^j} - \nabla_{\frac{\partial}{\partial u^j}} \tfrac{\partial}{\partial u^i} - [\tfrac{\partial}{\partial u^i}, \tfrac{\partial}{\partial u^j}]\Big) \otimes du^i \otimes du^j \\ &= \sum_{i,j} (-\Gamma^k_{ij} + \Gamma^k_{ji}) du^i \otimes du^j \otimes \tfrac{\partial}{\partial u^k} \\ &= -\sum_{i,j} \Gamma^k_{ij} du^i \wedge du^j \otimes \tfrac{\partial}{\partial u^k} = -2\sum_{i<j} \Gamma^k_{ij} du^i \wedge du^j \otimes \tfrac{\partial}{\partial u^k} \end{aligned}$$

We may add an arbitrary form $T \in \Omega^2(M;TM)$ to a given covariant derivative and we get a new covariant derivative with the same spray and geodesic structure, since the symmetrization of the Christoffel symbols stays the same.

Lemma. *Let $K : TTM \to M$ be the connector of the covariant derivative ∇, let $X, Y \in \mathfrak{X}(M)$. Then the torsion is given by*

$$\text{(3)} \qquad \operatorname{Tor}(X,Y) = (K \circ \kappa_M - K) \circ TX \circ Y.$$

If moreover $f : N \to M$ is smooth and $U, V \in \mathfrak{X}(N)$ then we get also

$$\begin{aligned} \text{(4)} \qquad \operatorname{Tor}(Tf.U, Tf.V) &= \nabla_U(Tf \circ V) - \nabla_V(Tf \circ U) - Tf \circ [U,V] \\ &= (K \circ \kappa_M - K) \circ TTf \circ TU \circ V. \end{aligned}$$

Proof. By (13.9.1), (6.14) (or (6.19)), and (13.8.9) we have

$$\begin{aligned} \operatorname{Tor}(X,Y) &= \nabla_X Y - \nabla_Y X - [X,Y] \\ &= K \circ TY \circ X - K \circ TX \circ Y - K \circ \operatorname{vl}_{TM} \circ (Y, [X,Y]), \\ K \circ \operatorname{vl}_{TM} \circ (Y, [X,Y]) &= K \circ (TY \circ X - \kappa_M \circ TX \circ Y) \\ &= K \circ TY \circ X - K \circ \kappa_M \circ TX \circ Y. \end{aligned}$$

Similarly we get

$$\begin{aligned} & K \circ \operatorname{vl}_{TM} \circ (Tf \circ V, Tf \circ [U,V]) = K \circ TTf \circ \operatorname{vl}_{TN} \circ (V, [U,V]) \\ & = K \circ TTf \circ (TV \circ U - \kappa_N \circ TU \circ V) \\ & = K \circ TTf \circ TV \circ U - K \circ \kappa_M \circ TTf \circ TU \circ V \\ & \nabla_U(Tf \circ V) - \nabla_V(Tf \circ U) - Tf \circ [X,Y] = \\ & = K \circ TTf \circ TV \circ U - K \circ TTf \circ TU \circ V - K \circ \operatorname{vl}_{TM} \circ (Tf \circ V, Tf \circ [U,V]) \\ & = (K \circ \kappa_M - K) \circ TTf \circ TU \circ V \end{aligned}$$

The rest will be proved locally, so let us assume now that M is open in $\mathbb{R}^m$ and $U(x) = (x, \bar U(x))$, etc. Then by (13.8.8) we have

$$\begin{aligned} & (TTf \circ TU \circ V)(x) = TTf(x, \bar U(x); \bar V(x), d\bar U(x)\bar V(x)) \\ & = (f(x), df(x).\bar U(x); df(x).\bar V(x), d^2 f(x)(\bar V(x), \bar U(x)) + df(x).d\bar U(x).\bar V(x)) \\ & ((K \circ \kappa_M - K) \circ TTf \circ TU \circ V)(x) = \\ & = \big(f(x), d^2 f(x)(\bar V(x), \bar U(x)) + df(x).d\bar U(x).\bar V(x) - \Gamma_{f(x)}(df(x).\bar U(x), df(x).\bar V(x))\big) \\ & - \big(f(x), d^2 f(x)(\bar V(x), \bar U(x)) + df(x).d\bar U(x).\bar V(x) - \Gamma_{f(x)}(df(x).\bar V(x), df(x).\bar U(x))\big) \\ & = \big(f(x), -\Gamma_{f(x)}(df(x).\bar U(x), df(x).\bar V(x)) + \Gamma_{f(x)}(df(x).\bar V(x), df(x).\bar U(x))\big) \\ & = \operatorname{Tor}(Tf \circ U, Tf \circ V)(x) . \quad \square \end{aligned}$$

13.11. The space of all covariant derivatives. If ∇^0 and ∇^1 are two covariant derivatives on a manifold M then $\nabla^1_X Y - \nabla^0_X Y$ turns out to be $C^\infty(M)$-linear in $X, Y \in \mathfrak{X}(M)$ and is thus a $\binom{1}{2}$-tensor field on M, see (13.10). Conversely, one may add an arbitrary $\binom{1}{2}$-tensor field A to a given covariant derivative and get a new covariant derivative. Thus the space of all covariant derivatives is an affine space with modelling vector space $\Gamma(T^*M \otimes T^*M \otimes TM)$.

13.12. The covariant derivative of tensor fields. Let ∇ be covariant derivative on on manifold M, and let $X \in \mathfrak{X}(M)$. Then the ∇_X can be extended uniquely to an operator ∇_X on the space of all tensor field on M with the following properties:

(1) For $f \in C^\infty(M)$ we have $\nabla_X f = X(f) = df(X)$.
(2) ∇_X respects the spaces of $\binom{p}{q}$-tenor fields.
(3) $\nabla_X(A \otimes B) = (\nabla_X A) \otimes B + A \otimes (\nabla_X B)$; a derivation with respect to the tensor product
(4) ∇_X commutes with any kind of contraction C (trace, see (6.18)): So for $\omega \in \Omega^1(M)$ and $Y \in \mathfrak{X}(M)$ we have $\nabla_X(\omega(Y)) = (\nabla_X \omega)(Y) + \omega(\nabla_X Y)$.

The correct way to understand this is to use the concepts of section (22.9)-(22.12): Recognize the linear connection as induced from a principal connection on the linear frame bundle $GL(\mathbb{R}^m, TM)$ and induce it then to all vector bundles associated to the representations of the sructure group $GL(m, \mathbb{R})$ in all tensor spaces. Contractions are then equivariant mappings and thus intertwine the induced covariant derivartives, which is most clearly seen from (22.15).

Nevertheless, we discuss here the traditional proof, since it helps in actual computations. For $\omega \in \Omega^1(M)$ and $Y \in \mathfrak{X}(M)$ and the total contraction C we have

$$\begin{aligned}
\nabla_X(\omega(Y)) &= \nabla_X(C(\omega \otimes Y)) \\
&= C(\nabla_X \omega \otimes Y + \omega \otimes \nabla_X Y) \\
&= (\nabla_X \omega)(Y) + \omega(\nabla_X Y), \\
(\nabla_X \omega)(Y) &= \nabla_X(\omega(Y)) - \omega(\nabla_X Y),
\end{aligned}$$

which is easily seen (as in (13.10)) to be $C^\infty(M)$-linear in Y. Thus $\nabla_X \omega$ is again a 1-form. For a $\binom{p}{q}$-tensor field A we choose $X_i \in \mathfrak{X}(M)$ and $\omega^j \in \Omega^1(M)$, and arrive similarly using again the total contraction) at

$$\begin{aligned}
(\nabla_X A)(X_1, \dots, X_q, \omega^1, \dots, \omega^p) &= X(A(X_1, \dots, X_q, \omega^1, \dots, \omega^p)) - \\
- A(\nabla_X X_1, \dots, X_q, \omega^1, \dots, \omega^p) &- A(X_1, \nabla_X X_2, \dots, X_q, \omega^1, \dots, \omega^p) - \dots \\
- A(X_1, \dots, \nabla_X X_q, \omega^1, \dots, \omega^p) &- A(X_1, \dots, X_q, \nabla_X \omega^1, \dots, \omega^p) \\
&\dots - A(X_1, \dots, X_q, \omega^1, \dots, \nabla_X \omega^p).
\end{aligned}$$

This expression is again $C^\infty(M)$-linear in each entry X_i or ω^j and defines thus the $\binom{p}{q}$-tensor field $\nabla_X A$. Obvioulsy ∇_X is a derivation with respect to the tensor product of fields, and commutes with all contractions. For the sake of completeness we also list the local expression

$$\begin{aligned}\nabla_{\frac{\partial}{\partial u^i}} du^j &= \sum_k \Big(\nabla_{\frac{\partial}{\partial u^i}} du^j\Big)(\tfrac{\partial}{\partial u^k})du^k = \sum_k \Big(\tfrac{\partial}{\partial u^i}\delta^k_j - du^j(\nabla_{\frac{\partial}{\partial u^i}} \tfrac{\partial}{\partial u^k})\Big)du^k \\ &= \sum_k \Gamma^j_{ik} du^k\end{aligned}$$

from which one can easily derive the expression for an arbitrary tensor field:

$$\begin{aligned}\nabla_{\frac{\partial}{\partial u^i}} A &= \sum \Big(\nabla_{\frac{\partial}{\partial u^i}} A\Big)(\tfrac{\partial}{\partial u^{i_1}}, \dots, \tfrac{\partial}{\partial u^{i_q}}, du^{j_1}, \dots, du^{j_p})du^{i_1} \otimes \dots \otimes \tfrac{\partial}{\partial u^{j^p}} \\ &= \sum \Big(\tfrac{\partial}{\partial u^i}\Big(A\Big(\tfrac{\partial}{\partial u^{i_1}}, \dots, du^{j_p}\Big)\Big) - A\Big(\nabla_{\frac{\partial}{\partial u^i}} \tfrac{\partial}{\partial u^{i_1}}, \dots, du^{j_p}\Big) - \dots \\ &\quad \dots - A\Big(\tfrac{\partial}{\partial u^{i_1}}, \dots, \nabla_{\frac{\partial}{\partial u^i}} du^{j_p}\Big)\Big)du^{i_1} \otimes \dots \otimes \tfrac{\partial}{\partial u^{j^q}} \\ &= \sum \Big(\tfrac{\partial}{\partial u^i} A^{j_1,\dots,j_p}_{i_1,\dots,i_q} + A^{j_1,\dots,j_p}_{k,i_2,\dots,i_q}\Gamma^k_{i,i_1} + A^{j_1,\dots,j_p}_{i_1,k,i_3,\dots,i_q}\Gamma^k_{i,i_2} + \dots \\ &\quad \dots - A^{j_1,\dots,j_{p-1},k}_{i_1,\dots,i_q}\Gamma^{j_p}_{i,k}\Big)du^{i_1} \otimes \dots \otimes \tfrac{\partial}{\partial u^{j^q}}.\end{aligned}$$

14. Riemann geometry of geodesics

14.1. Geodesics. On a pseudo Riemann manifold (M, g) we have a geodesic structure which is described by the flow of the geodesic spray on TM. The geodesic with initial value $X_x \in T_xM$ is denoted by $t \mapsto \exp(t.X_x)$ in terms of the pseudo Riemann exponential mapping exp and $\exp_x = \exp|T_xM$. We recall the properties of the geodesics which we will use.

(1) $\exp_x : T_xM \supset U_x \to M$ is defined on a maximal 'radial' open zero neighborhood U_x in T_xM. Here radial means, that for $X_x \in V_x$ we also have $[0, 1].X_x \subset V_x$. This follows from the flow properties since by (13.7) $\exp_x = \pi_M(\mathrm{Fl}^S_1|T_xM)$.
(2) $T_{0_x}(\exp|T_xM) = \mathrm{Id}_{T_xM}$, thus $\frac{\partial}{\partial t}\big|_0 \exp_x(t.X_x) = X_x$. See (13.7.4).
(3) $\exp(s.(\frac{\partial}{\partial t}\exp(t.X))) = \exp((t + s)X)$. See (13.6.3).
(4) $t \mapsto g(\frac{\partial}{\partial t}\exp(t.X), \frac{\partial}{\partial t}\exp(t.X))$ is constant in t, since for $c(t) = \exp(t.X)$ we have $\partial_t\, g(c', c') = 2g(\nabla_{\partial_t} c', c') = 0$. Thus in the Riemann case the length $|\frac{\partial}{\partial t}\exp(t.X)|_g = \sqrt{g(\frac{\partial}{\partial t}\exp(t.X), \frac{\partial}{\partial t}\exp(t.X))}$ is also constant.

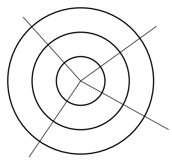
If for a geodesic c the (by (4)) constant $|c'(t)|_g$ is 1 we say that c is *parameterized by arc-length.*

14.2. Lemma. *(Gauß) Let (M, g) be a Riemann manifold. For $x \in M$ let $\varepsilon > 0$ be so small that $\exp_x : D_x(\varepsilon) := \{X \in T_xM : |X|_g < \varepsilon\} \to M$ is a diffeomorphism on its image. Then in $\exp_x(D_x(\varepsilon))$ the geodesic rays starting from x are all orthogonal to the 'geodesic spheres' $\{\exp_x(X) : |X|_g = k\} = \exp_x(k.S(T_xM, g))$ for $k < \varepsilon$.*

On pseudo Riemann manifolds this result holds too, with the following adaptation: Since the unit spheres in (T_xM, g_x) are hyperboloids they are not small and may not lie in the domain of definition of the geodesic exponental mapping; the result only holds in this domain.

Proof. $\exp_x(k.S(T_xM, g))$ is a submanifold of M since $\exp_x$ is a diffeomorphism on $D_x(\varepsilon)$. Let $s \mapsto v(s)$ be a smooth curve in $kS(T_xM, g) \subset T_xM$, and let $\gamma(t, s) := \exp_x(t.v(s))$. Then γ is a variation of the geodesic $\gamma(t, 0) = \exp_x(t.v(0)) =: c(t)$. In the energy of the geodesic $t \mapsto \gamma(t, s)$ the integrand is constant by (14.1.4):

$$\begin{aligned} E_0^1(\gamma(\quad, s)) &= \tfrac{1}{2}\int_0^1 g(\tfrac{\partial}{\partial t}\gamma(t,s), \tfrac{\partial}{\partial t}\gamma(t,s))\,dt \\ &= \tfrac{1}{2} g(\tfrac{\partial}{\partial t}\big|_0 \gamma(t,s), \tfrac{\partial}{\partial t}\big|_0 \gamma(t,s))\,dt \\ &= \tfrac{1}{2}k^2 \end{aligned}$$



Comparing this with the first variational formula (13.3)

$$\tfrac{\partial}{\partial s}|_0(E_0^1(\gamma(\quad, s))) = \int_0^1 0\,dt + g(c(1))(c'(1), \tfrac{\partial}{\partial s}|_0\gamma(1,s)) - g(c(0))(c'(0), 0).$$

we get $0 = g(c(1))(c'(1), \frac{\partial}{\partial s}|_0\gamma(1, s))$, where $\frac{\partial}{\partial s}|_0\gamma(1, s)$ is an arbitrary tangent vector of $\exp_x(kS(T_xM, g))$. □

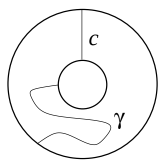
14.3. Corollary. *Let (M, g) be a Riemann manifold, $x \in M$, and $\varepsilon > 0$ be such that $\exp_x : D_x(\varepsilon) := \{X \in T_xM : |X|_g < \varepsilon\} \to M$ is a diffeomorphism on its image. Let $c : [a, b] \to \exp_x(D_x(\varepsilon)) \setminus \{x\}$ be a piecewise smooth curve, so that $c(t) = \exp_x(u(t).v(t))$ where $0 < u(t) < \varepsilon$ and $|v(t)|_{g_x} = 1$.*

Then for the length we have $L_a^b(c) \geq |u(b) - u(a)|$ with equality if and only if u is monotone and v is constant, so that c is a radial geodesic, reparameterized by u.

On pseudo Riemann manifolds this results holds only for in the domain of definition of the geodesic exponential mapping and only for curves with positive velocity vector (timelike curves).

Proof. We may assume that c is smooth by treating each smooth piece of c separately. Let $\alpha(u, t) := \exp_x(u.v(t))$. Then

$$\begin{aligned} c(t) &= \alpha(u(t), t) \\ \tfrac{\partial}{\partial t}c(t) &= \tfrac{\partial\alpha}{\partial u}(u(t), t).u'(t) + \tfrac{\partial\alpha}{\partial t}(u(t), t), \\ |\tfrac{\partial\alpha}{\partial u}|_{g_x} &= |v(t)|_{g_x} = 1, \\ 0 &= g(\tfrac{\partial\alpha}{\partial u}, \tfrac{\partial\alpha}{\partial t}), \quad \text{by lemma (14.2).} \end{aligned}$$



Putting this together we get

$$\begin{aligned} |c'|_g^2 &= g(c', c') = g(\tfrac{\partial\alpha}{\partial u}.u' + \tfrac{\partial\alpha}{\partial t}, \tfrac{\partial\alpha}{\partial u}.u' + \tfrac{\partial\alpha}{\partial t}) \\ &= |u'|^2|\tfrac{\partial\alpha}{\partial u}|_g^2 + |\tfrac{\partial\alpha}{\partial t}|_g^2 = |u'|^2 + |\tfrac{\partial\alpha}{\partial t}|_g^2 \geq |u'|^2 \end{aligned}$$

with equality if and only if $|\frac{\partial\alpha}{\partial t}|_g = 0$, thus $\frac{\partial\alpha}{\partial t} = 0$ and $v(t) = \text{constant}$. So finally:

$$L_a^b(c) = \int_a^b |c'(t)|_g\,dt \geq \int_a^b |u'(t)|\,dt \geq \left|\int_a^b u'(t)\,dt\right| = |u(b) - u(a)|$$

with equality if and only if u is monotone and v is constant. □

14.4. Corollary. *Let (M, g) be a Riemann manifold. Let $\varepsilon : M \to \mathbb{R}_{>0}$ be a continuous function such that for $\tilde V = \{X_x \in T_xM : |X_x| < \varepsilon(x) \text{ for all } x \in M\}$ the mapping $(\pi_m, \exp) : TM \supseteq \tilde V \to W \subseteq M \times M$ is a diffeomorphism from the open neighboorhood $\tilde V$ of the zero section in TM onto an open neighboorhood W of the diagonal in $M \times M$, as shown in* (13.7.6).

Then for each $(x, y) \in W$ there exists a unique geodesic c in M which connects x and y and has minimal length: For each piecewise smooth curve γ from x to y we have $L(\gamma) \geq L(c)$ with equality if and only if γ is a reparameterization of c.

Proof. The set $\tilde V \cap T_xM = D_x(\varepsilon(x))$ satisfies the condition of corollary (14.3). For $X_x = \exp_x^{-1}(y) = ((\pi_M, \exp)|\tilde V)^{-1}(x, y)$ the geodesic $t \mapsto c(t) = \exp_x(t.X_x)$ leads from x to y. Let $\delta > 0$ be small. Then c contains a segment which connects the geodesic spheres $\exp_x(\delta.S(T_xM, g))$ and $\exp_x(|X_x|_{g_x}.S(T_xM, g))$. By corollary (14.3) the length of this segment is $\geq |X_x|_g - \delta$ with equality if and only if this segment is radial, thus a reparameterization of c. Since this holds for all $\delta > 0$ the result follows. □

14.5. The geodesic distance. On a Riemann manifold (M, g) there is a natural topological metric defined by

$$\text{dist}^g(x, y) := \inf\left\{L_0^1(c) : c : [0, 1] \to M \text{ piecewise smooth, } c(0) = x, c(1) = y\right\},$$

which we call the *geodesic distance* (since 'metric' is heavily used). We either assume that M is connected or we take the distance of points in different connected components as ∞.

Lemma. *On a Riemann manifold (M, g) the geodesic distance is a topological metric which generates the topology of M. For $\varepsilon_x > 0$ small enough the open ball $B_x(\varepsilon_x) = \{y \in M : \text{dist}^g(x, y) < \varepsilon_x\}$ has the property that any two points in it can be connected by a geodesic of minimal length.*

Proof. This follows by (14.3) and (14.4). The triangle inequality is easy to check since we admit piecewise smooth curves. □

14.6. Theorem. *(Hopf, Rinov) For a Riemann manifold (M, g) the following assertions are equivalent:*

(1) *(M, dist^g) is a complete metrical space (Cauchy sequences converge).*
(2) *Each closed subset of M which is bounded for the geodesic distance is compact.*
(3) *Any geodesic is maximally definable on the whole of $\mathbb{R}$.*

(4) $\exp : TM \to M$ *is defined on the whole of* TM.
(5) *There exists a point* x *such that* $\exp_x : T_xM \to M$ *is defined on the whole of* T_xM*, in each connected component of* M.

If these equivalent conditions are satisfied, then (M, g) *is called a complete Riemann manifold. In this case we even have:*

(6) *On a complete connected Riemann manifold any two points can be connected by a geodesic of minimal length.*

Condition (6) does not imply the other conditions: Consider an open convex in $\mathbb{R}^m$.

Proof. (2) $\implies$ (1) is obvious.

(1) $\implies$ (3) Let c be a maximally defined geodesic, parametrized by arc-length. If c is defined on the interval (a, b) and if $b < \infty$, say, then by the definition of the distance (14.5) the sequence $c(b - \frac{1}{n})$ is a Cauchy sequence, thus by (1) $\lim_{n\to\infty} c(b - \frac{1}{n}) =: c(b)$ exists in M. For m, n large enough $(c(b-\frac{1}{n}), c(b-\frac{1}{m})) \in W$ where W is the open neighborhood of the diagonal in $M \times M$ from (14.4), thus the segment of c between $c(b - \frac{1}{n})$ and $c(b - \frac{1}{m})$ is of minimal length: $\operatorname{dist}^g(c(b - \frac{1}{n}), c(b - \frac{1}{m})) = |\frac{1}{n} - \frac{1}{m}|$. By continuity $\operatorname{dist}^g(c(b - \frac{1}{n}), c(b)) = |\frac{1}{n}|$. Now let us apply corollary (14.3) with center $c(b)$: In $\exp_{c(b)}(D_{c(b)}(\varepsilon))$ the curve $t \mapsto c(b + t)$ is a piecewise smooth curve of minimal length, by (14.3) a radial geodesic. Thus $\lim_{t\to b} c'(t) =: c'(b)$ exists and $t \mapsto \exp_{c(b)}((t - b)c'(b))$ equals $c(t)$ for $t < b$ and prolongs the geodesic c for $t \geq b$.

(3) $\implies$ (4) is obvious.

(4) $\implies$ (5) is obvious.

(5) $\implies$ (6) for special points, in each connected component separately. In detail: Let x, y be in one connected component of M where x is the special point with $\exp_x : T_xM \to M$ defined on the whole of T_xM. We shall prove that x can be connected to y by a geodesic of minimal length.

Let $\operatorname{dist}^g(x, y) = r > 0$. We consider the compact set $S := \exp_x(\delta.S(T_xM, g)) \subset \exp_x(T_xM)$ for $0 < \delta < r$ so small that $\exp_x$ is a diffeomorphism on $\{X \in T_xM : |X|_g < 2\delta\}$. There exists a unit vector $X_x \in S(T_xM, g_x)$ such that $z = \exp_x(\delta X_x)$ has the property that $\operatorname{dist}^g(z, y) = \min\{\operatorname{dist}^g(s, y) : s \in S\}$.

Claim (a) The curve $c(t) = \exp_x(t.X_x)$ satisfies the condition

$$(*) \qquad \operatorname{dist}^g(c(t), y) = r - t$$

for all $0 \leq t \leq r$. It will take some paper to prove this claim.

Since any piecewise smooth curve from x to y hits S (its initial segment does so in the diffeomorphic preimage in T_xM) we have

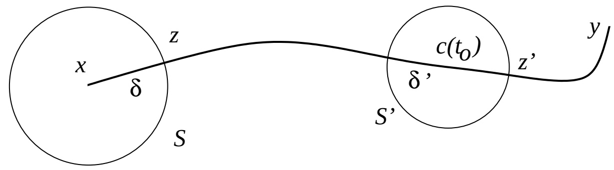
$$\begin{aligned} r = \operatorname{dist}^g(x, y) &= \inf_{s\in S}(\operatorname{dist}^g(x, s) + \operatorname{dist}^g(s, y)) = \inf_{s\in S}(\delta + \operatorname{dist}^g(s, y)) \\ &= \delta + \min_{s\in S} \operatorname{dist}^g(s, y) = \delta + \operatorname{dist}^g(z, y) \\ \operatorname{dist}^g(z, y) &= r - \delta, \qquad \text{thus (*) holds for } t = \delta. \end{aligned}$$

Claim (b) If (*) holds for $t \in [\delta, r]$ then also for all t' with $\delta \le t' \le t$, since we have

$$\begin{aligned}
\operatorname{dist}^g(c(t'), y) &\le \operatorname{dist}^g(c(t'), c(t)) + \operatorname{dist}^g(c(t), y) \le t - t' + r - t = r - t',\\
r = \operatorname{dist}^g(x, y) &\le \operatorname{dist}^g(x, c(t')) + \operatorname{dist}^g(c(t'), y),\\
\operatorname{dist}^g(c(t'), y) &\ge r - \operatorname{dist}^g(x, c(t')) \ge r - t' \qquad \Longrightarrow \textit{(b)}.
\end{aligned}$$

Now let $t_0 = \sup\{t \in [\delta, r] : \text{(*) holds for } t\}$. By continuity (*) is then also valid for t_0. Assume for contradiction that $t_0 < r$.

Let S' be the geodesic sphere with (small) radius δ' centered at $c(t_0)$, and let $z' \in S'$ be a point with minimal distance to y.



As above we see that

$$r - t_0 \overset{(*)}{=} \operatorname{dist}^g(c(t_0), y) = \inf_{s' \in S'} (\operatorname{dist}^g(c(t_0), s') + \operatorname{dist}^g(s', y)) = \delta' + \operatorname{dist}^g(z', y)$$

$$(**) \qquad \operatorname{dist}^g(z', y) = (r - t_0) - \delta'$$

$$\operatorname{dist}^g(x, z') = \operatorname{dist}^g(x, y) - \operatorname{dist}^g(z', y) = r - (r - t_0) + \delta' = t_0 + \delta'.$$

We consider now the piecewise smooth curve $\bar{c}$ which follows initially c from x to $c(t_0)$ and then the minimal geodesic from $c(t_0)$ to z', parameterized by arc-length. We just checked that the curve $\bar{c}$ has minimal length $t_0 + \delta'$. Thus each piece of $\bar{c}$ has also minimal length, in particular the piece between $\bar{c}(t_1)$ and $\bar{c}(t_2)$, where $t_1 < t_0 < t_2$. Since we may choose these two points near to each other, $\bar{c}$ is a minimal geodesic between them by (14.4). Thus $\bar{c}$ equals c, $z' = c(t_0 + \delta)$, $\operatorname{dist}^g(c(t_0 + \delta'), y) = \operatorname{dist}^g(z', y) = r - (\delta' + t_0)$ by (**), and (*) holds for $t_0 + \delta'$ also, which contradicts the maximality of t_0 for the validity of (*). Thus the assumption $t_0 < r$ is wrong and claim (a) follows.

Finally, by claim (a) we have $\operatorname{dist}^g(c(r), y) = r - r = 0$, thus $c(t) = \exp_x(t.X_x)$ is a geodesic from x to y of length $r = \operatorname{dist}^g(x, y)$, thus of minimal length, so (6) for the special points follows.

(4) $\Longrightarrow$ (6), by the foregoing proof, since then any point is special.

(5) $\Longrightarrow$ (2) Let $A \subset M$ be closed and bounded for the geodesic distance. Suppose that A has diameter $r < \infty$. Then A is completely contained in one connected component of M, by (14.5). Let x be the special point in this connected component with $\exp_x$ defined on the whole of T_xM. Take $y \in A$.

By (6) for the special point x (which follows from (5)), there exists a geodesic from x to y of minimal length $\operatorname{dist}^g(x, y) =: s < \infty$, and each point z of A can be connected to x by a geodesic of minimal length $\operatorname{dist}^g(x, z) \le \operatorname{dist}^g(x, y) + \operatorname{dist}^g(y, z) \le r + s$.

Thus the compact set (as continuous image of a compact ball) $\exp_x\{X_x \in T_xM : |X_x|_g \le r + s\}$ contains A. Since A is closed, it is compact too. $\square$

14.7. Conformal metrics. Two Riemann metrics g_1 and g_2 on a manifold M are called *conformal* if there exists a smooth nowhere vanishing function f with $g_2 = f^2.g_1$. Then g_1 and g_2 have the same angles, but not the same lengths. A local diffeomorphism $\varphi : (M_1, g_1) \to (M_2, g_2)$ is called *conformal* if $\varphi^* g_2$ is conformal to g_1.

As an example, which also explains the name, we mention that any holomorphic mapping with non-vanishing derivative between open domains in $\mathbb{C}$ is conformal for the Euclidean inner product. This is clear from the polar decomposition $\varphi'(z) = |\varphi'(z)| e^{i\arg(\varphi'(z))}$ of the derivative.

As another, not unrelated example we note that *the stereographic projection from* (1.2) *is a conformal mapping:*

$$u_+ : (S^n \setminus \{a\}, g^{S^n}) \to \{a\}^\perp \to (\mathbb{R}^n, \langle\quad,\quad\rangle), \qquad u_+(x) = \tfrac{x - \langle x,a\rangle a}{1 - \langle x,a\rangle}$$

To see this take $X \in T_x S^n \subset T_x \mathbb{R}^{n+1}$, so that $\langle X, x\rangle = 0$. Then we get:

$$\begin{aligned}
du_+(x)X &= \tfrac{(1-\langle x,a\rangle)(X - \langle X,a\rangle a) + \langle X,a\rangle (x - \langle x,a\rangle a)}{(1-\langle x,a\rangle)^2} \\
&= \tfrac{1}{(1-\langle x,a\rangle)^2}\big((1 - \langle x,a\rangle)X + \langle X,a\rangle x - \langle x,a\rangle a\big), \\
\langle du_+(x)X, du_+(x)Y\rangle &= \tfrac{1}{(1-\langle x,a\rangle)^2}\langle X,Y\rangle = \tfrac{1}{(1-\langle x,a\rangle)^2}\,(g^{S^n})_x(X,Y).
\end{aligned}$$

14.8. Theorem. *(Nomizu-Ozeki, Morrow) Let (M, g) be a connected Riemann manifold. Then we have:*

1. *There exist complete Riemann metrics on M which are conformal to g and are equal to g on any given compact subset of M.*
2. *There also exist Riemann metrics on M such that M has finite diameter, which are conformal to g and are equal to g on any given compact subset of M. If M is not compact then by* (14.6.2) *a Riemann metric for which M has finite diameter is not complete.*

Thus the sets of all complete Riemann metric and of all Riemann metric with bounded diameter are both dense in the compact C^∞-topology on the space of all Riemann metrics.

Proof. For $x \in M$ let

$$r(x) := \sup\{r : B_x(r) = \{y \in M : \operatorname{dist}^g(x,y) \le r\} \text{ is compact in } M\}.$$

If $r(x) = \infty$ for one x then g is a complete metric by (14.6.2). Since $\exp_x$ is a diffeomorphism near 0_x, $r(x) > 0$ for all x. We assume that $r(x) < \infty$ for all x.

Claim. $|r(x) - r(y)| \le \operatorname{dist}^g(x,y)$, thus $r : M \to \mathbb{R}$ is continuous, since: For small $\varepsilon > 0$ the set $B_x(r(x) - \varepsilon)$ is compact, $\operatorname{dist}^g(z,x) \le \operatorname{dist}^g(z,y) + \operatorname{dist}^g(y,x)$ implies that $B_y(r(x) - \varepsilon - \operatorname{dist}^g(x,y)) \subseteq B_x(r(x) - \varepsilon)$ is compact, thus $r(y) \ge r(x) - \operatorname{dist}^g(x,y) - \varepsilon$ and $r(x) - r(y) \le \operatorname{dist}^g(x,y)$. Now interchange x and y.

By a partition of unity argument we construct a smooth function $f \in C^\infty(M, \mathbb{R}_{>0})$ with $f(x) > \frac{1}{r(x)}$. Consider the Riemann metric $\bar g = f^2 g$.

Claim. $\bar B_x(\frac14) := \{y \in M : \operatorname{dist}^{\bar g}(x,y) \le \frac14\} \subset B_x(\frac12 r(x))$, thus compact.
Suppose $y \notin B_x(\frac12 r(x))$. For any piecewise smooth curve c from x to y we have

$$L^g(c) = \int_0^1 |c'(t)|_g\,dt > \frac{r(x)}{2},$$
$$L^{\bar g}(c) = \int f(c(t)).|c'(t)|_g\,dt = f(c(t_0))\int_0^1 |c'(t)|_g\,dt > \frac{L^g(c)}{r(c(t_0))},$$

for some $t_0 \in [0,1]$, by the mean value theorem of integral calculus. Moreover,

$$|r(c(t_0)) - r(x)| \le \operatorname{dist}^g(c(t_0), x) \le L^g(c) =: L$$
$$r(c(t_0)) \le r(x) + L$$
$$L^{\bar g}(c) \ge \frac{L}{r(x)+L} \ge \frac{L}{3L} = \frac13,$$

so $y \notin \bar B_x(\frac14)$ either.

Claim. $(M, \bar g)$ is a complete Riemann manifold.
Let $X \in T_xM$ with $|X|_{\bar g} = 1$. Then $\exp^{\bar g}(t.X)$ is defined for $|t| \le \frac15 < \frac14$. But also $\exp^{\bar g}(s.\frac{\partial}{\partial t}|_{t=\pm 1/5}\exp^{\bar g}(t.X))$ is defined for $|s| < \frac14$ which equals $\exp^{\bar g}((\pm\frac15 + s)X)$, and so on. Thus $\exp^{\bar g}(t.X)$ is defined for all $t \in \mathbb{R}$, and by (14.6.4) the metric $\bar g$ is complete.

Claim. We may choose f in such a way that $f = 1$ on a neighborhood of any given compact set $K \subset M$.
Let $C = \max\{\frac{1}{r(x)} : x \in K\} + 1$. By a partition of unity argument we construct a smooth function f with $f = 1$ on a neighborhood of K and $Cf(x) > \frac{1}{r(x)}$ for all x. By the arguments above, $C^2 f^2 g$ is then a complete metric, thus also $f^2 g$.

Proof of (2). Let g be a complete Riemann metric on M. We choose $x \in M$, a smooth function h with $h(y) > \operatorname{dist}^g(x,y)$, and we consider the Riemann metric $\tilde g_y = e^{-2h(y)} g_y$. By (14.6.6) for any $y \in M$ there exists a minimal g-geodesic c from x to y, parameterized by arc-length. Then $h(c(s)) > \operatorname{dist}^g(x, c(s)) = s$ for all $s \le \operatorname{dist}^g(x,y) =: L$. But then

$$L^{\tilde g}(c) = \int_0^L e^{-h(c(s))}|c'(s)|_g\,ds < \int_0^L e^{-s} 1\,ds < \int_0^\infty e^{-s} ds = 1,$$

so that M has diameter 1 for the Riemann metric $\tilde g$. We main also obtain that $\tilde g = g$ on a compact set as above. □

14.9. Proposition. *Let (M, g) be a complete Riemann manifold. Let $X \in \mathfrak{X}(M)$ be a vector field which is bounded with respect to g, $|X|_g \le C$.*

Then X is a complete vector field; it admits a global flow.

Proof. The flow of X is given by the differential equation $\frac{\partial}{\partial t}\operatorname{Fl}^X_t(x) = X(\operatorname{Fl}^X_t(x))$ with initial value $\operatorname{Fl}^X_0(x) = x$. Suppose that $c(t) = \operatorname{Fl}^X_t(x)$ is defined on (a, b) and that $b < \infty$, say. Then

$$\begin{aligned}\operatorname{dist}^g(c(b-1/n), c(b-1/m)) \le L_{b-1/n}^{b-1/m}(c) = \int_{b-1/n}^{b-1/m} |c'(t)|_g\, dt = \\ = \int_{b-1/n}^{b-1/m} |X(c(t))|_g\, dt \le \int_{b-1/n}^{b-1/m} C\, dt = C.(\tfrac{1}{m} - \tfrac{1}{n}) \to 0,\end{aligned}$$

so that $c(b-1/n)$ is a Cauchy sequence in the complete metrical space M and the limit $c(b) = \lim_{n\to\infty} c(b-1/n)$ exists. But then we may continue the flow beyond b by $\operatorname{Fl}^X_s(\operatorname{Fl}^X_b(x)) = \operatorname{Fl}^X_{b+s}$. □

14.10. Problem. *Unsolved till now (February 21, 2006), up to my knowledge. Let X be a complete vector field on a manifold M. Does there exist a complete Riemann metric g on M such that X is bounded with respect to g?*

The only inroad towards this problem is the following:

Proposition. *(Gliklikh, 1999) Let X be a complete vector field on a connected manifold M.*

Then there exists a complete Riemann metric g on the manifold $M \times \mathbb{R}$ such that the vector field $X \times \partial_t \in \mathfrak{X}(M \times \mathbb{R})$ is bounded with respect to g.

Proof. Since $\operatorname{Fl}^{X\times\partial_t}_t(x, s) = (\operatorname{Fl}^X_t(x), s+t)$, the vector field $X \times \partial_t$ is also complete. It is nowhere 0.

Choose a smooth proper function f_1 on M; for example, if a smooth function f_1 satisfies $f_1(x) > \operatorname{dist}^{\bar g}(x_0, x)$ for a complete Riemann metric $\bar g$ on M, then f_1 is proper by (14.6.2).

For a Riemann metric $\bar g$ on M we consider the Riemann metric $\tilde g$ on $M \times \mathbb{R}$ which equals g_x on $T_xM \cong T_xM \times 0_t = T_{(x,t)}(M \times \{t\})$ and satisfies $|X \times \partial_t|_{\tilde g} = 1$ and $\tilde g_{(x,t)}((X\times\partial_t)(x, t), T_{(x,t)}(M\times\{t\})) = 0$. We will also use the fiberwise $\tilde g$-orthogonal projections $\operatorname{pr}_M : T(M \times \mathbb{R}) \to TM \times 0$ and $\operatorname{pr}_X : T(M \times \mathbb{R}) \to \mathbb{R}.(X \times \partial_t) \cong \mathbb{R}$.

The smooth function $f_2(x, s) = f_1(\operatorname{Fl}^X_{-s}(x)) + s$ satisfies the following and is thus still proper:

$$\begin{aligned}(\mathcal{L}_{X\times\partial_t} f_2)(x, s) &= \tfrac{\partial}{\partial t}\big|_0 f_2(\operatorname{Fl}^{X\times\partial_t}_t(x, s)) = \tfrac{\partial}{\partial t}\big|_0 f_2(\operatorname{Fl}^X_t(x), s + t) = \\ &= \tfrac{\partial}{\partial t}\big|_0 \Big(f_1(\operatorname{Fl}^X_{-s-t}(\operatorname{Fl}^X_t(x))) + s + t\Big) = \tfrac{\partial}{\partial t}\big|_0 f_1(\operatorname{Fl}^X_{-s}(x)) + 1 = 1\end{aligned}$$

By a partition of unity argument we construct a smooth function $f_3 : M \times \mathbb{R} \to \mathbb{R}$ which satisfies

$$f_3(x, s)^2 > \max\big\{|Y(f_2)|^2 : Y \in T_{(x,s)}(M \times \{s\}), |Y|_{\tilde g} = 1\big\}$$

Finally we define a Riemann metric g on $M \times \mathbb{R}$ by

$$g_{(x,t)}(Y, Z) = f_3(x, t)^2\, \tilde g_{(x,t)}(\operatorname{pr}_M(Y), \operatorname{pr}_M(Z)) + \operatorname{pr}_X(Y) \cdot \operatorname{pr}_X(Z)$$

for $Y, Z \in T_{(x,t)}(M \times \mathbb{R})$, which satisfies $|X \times \partial_t|_g = 1$.

Claim. g is a complete Riemann metric on $M \times \mathbb{R}$.

Let c be a piecewise smooth curve which is parameterized by g-arc-length. Then

$$|c'|_g = 1, \quad \text{thus also} \quad |\operatorname{pr}_M(c')|_g \le 1, \quad |\operatorname{pr}_X(c')| \le 1$$

$$\tfrac{\partial}{\partial t} f_2(c(t)) = df_2(c'(t)) = (\operatorname{pr}_M(c'(t)))(f_2) + \operatorname{pr}_X(c'(t))(f_2)$$

$$\begin{aligned}|\tfrac{\partial}{\partial t} f_2(c(t))| &\le \left|\frac{\operatorname{pr}_M(c'(t))}{|\operatorname{pr}_M(c'(t))|_g}(f_2)\right| + \left|\frac{\operatorname{pr}_X(c'(t))}{|\operatorname{pr}_X(c'(t))|_g}(f_2)\right| \\ &= \left|\frac{1}{f_3(c(t))}\frac{\operatorname{pr}_M(c'(t))}{|\operatorname{pr}_M(c'(t))|_{\tilde g}}(f_2)\right| + |\mathcal{L}_{X\times\partial_t} f_2| < 2\end{aligned}$$

by the definition of g and the properties of f_3 and f_2. Thus

$$|f_2(c(t)) - f_2(c(0))| \le \int_0^t |\tfrac{\partial}{\partial t} f_2(c(t))|\, dt \le 2t$$

Since this holds for every such c we conclude that

$$|f_2(x) - f_2(y)| \le 2\operatorname{dist}^g(x,y)$$

and thus each closed and dist^g-bounded set is contained in some

$$\{y \in M \times \mathbb{R} : \operatorname{dist}^g(x,y) \le R\} \subset f_2^{-1}([f_2(x) - \tfrac{R}{2}, f_2(x) + \tfrac{R}{2}])$$

which is compact since f_2 is proper. So $(M \times \mathbb{R}, g)$ is a complete Riemann manifold by (14.6.2). □

15. Parallel transport and curvature

15.1. Parallel transport. Let (M, ∇) be a manifold with a covariant derivative, as treated in (13.7). The pair (M, ∇) is also sometimes called an *affine manifold*.

A vector field $Y : N \to TM$ along a smooth mapping $f = \pi_M \circ Y : N \to M$ is called *parallel* if $\nabla_X Y = 0$ for any vector field $X \in \mathfrak{X}(N)$.

If $Y : \mathbb{R} \to TM$ is a vector field along a given curve $c = \pi_M \circ Y : \mathbb{R} \to M$, then $\nabla_{\partial_t} Y = K \circ TY \circ \partial_t = 0$ takes the following form in a local chart, by (13.7.7)

$$K \circ TY \circ \partial_t = K(\bar c(t), \bar Y(t); \bar c'(t), \bar Y'(t)) = (\bar c(t), \bar Y'(t) - \Gamma_{\bar c(t)}(\bar Y(t), \bar c'(t))).$$

This is a linear ordinary differential equation of first order for $\bar Y$ (since $\bar c$ is given). Thus for every initial value $Y(t_0)$ for $t_0 \in \mathbb{R}$ the parallel vector field Y along c is uniquely determined for the whole parameter space $\mathbb{R}$. We formalize this by defining the *parallel transport* along the curve $c : \mathbb{R} \to M$ as

$$\operatorname{Pt}(c,t) : T_{c(0)}M \to T_{c(t)}M, \quad \operatorname{Pt}(c,t).Y(0) = Y(t),$$

where Y is any parallel vector field along c. Note that we treat this notion for principal bundles in (22.6) and for general fiber bundles in (20.8). This here is a special case.

Theorem. *On an affine manifold (M,∇) the parallel transport has the following properties.*

(1) $\operatorname{Pt}(c,t) : T_{c(0)}M \to T_{c(t)}M$ *is a linear isomorphism for each* $t \in \mathbb{R}$ *and each curve* $c : \mathbb{R} \to M$.
(2) *For smooth* $f : \mathbb{R} \to \mathbb{R}$ *we have* $\operatorname{Pt}(c, f(t)) = \operatorname{Pt}(c \circ f, t)\operatorname{Pt}(c, f(0))$*; the reparameterization invariance.*
(3) $\operatorname{Pt}(c,t)^{-1} = \operatorname{Pt}(c(\quad +t), -t)$.
(4) *If the covariant derivative is compatible with a pseudo Riemann metric g on M, then $\operatorname{Pt}(c,t)$ is isometric, i.e.* $g_{c(t)}(\operatorname{Pt}(c,t)X, \operatorname{Pt}(c,t)Y) = g_{c(0)}(X,Y)$.

Proof. (1) follows from the linearity of the differential equation.

(2) See also (20.8). Let X be parallel along c, $\nabla_{\partial_t}X = 0$ or $X(t) = \operatorname{Pt}(c,t)X(0)$. Then we have by (13.7.6)

$$\nabla_{\partial_t}(X \circ f) = \nabla_{T_tf.\,\partial_t}X = \nabla_{f'(t)\,\partial_t}X = f'(t)\nabla_{\partial_t}X = 0$$

thus $X \circ f$ is also parallel along $c \circ f$, with initial value $X(f(0)) = \operatorname{Pt}(c, f(0))X(0)$. Thus

$$\operatorname{Pt}(c, f(t))X(0) = X(f(t)) = \operatorname{Pt}(c \circ f, t)\operatorname{Pt}(c, f(0))X(0).$$

(3) follows from (2)

(4) Let X and Y be parallel vector fields along c, i.e. $\nabla_{\partial_t}X = 0$ etc. Then $\partial_t\, g(X(t), Y(t)) = g(\nabla_{\partial_t}X(t), Y(t)) + g(X(t), \nabla_{\partial_t}Y(t)) = 0$, thus $g(X(t), Y(t))$ is constant in t. □

15.2. Flows and parallel transports. Let $X \in \mathfrak{X}(M)$ be a vector field on an affine manifold (M,∇). Let $C : TM \times_M TM \to T^2M$ be the linear connection for the covariant derivative ∇, see (13.7). The *horizontal lift of the vector field X* is then given by $C(X, \quad) \in \mathfrak{X}(TM)$ which is π_M-related to X: $T(\pi_M) \circ C(X, \quad) = X \circ \pi_M$. A flow line $\operatorname{Fl}_t^{C(X, \quad)}(Y_x)$ is then a smooth curve in TM whose tangent vector is everywhere horizontal, so the curve is parallel, and $\pi_M(\operatorname{Fl}_t^{C(X, \quad)}(Y_x)) = \operatorname{Fl}_t^X(x)$ by (3.14). Thus

$$\operatorname{Pt}(\operatorname{Fl}^X, t) = \operatorname{Fl}_t^{C(X, \quad)} \tag{1}$$

Proposition. *For vector fields $X, Y \in \mathfrak{X}(M)$ we have:*

$$\begin{aligned} \nabla_X Y &= \tfrac{\partial}{\partial t}\big|_0 (\operatorname{Fl}_{-t}^{C(X, \quad)} \circ Y \circ \operatorname{Fl}_t^X) = \tfrac{\partial}{\partial t}\big|_0 \operatorname{Pt}(\operatorname{Fl}^X, -t) \circ Y \circ \operatorname{Fl}_t^X \\ &=: \tfrac{\partial}{\partial t}\big|_0 \operatorname{Pt}(\operatorname{Fl}^X, t)^* Y. \end{aligned} \tag{2}$$

$$\begin{aligned} \tfrac{\partial}{\partial t} \operatorname{Pt}(\operatorname{Fl}^X, -t) \circ Y \circ \operatorname{Fl}_t^X &= \tfrac{\partial}{\partial t} \operatorname{Pt}(\operatorname{Fl}^X, t)^* Y = \operatorname{Pt}(\operatorname{Fl}^X, t)^* \nabla_X Y \\ &= \operatorname{Pt}(\operatorname{Fl}^X, -t) \circ \nabla_X Y \circ \operatorname{Fl}_t^X = \nabla_X(\operatorname{Pt}(\operatorname{Fl}^X, t)^* Y) \end{aligned} \tag{3}$$

(4) *The local vector bundle isomorphism* $\operatorname{Pt}(\operatorname{Fl}^X, t)$ *over* Fl_t^X *induces vector bundle isomorphisms* $\operatorname{Pt}^{\otimes}(\operatorname{Fl}^X, t)$ *on all tensor bundles* $\bigotimes^p TM \otimes \bigotimes^q T^*M$ *over* Fl_t^X. *For*

each tensor field A we have

(2') $$\nabla_X A = \tfrac{\partial}{\partial t}\big|_0 \operatorname{Pt}^\otimes(\operatorname{Fl}^X, -t)\circ A\circ \operatorname{Fl}^X_t = \tfrac{\partial}{\partial t}\big|_0 \operatorname{Pt}^\otimes(\operatorname{Fl}^X, t)^* A.$$

(3') $$\tfrac{\partial}{\partial t}\operatorname{Pt}^\otimes(\operatorname{Fl}^X, t)^* A = \operatorname{Pt}^\otimes(\operatorname{Fl}^X, t)^*\nabla_X A = \operatorname{Pt}(\operatorname{Fl}^X, -t)\circ \nabla_X A\circ \operatorname{Fl}^X_t$$
$$= \nabla_X(\operatorname{Pt}^\otimes(\operatorname{Fl}^X, t)^* A).$$

Proof. (2) We compute

$$\begin{aligned}
&\tfrac{\partial}{\partial t}\big|_0 \operatorname{Fl}^{C(X,\ \ )}_{-t}(Y(\operatorname{Fl}^X_t(x))) = \\
&\quad = -C\left(X, \operatorname{Fl}^{C(X,\ \ )}_0(Y(\operatorname{Fl}^X_0(x)))\right) + T(\operatorname{Fl}^{C(X,\ \ )}_0)\ \tfrac{\partial}{\partial t}\big|_0 (Y(\operatorname{Fl}^X_t(x)))\\
&\quad = -C(X(x), Y(x)) + TY.X(x)\\
&\quad = TY.X(x) - C(T(\pi_M).TY.X(x), \pi_{TM}(TY.X(x)))\\
&\quad = (\operatorname{Id}_{T^2M} - \text{horizontal Projection})TY.X(x)\\
&\quad = \operatorname{vl}(Y(x), K.TY.X(x)) = \operatorname{vl}(Y(x), (\nabla_X Y)(x)).
\end{aligned}$$

The vertical lift disappears if we identify the tangent space to the fiber T_xM with the fiber.

(3) We did this several times already, see (3.13), (6.16), and (7.6).

$$\begin{aligned}
\tfrac{\partial}{\partial t}\operatorname{Pt}(\operatorname{Fl}^X, t)^* Y &= \tfrac{\partial}{\partial s}|_0 \left(\operatorname{Pt}(\operatorname{Fl}^X, -t)\circ \operatorname{Pt}(\operatorname{Fl}^X, -s)\circ Y\circ \operatorname{Fl}^X_s\circ \operatorname{Fl}^X_t\right)\\
&= \operatorname{Pt}(\operatorname{Fl}^X, -t)\circ \tfrac{\partial}{\partial s}|_0 \left(\operatorname{Pt}(\operatorname{Fl}^X, -s)\circ Y\circ \operatorname{Fl}^X_s\right)\circ \operatorname{Fl}^X_t\\
&= \operatorname{Pt}(\operatorname{Fl}^X, -t)\circ (\nabla_X Y)\circ \operatorname{Fl}^X_t = \operatorname{Pt}(\operatorname{Fl}^X, t)^*\nabla_X Y.\\
\tfrac{\partial}{\partial t}\operatorname{Pt}(\operatorname{Fl}^X, t)^* Y &= \tfrac{\partial}{\partial s}|_0 \operatorname{Pt}(\operatorname{Fl}^X, s)^* \operatorname{Pt}(\operatorname{Fl}^X, t)^* Y = \nabla_X(\operatorname{Pt}(\operatorname{Fl}^X, t)^* Y).
\end{aligned}$$

(4) For a tensor A with foot point $\operatorname{Fl}^X_t(x)$ let us define $\operatorname{Pt}^\otimes(\operatorname{Fl}^X, t)^* A$ with foot point x by

$$\begin{aligned}
&(\operatorname{Pt}^\otimes(\operatorname{Fl}^X, t)A)(X_1, \dots, X_q, \omega^1, \dots, \omega^p) =\\
&\quad = A(\operatorname{Pt}(\operatorname{Fl}^X, t)X_1, \dots, \operatorname{Pt}(\operatorname{Fl}^X, t)X_q, \operatorname{Pt}(\operatorname{Fl}^X, -t)^*\omega^1, \dots, \operatorname{Pt}(\operatorname{Fl}^X, -t)^*\omega^p).
\end{aligned}$$

Thus $\operatorname{Pt}^\otimes(\operatorname{Fl}^X, t)$ is fiberwise an algebra homomorphism of the tensor algebra which commutes with all contractions. Thus $\frac{\partial}{\partial t}\big|_0 \operatorname{Pt}^\otimes(\operatorname{Fl}^X, t)^*$ becomes a derivation on the algebra of all tensor fields which commutes with contractions and equals ∇_X on vector fields. Thus by (13.12) it coincides with ∇_X on all tensor fields. This implies (2').

(3') can be proved in the same way as (3). □

15.3. Curvature. Let (M, ∇) be an affine manifold. The *curvature of the covariant derivative* ∇ is given by

(1) $$\begin{aligned}
R(X,Y)Z &= \nabla_X\nabla_Y Z - \nabla_Y\nabla_X Z - \nabla_{[X,Y]}Z\\
&= ([\nabla_X, \nabla_Y] - \nabla_{[X,Y]})Z, \quad \text{for} \quad X, Y, Z \in \mathfrak{X}(M).
\end{aligned}$$

A straightforward computation shows that $R(X,Y)Z$ is $C^\infty(M)$-linear in each entry, thus R is a $\binom{1}{3}$-tensor field on M.

In a local chart (U,u) we have (where $\partial_i = \frac{\partial}{\partial u^i}$):

$$\begin{aligned}
X|_U &= \sum X^i\,\partial_i, \qquad Y|_U = \sum Y^j\,\partial_j, \qquad Z|_U = \sum Z^k\,\partial_k,\\
R(X,Y)(Z)|_U &= \sum X^iY^jZ^kR(\partial_i,\partial_j)(\partial_k)\\
&=: \Big(\sum R^l_{i,j,k}\,du^i\otimes du^j\otimes du^k\otimes\partial_l\Big)(X,Y,Z)\\
\sum R^l_{i,j,k}\,\partial_l &= R(\partial_i,\partial_j)(\partial_k) = \nabla_{\partial_i}\nabla_{\partial_j}\partial_k - \nabla_{\partial_j}\nabla_{\partial_i}\partial_k - 0\\
&= \nabla_{\partial_i}(-\sum\Gamma^m_{j,k}\,\partial_m) - \nabla_{\partial_j}(-\sum\Gamma^m_{i,k}\,\partial_m)\\
&= -\sum\partial_i\,\Gamma^m_{j,k}\,\partial_m - \sum\Gamma^m_{j,k}\nabla_{\partial_i}\partial_m + \sum\partial_j\,\Gamma^m_{i,k}\,\partial_m + \sum\Gamma^m_{i,k}\nabla_{\partial_j}\partial_m\\
&= -\sum\partial_i\,\Gamma^l_{j,k}\,\partial_l + \sum\Gamma^m_{j,k}\Gamma^l_{i,m}\,\partial_l + \sum\partial_j\,\Gamma^l_{i,k}\,\partial_l - \sum\Gamma^m_{i,k}\Gamma^l_{j,m}\,\partial_l
\end{aligned}$$

We can collect all local formulas here, also from (13.9.7) or (13.5.6), and (13.4.2) in the case of a Levi Civita connection (where $X = (x,\bar X)$, etc.):

(2)
$$\begin{aligned}
\nabla_{\partial_i}\partial_j &= -\sum\Gamma^l_{i,j}, \quad \Gamma^k_{ij} = \tfrac12\sum g^{kl}(\partial_l\,g_{ij} - \partial_i\,g_{lj} - \partial_j\,g_{il}),\\
R^l_{i,j,k} &= -\partial_i\,\Gamma^l_{j,k} + \partial_j\,\Gamma^l_{i,k} + \sum\Gamma^m_{j,k}\Gamma^l_{i,m} - \sum\Gamma^m_{i,k}\Gamma^l_{j,m},\\
\bar R(\bar X,\bar Y)\bar Z &= -d\Gamma(x)(\bar X)(\bar Y,\bar Z) + d\Gamma(x)(\bar Y)(\bar X,\bar Z) +\\
&\quad + \Gamma_x(\bar X,\Gamma_x(\bar Y,\bar Z)) - \Gamma_x(\bar Y,\Gamma_x(\bar X,\bar Z))
\end{aligned}$$

15.4. Theorem. *Let ∇ be a covariant derivative on a manifold M, with torsion* Tor*, see* (13.10)*. Then the curvature R has the following properties, where $X,Y,Z,U \in \mathfrak{X}(M)$.*

(1) $$R(X,Y)Z = -R(Y,X)Z$$

(2) $$\sum_{\text{cyclic}} R(X,Y)Z = \sum_{cyclic}\Big((\nabla_X\operatorname{Tor})(Y,Z) + \operatorname{Tor}(\operatorname{Tor}(X,Y),Z)\Big)$$

Algebraic Bianchi identity.

(3)
$$\sum_{\text{cyclic}}\Big((\nabla_XR)(Y,Z) + R(\operatorname{Tor}(X,Y),Z)\Big) = 0 \quad \textit{Bianchi identity.}$$

If the connection ∇ is torsionfree, we have

(2') $$\sum_{\text{cyclic}} R(X,Y)Z = 0 \qquad \textit{Algebraic Bianchi identity.}$$

(3') $$\sum_{\substack{\text{cyclic}\\ X,Y,Z}} (\nabla_XR)(Y,Z) = 0 \qquad \textit{Bianchi identity.}$$

If ∇ is the (torsionfree) Levi Civita connection of a pseudo Riemann metric g, then we have moreover:

(4) $$g(R(X,Y)Z,U) = g(R(Z,U)X,Y)$$

(5) $$g(R(X,Y)Z,U) = -g(R(X,Y)U,Z)$$

Proof. (2) The extension of ∇_X to tensor fields was treated in (13.12):

(6) $$(\nabla_X \operatorname{Tor})(Y,Z) = \nabla_X(\operatorname{Tor}(Y,Z)) - \operatorname{Tor}(\nabla_X Y, Z) - \operatorname{Tor}(Y, \nabla_X Z).$$

From the definition (13.10.1) of the torsion:

$$\begin{aligned}\operatorname{Tor}(\operatorname{Tor}(X,Y),Z) &= \operatorname{Tor}(\nabla_X Y - \nabla_Y X - [X,Y], Z)\\ &= \operatorname{Tor}(\nabla_X Y, Z) + \operatorname{Tor}(Z, \nabla_Y X) - \operatorname{Tor}([X,Y],Z)\end{aligned}$$

These combine to

$$\sum_{\text{cyclic}} \operatorname{Tor}(\operatorname{Tor}(X,Y),Z) = \sum_{\text{cyclic}} \Big(\nabla_X(\operatorname{Tor}(Y,Z)) - (\nabla_X \operatorname{Tor})(Y,Z) - \operatorname{Tor}([X,Y],Z)\Big)$$

and then

$$\begin{aligned}\sum_{\text{cyclic}} \Big((\nabla_X \operatorname{Tor})(Y,Z) + \operatorname{Tor}(\operatorname{Tor}(X,Y),Z)\Big) &= \sum_{\text{cyclic}} \Big(\nabla_X(\operatorname{Tor}(Y,Z)) - \operatorname{Tor}([X,Y],Z)\Big)\\ = \sum_{\text{cyclic}} \Big(\nabla_X\nabla_Y Z - \nabla_X\nabla_Z Y - \nabla_X[Y,Z] - \nabla_{[X,Y]}Z + \nabla_Z[X,Y] + [[X,Y],Z]\Big)&\\ = \sum_{\text{cyclic}} \Big(\nabla_X\nabla_Y Z - \nabla_X\nabla_Z Y - \nabla_{[X,Y]}Z\Big) = \sum_{\text{cyclic}} R(X,Y)Z.&\end{aligned}$$

(3) We have

$$\begin{aligned}\sum_{\text{cyclic}} R(\operatorname{Tor}(X,Y),Z) &= \sum_{\text{cyclic}} R(\nabla_X Y - \nabla_Y X - [X,Y], Z)\\ &= \sum_{\text{cyclic}} \Big(R(\nabla_X Y, Z) + R(Z, \nabla_Y X) - R([X,Y],Z)\Big)\end{aligned}$$

and

$$\sum_{\text{cyclic}} (\nabla_X R)(Y,Z) = \sum_{\text{cyclic}} \Big(\nabla_X R(Y,Z) - R(\nabla_X Y, Z) - R(Y, \nabla_X Z) - R(Y,Z)\nabla_X\Big)$$

which combines to

$$\begin{aligned}\sum_{\text{cyclic}} \Big((\nabla_X R)(Y,Z) + R(\operatorname{Tor}(X,Y),Z)\Big) &=\\ = \sum_{\text{cyclic}} \Big(\nabla_X R(Y,Z) - R(Y,Z)\nabla_X - R([X,Y],Z)\Big)&\\ = \sum_{\text{cyclic}} \Big(\nabla_X\nabla_Y\nabla_Z - \nabla_X\nabla_Z\nabla_Y - \nabla_X\nabla_{[Y,Z]}&\\ - \nabla_Y\nabla_Z\nabla_X + \nabla_Z\nabla_Y\nabla_X + \nabla_{[Y,Z]}\nabla_X&\\ - \nabla_{[X,Y]}\nabla_Z + \nabla_Z\nabla_{[X,Y]} + \nabla_{[[X,Y],Z]}\Big) = 0.&\end{aligned}$$

(5) It suffices to prove $g(R(X,Y)Z,Z)=0$.

$$\begin{aligned}
0 &= \mathcal{L}_0(g(Z,Z)) = (XY - YX - [X,Y])g(Z,Z) \\
&= 2Xg(\nabla_Y Z, Z) - 2Yg(\nabla_X Z, Z) - 2g(\nabla_{[X,Y]}Z, Z) \\
&= 2g(\nabla_X\nabla_Y Z, Z) + 2g(\nabla_Y Z, \nabla_X Z) \\
&\quad - 2g(\nabla_Y\nabla_X Z, Z) - 2g(\nabla_X Z, \nabla_Y Z) - 2g(\nabla_{[X,Y]}Z, Z) \\
&= 2g((\nabla_X\nabla_Y - \nabla_Y\nabla_X - \nabla_{[X,Y]})Z, Z) = 2g(R(X,Y)Z,Z).
\end{aligned}$$

(4) is an algebraic consequence of (1), (2'), and (5). Take (2') four times, cyclically permuted, with different signs:

$$\begin{aligned}
g(R(X,Y)Z,U) + g(R(Y,Z)X,U) + g(R(Z,X)Y,U) &= 0 \\
g(R(Y,Z)U,X) + g(R(Z,U)Y,X) + g(R(U,Y)Z,X) &= 0 \\
-g(R(Z,U)X,Y) - g(R(U,X)Z,Y) - g(R(X,Z)U,Y) &= 0 \\
-g(R(U,X)Y,Z) - g(R(X,Y)U,Z) - g(R(Y,U)X,Z) &= 0
\end{aligned}$$

Add these:

$$2g(R(X,Y)Z,U) - 2g(R(Z,U)X,Y) = 0. \quad \square$$

15.5. Theorem. *Let $K : TTM \to TM$ be the connector of the covariant derivative ∇ on M. If $s : N \to TM$ is a vector field along $f := \pi_M \circ s : N \to M$ then we have for vector fields X, $Y \in \mathfrak{X}(N)$*

$$\begin{aligned}
\nabla_X\nabla_Y s - \nabla_Y\nabla_X s - \nabla_{[X,Y]}s &= \\
&= (K \circ TK \circ \kappa_{TM} - K \circ TK) \circ TTs \circ TX \circ Y = \\
&= R \circ (Tf \circ X, Tf \circ Y)s : N \to TM,
\end{aligned}$$

where $R \in \Omega^2(M; L(TM,TM))$ is the curvature.

Proof. Recall from (13.9) that $\nabla_X s = K \circ Ts \circ X$. For $A, B \in T_Z(TM)$ we have

$$\begin{aligned}
\mathrm{vl}_{TM}(K(A),K(B)) &= \partial_t|_0(K(A) + tK(B)) = \partial_t|_0 K(A+tB) = \\
&= TK \circ \partial_t|_0(A+tB) = TK \circ \mathrm{vl}_{(TTM,\pi_{TM},TM)}(A,B).
\end{aligned}$$

We use then (13.8.9) and some obvious commutation relations

$$\begin{aligned}
&\nabla_X\nabla_Y s - \nabla_Y\nabla_X s - \nabla_{[X,Y]}s = \\
&\quad = K \circ T(K \circ Ts \circ Y) \circ X - K \circ T(K \circ Ts \circ X) \circ Y - K \circ Ts \circ [X,Y] \\
&K \circ Ts \circ [X,Y] = K \circ \mathrm{vl}_{TM} \circ (K \circ Ts \circ Y, K \circ Ts \circ [X,Y]) \quad \text{by (13.8.9)} \\
&\quad = K \circ TK \circ \mathrm{vl}_{TTM} \circ (Ts \circ Y, Ts \circ [X,Y]) \\
&\quad = K \circ TK \circ TTs \circ \mathrm{vl}_{TN} \circ (Y, [X,Y]) \\
&\quad = K \circ TK \circ TTs \circ (TY \circ X - \kappa_N \circ TX \circ Y) \quad \text{by (6.14)} \\
&\quad = K \circ TK \circ TTs \circ TY \circ X - K \circ TK \circ TTs \circ \kappa_N \circ TX \circ Y.
\end{aligned}$$

Now we sum up and use $TTs \circ \kappa_N = \kappa_{TM} \circ TTs$ to get the first result. If in particular we choose $f = \mathrm{Id}_M$ so that X, Y, s are vector fields on M then we get the curvature R.

To see that in the general case $(K \circ TK \circ \kappa_E - K \circ TK) \circ TTs \circ TX \circ Y$ coincides with $R(Tf \circ X, Tf \circ Y)s$ we have to write out $(TTs \circ TX \circ Y)(x) \in TTTM$ in canonical charts induced from charts of N and M. There we have $X(x) = (x, \bar X(x))$, $Y(x) = (x, \bar Y(x))$, and $s(x) = (f(x), \bar s(x))$.

$$\begin{aligned}
&(TTs \circ TX \circ Y)(x) = TTs(x, \bar X(x); \bar Y(x), d\bar X(x)\bar Y(x)) = \\
(1)\qquad &= \Big(f(x), \bar s(x), df(x).\bar X(x), d\bar s(x).\bar X(x); df(x).\bar Y(x), d\bar s(x).\bar Y(x), \\
&\qquad d^2 f(x)(\bar Y(x), \bar X(x)) + df(x).d\bar X(x).\bar Y(x), \\
&\qquad d^2 \bar s(x)(\bar Y(x), \bar X(x)) + d\bar s(x).d\bar X(x).\bar Y(x)\Big)
\end{aligned}$$

Recall (13.8.7) which said $K(x, y; a, b) = (x, b - \Gamma_x(a, y))$. Differentiating this we get

$$\begin{aligned}
&TK(x, y, a, b; \xi, \eta, \alpha, \beta) = \\
&\qquad = \Big(x, b - \Gamma_x(a, y); \xi, \beta - d\Gamma(x)(\xi)(a, y) - \Gamma_x(\alpha, y) - \Gamma_x(a, \eta)\Big)
\end{aligned}$$

Thus

$$\begin{aligned}
&(K \circ TK \circ \kappa_{TM} - K \circ TK)(x, y, a, b; \xi, \eta, \alpha, \beta) = \\
&\qquad = (K \circ TK)(x, y, \xi, \eta; a, b, \alpha, \beta) - (K \circ TK)(x, y, a, b; \xi, \eta, \alpha, \beta) \\
&\qquad = K\big(x, \eta - \Gamma_x(\xi, y); a, \beta - d\Gamma(x)(a)(\xi, y) - \Gamma_x(\alpha, y) - \Gamma_x(\xi, b)\big) \\
&\qquad\quad - K\big(x, b - \Gamma_x(a, y); \xi, \beta - d\Gamma(x)(\xi)(a, y) - \Gamma_x(\alpha, y) - \Gamma_x(a, \eta)\big) \\
(2)\qquad &\qquad = \big(x, -d\Gamma(x)(a)(\xi, y) + d\Gamma(x)(\xi)(a, y) + \Gamma_x(a, \Gamma_x(\xi, y)) - \Gamma_x(\xi, \Gamma_x(a, y))\big)\ .
\end{aligned}$$

Now we insert (1) into (2) and get

$$(K \circ TK \circ \kappa_{TM} - K \circ TK) \circ TTs \circ TX \circ Y = R \circ (Tf \circ X, Tf \circ Y)s. \quad \square$$

15.6. Curvature and integrability of the horizontal bundle. What is it that the curvature is measuring? We give several answers, one of them is the following, which is intimately related to (19.13), (20.4), (22.2).

Let $C : TM \times_M TM \to T^2M$ be the linear connection corresponding to a covariant derivative ∇. For $X \in \mathfrak{X}(M)$ we denoted by $C(X, \quad) \in \mathfrak{X}(TM)$ the horizontal lift of the vector field X.

Lemma. *In this situation we have for $X, Y \in \mathfrak{X}(M)$ and $Z \in TM$*

$$[C(X, \quad), C(Y, \quad)](Z) - C([X, Y], Z) = -\operatorname{vl}(Z, R(X, Y)Z).$$

Proof. We compute locally, in charts induced by a chart (U,u) on M. A global proof can be found in (20.4) for general fiber bundles, and in (22.2) for principal fiber bundles, see also (22.16). Writing $X(x)=(x,\bar X(x))$, $Y(x)=(x,\bar Y(x))$, and $Z=(x,\bar Z)$, we have

$$\begin{aligned}
&C(X,Z)=(x,\bar Z;\bar X(x),\Gamma_x(\bar X(x),\bar Z)),\\
&C(Y,Z)=(x,\bar Z;\bar Y(x),\Gamma_x(\bar Y(x),\bar Z)),\\
&[C(X,\quad),C(Y,\quad)](Z)=\\
&=\big(x,\bar Z;d\bar Y(x).\bar X(x),d\Gamma(x)(\bar X(x))(\bar Y(x),\bar Z)+\Gamma_x(d\bar Y(x).\bar X(x),\bar Z)+\\
&\qquad\qquad\qquad\qquad\qquad\qquad+\Gamma_x(\bar Y(x),\Gamma_x(\bar X(x),\bar Z))\big)\\
&\quad-\big(x,\bar Z;d\bar X(x).\bar Y(x),d\Gamma(x)(\bar Y(x))(\bar X(x),\bar Z)+\Gamma_x(d\bar X(x).\bar Y(x),\bar Z)+\\
&\qquad\qquad\qquad\qquad\qquad\qquad+\Gamma_x(\bar X(x),\Gamma_x(\bar Y(x),\bar Z))\big)\\
&=\big(x,\bar Z;d\bar Y(x).\bar X(x),-d\bar X(x).\bar Y(x),\\
&\qquad\quad\Gamma_x(d\bar Y(x).\bar X(x)-d\bar X(x).\bar Y(x),\bar Z)+\\
&\qquad\quad+d\Gamma(x)(\bar X(x))(\bar Y(x),\bar Z)-d\Gamma(x)(\bar Y(x))(\bar X(x),\bar Z)+\\
&\qquad\quad+\Gamma_x(\bar Y(x),\Gamma_x(\bar X(x),\bar Z))-\Gamma_x(\bar X(x),\Gamma_x(\bar Y(x),\bar Z))\big)\\
&=\big(x,\bar Z;\overline{[X,Y]}(x),\Gamma_x(\overline{[X,Y]}(x),\bar Z)\big)+\\
&\quad+\big(x,\bar Z;0,+d\Gamma(x)(\bar X(x))(\bar Y(x),\bar Z)-d\Gamma(x)(\bar Y(x))(\bar X(x),\bar Z)+\\
&\qquad\quad+\Gamma_x(\bar Y(x),\Gamma_x(\bar X(x),\bar Z))-\Gamma_x(\bar X(x),\Gamma_x(\bar Y(x),\bar Z))\big)\\
&=C([X,Y],Z)+\operatorname{vl}(Z,-R(X(x),Y(x))Z),\quad\text{by (15.3.2)}.\quad\square
\end{aligned}$$

The horizontal lift $C(X,\quad)$ is a section of the horizontal bundle $C(TM,\quad)\subset T(TM)$, and any section is of that form. If the curvature vanishes, then by the theorem of Frobenius (3.20) the horizontal bundle is integrable and we get the leaves of the horizontal foliation.

Lemma. *Let M be a manifold and let ∇ be a flat covariant derivative on M (with vanishing curvature). Let $H\subset TM$ be a leaf of the horizontal foliation. Then $\pi_M|_H:H\to M$ is a covering map.*

Proof. Since $T(\pi_M|_H)=T(\pi_M)|C(TM,\quad)$ is fiberwise a linear isomorphism, $\pi_M:H\to M$ is a local diffeomorphism. Let $x\in M$, let $(U,u:U\to u(U)=\mathbb R^m)$ be a chart of M centered at x and let $X\in(\pi_M|_H)^{-1}(x)$. Consider $s:U\to H$ given by $s(u^{-1}(z))=\operatorname{Pt}(u^{-1}(t\mapsto t.z),1).X$. Then $\pi_M\circ s=\operatorname{Id}_U$ and $s(U)\subset H$ is diffeomorphic to U, the branch of H through X over U. Since $X\in(\pi_M|_H)^{-1}(x)$ was arbitrary, the set $(\pi_M|_H)^{-1}(U)$ is the disjoint union of open subsets which are all diffeomorphic via π_M to U. Thus $\pi_M:H\to M$ is a covering map. $\square$

15.7. Theorem. *Let (M,g) be a pseudo Riemann manifold with vanishing curvature. Then M is locally isometric to $\mathbb R^m$ with the standard inner product of the same signature: For each $x\in M$ there exists a chart (U,u) centered at x such that $g|U=u^*\langle\quad,\quad\rangle$.*

Proof. Choose an orthonormal basis $X_1(x), \dots, X_m(x)$ of (T_xM, g_x); this means $g_x(X_i(x), X_j(x)) = \eta_{ii}\delta_{ij}$, where $\eta = \operatorname{diag}(1, \dots, 1, -1, \dots, -1)$ is the standard inner product of signature (p, q). Since the curvature R vanishes we may consider the horizontal foliation of (15.6). Let H_i denote the horizontal leaf through $X_i(x)$ and define $X_i : U \to TM$ by $X_i = (\pi_M|_{H_i})^{-1} : U \to H_i \subset TM$, where U is a suitable (simply connected) neighborhood of x in M. Since $X_i \circ c$ is horizontal in TM for any curve c in U, we have $\nabla_X X_i = 0$ for any $X \in \mathfrak{X}(M)$ for the Levi-Civita covariant derivative of g. Vector fields X_i with this property are called *Killing fields*. Moreover $X(g(X_i, X_j)) = g(\nabla_X X_i, X_j) + g(X_i, \nabla_X X_j) = 0$, thus $g(X_i, X_j) =$ constant $= g(X_i(x), X_j(x)) = \eta_{ii}\delta_{ij}$ and $X_i, \dots, X_j$ is an orthonormal frame on U. Since ∇ has no torsion we have

$$0 = \operatorname{Tor}(X_i, X_j) = \nabla_{X_i} X_j - \nabla_{X_j} X_i - [X_i, X_j] = [X_i, X_j].$$

By theorem (3.17) there exists a chart (U, u) on M centered at x such that $X_i = \frac{\partial}{\partial u^i}$, i.e. $Tu.X_i(x) = (u(x), e_i)$ for the standard basis e_i of $\mathbb{R}^m$. Thus Tu maps an orthonormal frame on U to an orthonormal frame on $u(U) \in \mathbb{R}^m$, and u is an isometry. □

15.8. Sectional curvature. Let (M, g) be a Riemann manifold, let $P_x \subset T_xM$ be a 2-dimensional linear subspace of T_xM, and let X_x, Y_x be an orthonormal basis of P_x. Then the number

$$k(P_x) := -g(R(X_x, Y_x)X_x, Y_x) \tag{1}$$

is called the *sectional curvature* of this subspace. That $k(P_x)$ does not depend on the choice of the orthonormal basis is shown by the following lemma.

For pseudo Riemann manifolds one can define the sectional curvature only for those subspaces P_x on which g_x is non-degenerate. This notion is rarely used in general relativity.

Lemma.

(2) *Let $A = (A^i_j)$ be a real (2×2)-matrix and $X_1, X_2 \in T_xM$. Then for $X'_i = A^1_i X_1 + A^2_i X_2$ we have $g(R(X'_1, X'_2)X'_1, X'_2) = \det(A)^2\, g(R(X_1, X_2)X_1, X_2)$.*

(3) *Let X', Y' be linearly independent in $P_x \subset T_xM$ then*

$$k(P_x) = -\frac{g(R(X', Y')X', Y')}{|X'|^2|Y'|^2 - g(X', Y')^2}.$$

Proof. (2) Since $g(R(X_i, X_j)X_k, X_l) = 0$ for $i = j$ or $k = l$ we have

$$\begin{aligned} &g(R(X'_1, X'_2)X'_1, X'_2) = \sum A^i_1 A^j_2 A^k_1 A^l_2 g(R(X_i, X_j)X_k, X_l) \\ &= g(R(X_1, X_2)X_1, X_2)(A^1_1A^2_2A^1_1A^2_2 - A^1_1A^2_2A^2_1A^1_2 - A^2_1A^1_2A^1_1A^2_2 + A^2_1A^1_2A^2_1A^1_2) \\ &= g(R(X_1, X_2)X_1, X_2)(A^1_1A^2_2 - A^1_2A^2_1)^2. \quad \square \end{aligned}$$

(3) Let X, Y be an orthonormal basis of P_x, let $X' = A^1_1X + A^2_1Y$ and $Y' = A^1_2X + A^2_2Y$. Then $\det(A)^2$ equals the area^2 of the parallelogram spanned by X' and Y' which is $|X'|^2|Y'|^2 - g(X', Y')^2$. Now use (2). □

15.9. Computing the sectional curvature. *Let $g : U \to S^2(\mathbb{R}^m)$ be a pseudo-Riemannian metric in an open subset of $\mathbb{R}^m$. Then for $X, Y \in T_x\mathbb{R}^m$ we have:*

$$\begin{aligned}
&2R_x(X,Y,X,Y) = 2g_x(R_x(X,Y)X,Y) = \\
&= -2d^2g(x)(X,Y)(Y,X) + d^2g(x)(X,X)(Y,Y) + d^2g(x)(Y,Y)(X,X) \\
&\quad - 2g(\Gamma(Y,X),\Gamma(X,Y)) + 2g(\Gamma(X,X),\Gamma(Y,Y))
\end{aligned}$$

Proof. The Christoffels $\Gamma : U \times \mathbb{R}^m \times \mathbb{R}^m \to \mathbb{R}^m$ are given by (13.4.1)

$$(1) \qquad 2g_x(\Gamma_x(Y,Z),U) = dg(x)(U)(Y,Z) - dg(x)(Y)(Z,U) - dg(x)(Z)(U,Y).$$

and the curvature in terms of the Christoffels is (15.3.2)

$$\begin{aligned}
R(X,Y)Z &= (\nabla_X\nabla_Y - \nabla_Y\nabla_X - \nabla_{[X,Y]})Z \\
(2) \qquad &= -d\Gamma(X)(Y,Z) + d\Gamma(Y)(X,Z) + \Gamma(X,\Gamma(Y,Z)) - \Gamma(Y,\Gamma(X,Z)).
\end{aligned}$$

We differentiate (1) once more:

$$\begin{aligned}
&2dg(x)(X)(\Gamma_x(Y,Z),U) + 2g_x(d\Gamma(x)(X)(Y,Z),U) = \\
(3) \qquad &= +d^2g(x)(X,U)(Y,Z) - d^2g(x)(X,Y)(Z,U) - d^2g(x)(X,Z)(U,Y),
\end{aligned}$$

Let us compute the combination from (2), using (3):

$$\begin{aligned}
&- 2g_x(d\Gamma(x)(X)(Y,Z),U) + 2g_x(d\Gamma(x)(Y)(X,Z),U) \\
&= 2dg(x)(X)(\Gamma_x(Y,Z),U) - 2dg(x)(Y)(\Gamma_x(X,Z),U) \\
&\quad - d^2g(x)(X,U)(Y,Z) + d^2g(x)(X,Y)(Z,U) + d^2g(x)(X,Z)(U,Y) \\
&\quad + d^2g(x)(Y,U)(X,Z) - d^2g(x)(Y,X)(Z,U) - d^2g(x)(Y,Z)(U,X) \\
&= 2dg(x)(X)(\Gamma_x(Y,Z),U) - 2dg(x)(Y)(\Gamma_x(X,Z),U) \\
&\quad - d^2g(x)(X,U)(Y,Z) + d^2g(x)(X,Z)(U,Y) \\
&\quad + d^2g(x)(Y,U)(X,Z) - d^2g(x)(Y,Z)(U,X)
\end{aligned}$$

Thus we have

$$\begin{aligned}
&2R_x(X,Y,Z,U) := 2g_x(R_x(X,Y)Z,U) \\
&= 2g\Big(-d\Gamma(X)(Y,Z) + d\Gamma(Y)(X,Z) + \Gamma(X,\Gamma(Y,Z)) - \Gamma(Y,\Gamma(X,Z)),U\Big) \\
&= 2dg(x)(X)(\Gamma_x(Y,Z),U) - 2dg(x)(Y)(\Gamma_x(X,Z),U) \\
&\quad - d^2g(x)(X,U)(Y,Z) + d^2g(x)(X,Z)(U,Y) \\
&\quad + d^2g(x)(Y,U)(X,Z) - d^2g(x)(Y,Z)(U,X) \\
&\quad + 2g(\Gamma(X,\Gamma(Y,Z)),U) - 2g(\Gamma(Y,\Gamma(X,Z)),U)
\end{aligned}$$

and for the sectional curvature we get

$$\begin{aligned}
(4) \qquad &2R_x(X,Y,X,Y) = 2g_x(R_x(X,Y)X,Y) = \\
&= 2dg(x)(X)(\Gamma_x(Y,X),Y) - 2dg(x)(Y)(\Gamma_x(X,X),Y) \\
&\quad - 2d^2g(x)(X,Y)(Y,X) + d^2g(x)(X,X)(Y,Y) + d^2g(x)(Y,Y)(X,X) \\
&\quad + 2g(\Gamma(X,\Gamma(Y,X)),Y) - 2g(\Gamma(Y,\Gamma(X,X)),Y)
\end{aligned}$$

Let us check how skew-symmetric the Christoffels are. From (1) we get

$$\begin{aligned}
&2g_x(\Gamma_x(Y,Z),U) + 2g_x(Z,\Gamma_x(Y,U)) = 2g_x(\Gamma_x(Y,Z),U) + 2g_x(\Gamma_x(Y,U),Z)\\
&= +dg(x)(U)(Y,Z) - dg(x)(Y)(Z,U) - dg(x)(Z)(U,Y)\\
&\quad + dg(x)(Z)(Y,U) - dg(x)(Y)(U,Z) - dg(x)(U)(Z,Y)\\
&= -2dg(x)(Y)(Z,U).
\end{aligned}$$

Thus

$$2dg(x)(Y)(\Gamma(X,V),U) = -2g(\Gamma(Y,\Gamma(X,V)),U) - 2g(\Gamma(X,V),\Gamma(Y,U))$$

Using this in (4) we get finally

$$\begin{aligned}
(5)\quad & 2R_x(X,Y,X,Y) = 2g_x(R_x(X,Y)X,Y) =\\
&= -2g(\Gamma(X,\Gamma(Y,X)),Y) - 2g(\Gamma(Y,X),\Gamma(X,Y))\\
&\quad + 2g(\Gamma(Y,\Gamma(X,X)),Y) + 2g(\Gamma(X,X),\Gamma(Y,Y))\\
&\quad - 2d^2g(x)(X,Y)(Y,X) + d^2g(x)(X,X)(Y,Y) + d^2g(x)(Y,Y)(X,X)\\
&\quad + 2g(\Gamma(X,\Gamma(Y,X)),Y) - 2g(\Gamma(Y,\Gamma(X,X)),Y)\\
&= -2d^2g(x)(X,Y)(Y,X) + d^2g(x)(X,X)(Y,Y) + d^2g(x)(Y,Y)(X,X)\\
&\quad - 2g(\Gamma(Y,X),\Gamma(X,Y)) + 2g(\Gamma(X,X),\Gamma(Y,Y)) \quad \square
\end{aligned}$$

16. Computing with adapted frames, and examples

16.1. Frames. We recall that a *local frame* or *frame field* s on an open subset U of a pseudo Riemann manifold (M,g) of dimension m is an m-tuple $s_1,\dots,s_m$ of vector fields on U such that $s_1(x),\dots,s_m(x)$ is a basis of the tangent space T_xM for each $x\in U$. Note that then s is a local section of the linear frame bundle $GL(\mathbb{R}^m,TM)\to M$, a principal fiber bundle, as we treat it in (21.11). We view $s(x)=(s_1(x),\dots,s_m(x))$ as a linear isomorphism $s(x):\mathbb{R}^m\to T_xM$. The frame field s is called *orthonormal frame* if $s_1(x),\dots,s_m(x)$ is an orthonormal basis of (T_xM,g_x) for each $x\in U$. By this we mean that $g_x(X_i(x),X_j(x))=\eta_{ii}\delta_{ij}$, where $\eta=\operatorname{diag}(1,\dots,1,-1,\dots,-1)$ is the standard inner product of signature $(p,q=m-p)$.

If (U,u) is a chart on M then $\frac{\partial}{\partial u^1},\dots,\frac{\partial}{\partial u^m}$ is a frame field on U. Out of this we can easily build one which contains no isotropic vectors (i.e. ones with $g(X,X)=0$) and order them in such a way the fields with $g(X,X)>0$ are at the beginning. Using the Gram-Schmidt orthonormalization procedure we can change this frame field then into an orthonormal one on a possibly smaller open set U. Thus there exist always orthonormal frame fields.

If $s=(s_1,\dots,s_m)$ and $s'=(s'_1,\dots,s'_m)$ are two frame fields on $U,V\subset M$, respectively, then on $U\cap V$ we have

$$s'=s.h,\quad s'_i=\textstyle\sum_j s_jh^j_i,\quad s'_i(x)=\sum_j s_j(x)h^j_i(x),$$
$$h=(h^i_j):U\cap V\to GL(m,\mathbb{R}).$$

16.2. Connection forms. If s is a local frame on an open subset U in a manifold M, and if ∇ is a covariant derivative on M we put

$$(1)\qquad \nabla_X s_i = \sum_j s_j.\omega_i^j(X), \quad \nabla_X s = s.\omega(X), \quad \nabla s = s.\omega$$
$$\omega = (\omega_i^j) \in \Omega^1(U, \mathfrak{gl}(m)), \qquad \text{the connection form of } \nabla.$$

Proposition. *We have:*

(2) *If* $Y = \sum s_j u^j \in \mathfrak{X}(U)$ *then*

$$\nabla Y = \sum_k s_k(\sum_j \omega_j^k u^j + du^k) = s.\omega.u + s.du.$$

(3) *Let* s *and* $s' = s.h$ *be two local frames on* U *then the connection forms* $\omega, \omega' \in \Omega^1(U, \mathfrak{gl}(m))$, *are related by*

$$h.\omega' = dh + \omega.h$$

(4) *If* s *is a local orthonormal frame for a Riemann metric* g *which is respected by* ∇ *then*

$$\omega_i^j = -\omega_j^i, \quad \omega = (\omega_i^j) \in \Omega^1(U, \mathfrak{so}(m)).$$

If s *is a local orthonormal frame for a pseudo Riemann metric* g *which is respected by* ∇ *and if* $\eta_{ij} = g(s_i, s_j) = \operatorname{diag}(1, \dots, 1, -1, \dots, -1)$ *is the standard inner product matrix of the same signature* (p, q), *then*

$$\eta_{jj}\omega_i^j = -\eta_{ii}\omega_j^i, \quad \omega = (\omega_i^j) \in \Omega^1(U, \mathfrak{so}(p, q)).$$

Proof. (2)

$$\nabla_X Y = \nabla_X(\sum_j s_j u^j) = \sum_j(\nabla_X s_j)u^j + \sum_j s_j X(u^j)$$
$$= \sum_k s_k \sum_j \omega_j^k(X)u^j + \sum_k s_k du^k(X).$$

(3)

$$\nabla s' = s'.\omega' = s.h.\omega'$$
$$\nabla s' = \nabla(s.h) = (\nabla s).h + s.dh = s.\omega.h + s.dh.$$

(4) It suffices to prove the second assertion. We differentiate the constant $\eta_{ij} = g(s_i, s_j)$

$$0 = X(g(s_i, s_j)) = g(\nabla_X s_i, s_j) + g(s_i, \nabla_X s_j)$$
$$= g(\sum s_k\omega_i^k(X), s_j) + g(s_i, \sum s_k\omega_j^k(X))$$
$$= \sum g(s_k, s_j)\omega_i^k(X) + \sum g(s_i, s_k)\omega_j^k(X) = \eta_{jj}\omega_i^j(X) + \eta_{ii}\omega_j^i(X). \quad \square$$

16.3. Curvature forms. Let s be a local frame on U, and let ∇ be a covariant derivative with curvature R. We put $R(X,Y)s = (R(X,Y)s_1, \dots, R(X,Y)s_m)$. Then we have

$$(1) \qquad Rs_j = \sum s_k.(d\omega_j^k + \sum \omega_l^k \wedge \omega_j^l), \quad Rs = s.(d\omega + \omega\wedge\omega),$$

where $\omega\wedge\omega = (\sum \omega_k^i \wedge \omega_j^k)_j^i \in \Omega^2(U, \mathfrak{gl}(m))$, since

$$\begin{aligned}
R(X,Y)s &= \nabla_X\nabla_Y s - \nabla_Y\nabla_X s - \nabla_{[X,Y]}s\\
&= \nabla_X(s.\omega(Y)) - \nabla_Y(s.\omega(X)) - s.\omega([X,Y])\\
&= s.X(\omega(Y)) + s.\omega(X).\omega(Y) - s.Y(\omega(X)) - s.\omega(Y).\omega(X) - s.\omega([X,Y])\\
&= s.\big(X(\omega(Y)) - Y(\omega(X)) - \omega([X,Y]) + \omega(X).\omega(Y) - \omega(Y).\omega(X)\big)\\
&= s.(d\omega + \omega\wedge\omega)(X,Y)
\end{aligned}$$

We thus get the *curvature matrix*

$$(2) \qquad \Omega = d\omega + \omega\wedge\omega \in \Omega^2(U, \mathfrak{gl}(m)),$$

and note its defining equation $R.s = s.\Omega$.

Proposition.

(3) *If s and $s' = s.h$ are two local frames, then the curvature matrices are related by*

$$h.\Omega' = \Omega.h.$$

(4) *The second Bianchi identity becomes*

$$d\Omega + \omega\wedge\Omega - \Omega\wedge\omega = 0.$$

(5) *If s is a local orthonormal frame for a Riemann metric g which is respected by ∇ then*

$$\Omega_i^j = -\Omega_j^i, \quad \Omega = (\Omega_i^j) \in \Omega^2(U, \mathfrak{so}(m)).$$

If s is a local orthonormal frame for a pseudo Riemann metric g which is respected by ∇ and if $\eta_{ij} = g(s_i, s_j) = \operatorname{diag}(1,\dots,1,-1,\dots,-1)$ is the standard inner product matrix of the same signature (p,q), then

$$\eta_{jj}\Omega_i^j = -\eta_{ii}\Omega_j^i, \quad \Omega = (\Omega_i^j) \in \Omega^2(U, \mathfrak{so}(p,q)).$$

Proof. (3) Since R is a tensor field, we have $s.h.\Omega' = s'.\Omega' = Rs' = Rs.h = s.\Omega.h$. A second, direct proof goes as follows. By (16.2.3) we have $h.\omega' = \omega.h + dh$, thus

$$\begin{aligned}
h.\Omega' &= h.(d\omega' + \omega'\wedge\omega')\\
&= h.d(h^{-1}.\omega.h + h^{-1}.dh) + (\omega.h + dh)\wedge(h^{-1}.\omega.h + h^{-1}.dh)\\
&= h.(-h^{-1}.dh.h)\wedge\omega.h + h.h^{-1}.d\omega.h - h.h^{-1}.\omega\wedge dh\\
&\quad + h.(-h^{-1}.dh.h^{-1})\wedge dh + h.h^{-1}.ddh\\
&\quad + \omega\wedge h.h^{-1}.\omega + \omega\wedge h.h^{-1}.dh + dh.h^{-1}\wedge\omega.h + dh.h^{-1}\wedge dh\\
&= d\omega.h + \omega\wedge\omega.h = \Omega.h.
\end{aligned}$$

(4) $d\Omega = d(d\omega + \omega\wedge\omega) = 0 + d\omega\wedge\omega - \omega\wedge d\omega = (d\omega+\omega\wedge\omega)\wedge\omega - \omega\wedge(d\omega+\omega\wedge\omega)$.

(5) We prove only the second case.

$$\begin{aligned}\eta_{jj}\Omega^j_i &= \eta_{jj}d\omega^j_i + \textstyle\sum_k \eta_{jj}\omega^j_k\wedge\omega^k_i = -\eta_{ii}d\omega^i_j - \sum_k \eta_{kk}\omega^k_j\wedge\omega^k_i \\ &= -\eta_{ii}d\omega^i_j + \textstyle\sum_k \eta_{ii}\omega^k_j\wedge\omega^i_k = -\eta_{ii}(d\omega^i_j + \sum_k \omega^i_k\wedge\omega^k_j) = -\eta_{ii}\Omega^i_j \quad \square\end{aligned}$$

16.4. Coframes. For a local frame $s = (s_1, \dots, s_m)$ on $U \subset M$ we consider the dual coframe

$$\sigma = \begin{pmatrix}\sigma^1\\ \vdots \\ \sigma^m\end{pmatrix}, \qquad \sigma^i \in \Omega^1(U),$$

which forms the dual basis of T^*_xM for each $x \in U$. We have $\langle\sigma^i, s_j\rangle = \sigma^i(s_j) = \delta^i_j$. If $s' = s.h$ is another local frame, then its *dual coframe* is given by

(1) $$\sigma' = h^{-1}.\sigma, \quad \sigma'^i = \textstyle\sum_k (h^{-1})^i_k\sigma^k,$$

since $\langle\sum_k (h^{-1})^i_k\sigma^k, s'_j\rangle = \sum_{k,l}(h^{-1})^i_k\,\langle\sigma^k, s_l\rangle\, h^l_j = \delta^i_j$.

Let s be a local frame on U, let ∇ be a covariant derivative. We define the *torsion form* Θ by

(2) $$\mathrm{Tor} = s.\Theta, \quad \mathrm{Tor}(X,Y) =: \textstyle\sum_j s_j\Theta^j(X,Y), \quad \Theta\in\Omega^2(U,\mathbb{R}^m).$$

Proposition.

(3) *If s and $s' = s.h$ are two local frames, then the torsion forms of a covariant derivative are related by*

$$\Theta' = h^{-1}.\Theta.$$

(4) *If s is a local frame with dual coframe σ, then for a covariant derivative with connection form $\omega \in \Omega^1(U, \mathfrak{gl}(m))$ and torsion form $\Theta \in \Omega^2(U,\mathbb{R}^m)$ we have*

$$d\sigma = -\omega\wedge\sigma + \Theta, \quad d\sigma^i = -\textstyle\sum_k \omega^i_k\wedge\sigma^k + \Theta^i.$$

(5) *The algebraic Bianchi identity for a covariant derivative takes the following form:*

$$d\Theta + \omega\wedge\Theta = \Omega\wedge\sigma, \quad d\Theta^k + \textstyle\sum_l \omega^k_l\wedge\Theta^l = \sum_l \Omega^k_l\wedge\sigma^l.$$

Proof. (3) Since Tor is a tensor field we have $s.\Theta = \mathrm{Tor} = s'\Theta' = s.h.\Theta'$, thus $h.\Theta' = \Theta$ and $\Theta' = h^{-1}.\Theta$.

(4) For $X \in \mathfrak{X}(U)$ we have $X = \sum_i s_i.\sigma^i(X)$, short $X = s.\sigma(X)$. Then

$$\begin{aligned}
\nabla_X Y &= \nabla_X(s.\sigma(Y)) = (\nabla_X s).\sigma(Y) + s.X(\sigma(Y)) \\
&= s.\omega(X).\sigma(Y) + s.X(\sigma(Y)) \\
s.\Theta(X,Y) &= \operatorname{Tor}(X,Y) = \nabla_X Y - \nabla_Y X - [X,Y] \\
&= s.\omega(X).\sigma(Y) + s.X(\sigma(Y)) - s.\omega(Y).\sigma(X) - s.Y(\sigma(X)) - s.\sigma([X,Y]) \\
&= s.(\omega(X).\sigma(Y) - \omega(Y).\sigma(X) + X(\sigma(Y)) - Y(\sigma(X)) - \sigma([X,Y])) \\
&= s.(\omega \wedge \sigma(X) + d\sigma)(X,Y).
\end{aligned}$$

Direct proof of (3):

$$\begin{aligned}
\Theta' &= \omega' \wedge \sigma' + d\sigma' = (h^{-1}.\omega.h + h^{-1}.dh) \wedge h^{-1}.\sigma + d(h^{-1}.\sigma) \\
&= h^{-1}.\omega \wedge \sigma + h^{-1}.dh \wedge h^{-1}.\sigma - h^{-1}.dh.h^{-1}.\sigma + h^{-1}.d\sigma \\
&= h^{-1}(\omega \wedge \sigma + d\sigma) = h^{-1}.\Theta.
\end{aligned}$$

(5)
$$\begin{aligned}
d\Theta &= d(\omega \wedge \sigma + d\sigma) = d\omega \wedge \sigma - \omega \wedge d\sigma + 0 \\
&= (d\omega + \omega \wedge \omega) \wedge \sigma - \omega \wedge (\omega \wedge \sigma + d\sigma) = \Omega \wedge \sigma - \omega \wedge \Theta. \quad \square
\end{aligned}$$

16.5. Collection of formulas. *Let (M,g) be a Riemann manifold, let s be an orthonormal local frame on U with dual coframe σ, and let ∇ be the Levi-Civita covariant derivative. Then we have:*

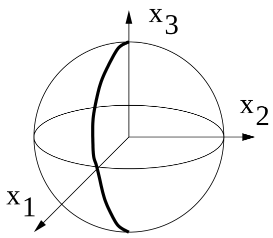
(1) $g|_U = \sum_i \sigma^i \otimes \sigma^i$.
(2) $\nabla s = s.\omega$, $\omega^i_j = -\omega^j_i$, *so* $\omega \in \Omega^1(U, \mathfrak{so}(m))$.
(3) $d\sigma + \omega \wedge \sigma = 0$, $d\sigma^i + \sum_k \omega^i_k \wedge \sigma^k = 0$.
(4) $Rs = s.\Omega$, $\Omega = d\omega + \omega \wedge \omega \in \Omega^2(U, \mathfrak{so}(m))$, $\Omega^i_j = d\omega^i_j + \sum_k \omega^i_k \wedge \omega^k_j$,
(5) $\Omega \wedge \sigma = 0$, $\sum_k \Omega^i_k \wedge \sigma^k = 0$, *the first Bianchi identity.*
(6) $d\Omega + \omega \wedge \Omega - \Omega \wedge \omega = d\Omega + [\omega, \Omega]_\wedge = 0$, *the second Bianchi identity.*

If (M,g) is a pseudo Riemann manifold, $\eta_{ij} = g(s_i, s_j) = \operatorname{diag}(1,\dots,1,-1,\dots,-1)$ the standard inner product matrix of the same signature (p,q), then we have instead:

(1') $g = \sum_i \eta_{ii}\sigma^i \otimes \sigma^i$.
(2') $\eta_{jj}\omega^j_i = -\eta_{ii}\omega^i_j$, *thus* $\omega = (\omega^j_i) \in \Omega^1(U, \mathfrak{so}(p,q))$.
(1') $\eta_{jj}\Omega^j_i = -\eta_{ii}\Omega^i_j$, *thus* $\Omega = (\Omega^j_i) \in \Omega^2(U, \mathfrak{so}(p,q))$.

16.6. Example: The sphere $S^2 \subset \mathbb{R}^3$. We consider the parameterization (leaving out one longitude):

$$\begin{aligned}
&f : (0, 2\pi) \times (-\pi, \pi) \to \mathbb{R}^3, \\
&f(\varphi, \theta) = \begin{pmatrix} \cos\varphi\ \cos\theta \\ \sin\varphi\ \cos\theta \\ \sin\theta \end{pmatrix} \\
&g = f^*(\text{metric}) = f^*(\textstyle\sum_i dx^i \otimes dx^i) \\
&\quad = \sum_{i=1}^3 df^i \otimes df^i = \cos^2\theta\ d\varphi \otimes d\varphi + d\theta \otimes d\theta.
\end{aligned}$$



From this we can read off the orthonormal coframe and then the orthonormal frame:

$$\sigma^1 = d\theta, \quad \sigma^2 = \cos\theta\, d\varphi, \qquad s_1 = \frac{\partial}{\partial\,\theta}, \quad s_2 = \frac{1}{\cos\theta}\frac{\partial}{\partial\,\varphi}.$$

We compute $d\sigma^1 = 0$ and $d\sigma^2 = -\sin\theta\ d\theta \wedge d\varphi = -\tan\theta\ \sigma^1 \wedge \sigma^2$. For the connection forms we have $\omega^1_1 = \omega^2_2 = 0$ by skew symmetry. The off-diagonal terms we compute from (16.5.3): $d\sigma + \omega \wedge \sigma = 0$.

$$\begin{aligned}
-d\sigma^1 &= 0 + \omega^1_2 \wedge \sigma^2 = 0, && \Rightarrow \omega^1_2 = c(\varphi,\theta)\sigma^2\\
-d\sigma^2 &= \omega^2_1 \wedge \sigma^1 + 0 = \tan\theta\, \sigma^1 \wedge \sigma^2, && \Rightarrow \omega^1_2 = \tan\theta\, \sigma^2 = \sin\theta\, d\varphi\\
\omega &= \begin{pmatrix} 0 & \sin\theta\, d\varphi \\ -\sin\theta\, d\varphi & 0 \end{pmatrix}
\end{aligned}$$

For the curvature forms we have again $\Omega^1_1 = \Omega^2_2 = 0$ by skew symmetry, and then we may compute the curvature:

$$\begin{aligned}
\Omega^1_2 &= d\omega^1_2 + \omega^1_1 \wedge \omega^1_2 + \omega^1_2 \wedge \omega^2_2 = d(\sin\theta\, d\varphi) = \cos\theta\, d\theta \wedge d\varphi = \sigma^1 \wedge \sigma^2\\
\Omega &= \begin{pmatrix} 0 & \sigma^1 \wedge \sigma^2 \\ -\sigma^1 \wedge \sigma^2 & 0 \end{pmatrix}
\end{aligned}$$

For the sectional curvature we get

$$\begin{aligned}
k(S^2) &= -g(R(s_1,s_2)s_1,s_2) = -g(\textstyle\sum_k s_k \Omega^k_1(s_1,s_2),s_2)\\
&= -g(s_2(-\sigma^1 \wedge \sigma^2)(s_1,s_2),s_2) = 1.
\end{aligned}$$

16.7. Example: The Poincaré upper half-plane. This is the set $H^2_+ = \{(x,y) \in \mathbb{R}^2 : y > 0\}$ with metric $ds^2 = \frac{1}{y^2}(dx^2 + dy^2)$ or

$$g = \frac{1}{y}dx \otimes \frac{1}{y}dx + \frac{1}{y}dy \otimes \frac{1}{y}dy),$$

which is conformal with the standard inner product.

The curvature. The orthonormal coframe and frame are then, by (16.5.1):

$$\sigma^1 = \frac{1}{y}dx, \quad \sigma^2 = \frac{1}{y}dy \qquad s_1 = y\frac{\partial}{\partial\,x}, \quad s_2 = y\frac{\partial}{\partial\,y}.$$

We have $d\sigma^1 = d(\frac{1}{y}dx) = \frac{1}{y^2}dx \wedge dy = \sigma^1 \wedge \sigma^2$ and $d\sigma^2 = 0$. The connection forms we compute from (16.5.3): $d\sigma + \omega \wedge \sigma = 0$.

$$\begin{aligned}
-d\sigma^1 &= 0 + \omega^1_2 \wedge \sigma^2 = -\sigma^1 \wedge \sigma^2,\\
-d\sigma^2 &= \omega^2_1 \wedge \sigma^1 + 0 = 0, \quad \Rightarrow \omega^1_2 = -\sigma^1 = -y^{-1}dx\\
\omega &= \begin{pmatrix} 0 & -\sigma^1 \\ \sigma^1 & 0 \end{pmatrix}
\end{aligned}$$

For the curvature forms we get

$$\begin{aligned}\Omega^1_2 &= d\omega^1_2 + \omega^1_1\wedge\omega^1_2 + \omega^1_2\wedge\omega^2_2 = d(-y^{-1}dx) = -\sigma^1\wedge\sigma^2\\ \Omega &= \begin{pmatrix} 0 & -\sigma^1\wedge\sigma^2\\ +\sigma^1\wedge\sigma^2 & 0\end{pmatrix}\end{aligned}$$

For the sectional curvature we get

$$\begin{aligned}k(H^2_+) &= -g(R(s_1,s_2)s_1,s_2) = -g(\textstyle\sum_k s_k\Omega^k_1(s_1,s_2),s_2)\\ &= -g(s_2(\sigma^1\wedge\sigma^2)(s_1,s_2),s_2) = -1.\end{aligned}$$

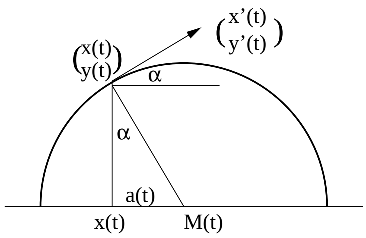
The geodesics. For deriving the geodesic equation let:

$$c(t) = \begin{pmatrix}x(t)\\ y(t)\end{pmatrix},\quad c'(t) = \begin{pmatrix}x'(t)\\ y'(t)\end{pmatrix} = \frac{x'}{y}y\frac{\partial}{\partial x} + \frac{y'}{y}y\frac{\partial}{\partial y} = \frac{x'}{y}s_1 + \frac{y'}{y}s_2 =: (s\circ c).u.$$

The geodesic equation is then

$$\begin{aligned}\nabla_{\partial_t}c' &= \nabla_{\partial_t}((s\circ c).u) = s.\omega(c').u + s.du(\partial_t)\\ &= (s_1,s_2)\begin{pmatrix}0 & \omega^1_2(c')\\ -\omega^1_2(c') & 0\end{pmatrix}\begin{pmatrix}\frac{x'}{y}\\ \frac{y'}{y}\end{pmatrix} + (s_1,s_2)\begin{pmatrix}(\frac{x'}{y})'\\ (\frac{y'}{y})'\end{pmatrix}\\ &= \frac{x'^2}{y}\frac{\partial}{\partial y} - \frac{x'y'}{y}\frac{\partial}{\partial x} + \frac{x''y - x'y'}{y}\frac{\partial}{\partial x} + \frac{y''y - y'^2}{y}\frac{\partial}{\partial y} = 0\\ &\begin{cases} x''y - 2x'y' = 0\\ x'^2 + y''y - y'^2 = 0\end{cases}\end{aligned}$$

To see the shape of the geodesics we first investigate $x(t) =$ constant. Then $y''y - y'^2 = 0$ has a unique solution for each initial value $y(0), y'(0)$, thus the verticals $t\mapsto\binom{\text{constant}}{y(t)}$ are geodesics. If $x'(t) = 0$ for a single t then for all t since then the geodesic is already vertical. If $x'(t)\neq 0$ we claim that the geodesics are upper half circles with center $M(t)$ on the x-axis.



$$\begin{aligned}\frac{y'(t)}{x'(t)} &= \tan\alpha(t) = \frac{a(t)}{y(t)},\quad \Rightarrow a = \frac{y'y}{x'},\\ M(t) &= x + \frac{y'y}{x'} = \frac{x'x + y'y}{x'}\\ M'(t) &= \left(\frac{x'x + y'y}{x'}\right)' = \dots = 0,\end{aligned}$$

Thus $M(t) = M$, a constant. Moreover,

$$\begin{aligned}\left|\begin{pmatrix}x(t)\\ y(t)\end{pmatrix} - \begin{pmatrix}M\\ 0\end{pmatrix}\right|^2 &= (x-M)^2 + y^2 = \left(\frac{y'y}{x'}\right)^2 + y^2,\\ \frac{d}{dt}\left|\begin{pmatrix}x(t)\\ y(t)\end{pmatrix} - \begin{pmatrix}M\\ 0\end{pmatrix}\right|^2 &= \left(\left(\frac{y'y}{x'}\right)^2 + y^2\right)' = \dots = 0.\end{aligned}$$

Thus the geodesics are half circles as asserted. Note that this violates Euclids parallel axiom: we have a non-Euclidean geometry.

Isometries and the Poincaré upper half plane as symmetric space. The projective action of the Lie group $SL(2,\mathbb{R})$ on $\mathbb{C}P^1$, viewed in the projective chart $\mathbb{C} \ni z \mapsto [z:1]$, preserves the upper half-plane: A matrix $\left(\begin{smallmatrix} a & b \\ c & d \end{smallmatrix}\right)$ acts by $[z:1] \mapsto [az+b:cz+d] = [\frac{az+b}{cz+d}:1]$. Moreover for $z = x+iy$ the expression

$$\frac{az+b}{cz+d} = \frac{(az+b)(c\bar z+d)}{|cz+d|^2} = \frac{ac(x^2+y^2)+(ad+bc)x+db}{(cx+d)^2+(cy)^2} + i\frac{(ad-bc)y}{(cx+d)^2+(cy)^2}$$

has imaginary part >0 if and only if $y>0$.

We denote the action by $m: SL(2,\mathbb{R}) \times H^2_+ \to H^2_+$, so that $m\left(\begin{smallmatrix} a & b \\ c & d \end{smallmatrix}\right)(z) = \frac{az+b}{cz+d}$. Transformations of this form are called a *fractional linear transformations* or *Möbius transformations*.

(1) $SL(2,\mathbb{R})$ acts transitively on H^2_+, since $m\left(\begin{smallmatrix} \sqrt{y} & x/\sqrt{y} \\ 0 & 1/\sqrt{y} \end{smallmatrix}\right)(i) = x+iy$. The isotropy group fixing i is $SO(2) \subset SL(2)$, since $i = \frac{ai+b}{ci+d} = \frac{bd+ac+i}{c^2+d^2}$ if and only if $cd+ac=0$ and $c^2+d^2=1$. Thus $H^2_+ = SL(2,\mathbb{R})/SO(2,\mathbb{R})$. Any Möbius transformation by an element of $SL(2)$ *is an isometry*:

$$\begin{aligned}
A &:= \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in SL(2,\mathbb{R}),\\
m_A(z) - m_A(z') &= \frac{az+b}{cz+d} - \frac{az'+b}{cz'+d} = \dots = \frac{z-z'}{(cz+d)(cz'+d)}\\
(m_A)'(z) &= \lim_{z'\to z} \frac{1}{z-z'}\frac{z-z'}{(cz+d)(cz'+d)} = \frac{1}{(cz+d)^2}\\
m_A(z) - m_A(z') &= \sqrt{(m_A)'(z)}\sqrt{(m_A)'(z')}(z-z'),
\end{aligned}$$

for always the same branch of $\sqrt{(m_A)'(z)}$. Expressing the metric in the complex variable we then have

$$\begin{aligned}
g &= \frac{1}{y^2}(dx^2+dy^2) = \frac{1}{\operatorname{Im}(z)^2}\operatorname{Re}(dz.d\bar z)\\
(m_A)^*g &= (m_A)^*\left(\frac{1}{\operatorname{Im}(z)^2}\operatorname{Re}(dz.d\bar z)\right)\\
&= \frac{1}{\operatorname{Im}((m_A)(z))^2}\operatorname{Re}\big((m_A)'(z)dz.(m_A)'(\bar z)d\bar z\big)\\
&= \operatorname{Im}((m_A)(z))^{-2}|cz+d|^{-4}\operatorname{Re}\big(dz.d\bar z\big) = \frac{1}{\operatorname{Im}(z)^2}\operatorname{Re}(dz.d\bar z), \qquad \text{since}
\end{aligned}$$

$$\begin{aligned}
\operatorname{Im}((m_A)(z))|cz+d|^2 &= \frac{1}{2i}(m_A(z) - m_A(\bar z))|cz+d|^2\\
&= \frac{1}{2i}\frac{z-\bar z}{(cz+d)(c\bar z+d)}|cz+d|^2 = \operatorname{Im}(z).
\end{aligned}$$

(2) For further use we note the Möbius transformations

$$\begin{aligned}
m_1 &= m\begin{pmatrix} 1 & r \\ 0 & 1 \end{pmatrix} : z \mapsto z+r, \quad r \in \mathbb{R}\\
m_2 &= m\begin{pmatrix} \sqrt{r} & 0 \\ 0 & 1/\sqrt{r} \end{pmatrix} : z \mapsto r.z, \quad r \in \mathbb{R}_{>0}\\
m_3 &= m\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} : z \mapsto \frac{-1}{z} = \frac{-\bar z}{|z|^2} = \frac{-x+iy}{x^2+y^2}
\end{aligned}$$

We can now use these three isometries to determine again the form of all geodesics in H^2_+. For this note that: *If the fixed point set* $(H^2_x)^m = \{z \in H^2_+ : m(z) = z\}$ *of an isometry is a connected 1-dimensional submanifold, then this is the image of a geodesic,* since for any vector $X_z \in T_z H^2_+$ tangent to the fixed point set we have $m(\exp(tX)) = \exp(tT_z m.X) = \exp(tX)$. We first use the isometry $\psi(x,y) = (-x,y)$ which is not a Möbius transformation since it reverses the orientation. Its fixed point set is the vertical line $\{(0,y) : y > 0\}$ which thus is a geodesic. The image under m_1 is then the geodesic $\{(r,y) : y > 0\}$. The fixed point set of the isometry $\psi \circ m_3$ is the upper half of the unit circle, which thus is a geodesic. By applying m_1 and m_2 we may map it to any upper half circle with center in the real axis.

(3) *The group* $SL(2,\mathbb{R})$ *acts isometrically doubly transitively on* H^2_+*: Any two pairs of points with the same geodesic distance can be mapped to each other by a Möbius transformation.* For $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ in the isotropy group $SO(2)$ of i we have $m'_A(i) = \frac{1}{(ci+d)^2}$; it double covers the unit circle in $T_i(H^2_+)$. Thus $SL(2,\mathbb{R})$ acts transitively on the set of all unit tangent vectors in H^2_+, and a shortest geodesic from z_1 to z_2 can thus be mapped by a Möbius transformation to a shortest geodesic of the same length from z'_1 to z'_2.

(4) H^2_+ *is a complete Riemann manifold, and the geodesic distance is given by*

$$\operatorname{dist}(z_1, z_2) = 2 \operatorname{artanh} \left| \frac{z_1 - z_2}{z_1 - \bar z_2} \right|.$$

The shortest curve from iy_1 to iy_2 is obviously on the vertical line since for $z(t) = x(t) + iy(t)$ the length

$$L(c) = \int_0^1 \frac{1}{y(t)} \sqrt{x'(t)^2 + y'(t)^2}\, dt$$

is minimal for $x'(t) = 0$, thus $x(t) =$ constant. By the invariance under reparameterizations of the length we have

$$\operatorname{dist}(iy_1, iy_2) = \Big| \int_{y_1}^{y_2} \frac{1}{t}\, dt \Big| = |\log y_2 - \log y_1| = |\log(\tfrac{y_2}{y_1})|$$

From the formulas in (1) we see that the *double ratio* $|\frac{z_1 - z_2}{z_1 - \bar z_2}|$ is invariant under $SL(2,\mathbb{R})$ since:

$$\left| \frac{m_A(z_1) - m_A(z_2)}{m_A(z_1) - \overline{m_A(z_2)}} \right| = \left| \frac{\frac{z_1 - z_2}{(cz_1+d)(cz_2+d)}}{\frac{z_1 - \bar z_2}{(cz_1+d)(c\bar z_2+d)}} \right| = \left| \frac{z_1 - z_2}{z_1 - \bar z_2} \right|.$$

On the vertical geodesic we have

$$\begin{aligned}\left| \frac{iy_1 - iy_2}{iy_1 + iy_2} \right| &= \left| \frac{\frac{y_1}{y_2} - 1}{\frac{y_1}{y_2} + 1} \right| = \left| \frac{e^{\log(\frac{y_1}{y_2})} - 1}{e^{\log(\frac{y_1}{y_2})} + 1} \right| = \left| \frac{e^{\frac12 |\log(\frac{y_1}{y_2})|} - e^{-\frac12 |\log(\frac{y_1}{y_2})|}}{e^{\frac12 |\log(\frac{y_1}{y_2})|} + e^{-\frac12 |\log(\frac{y_1}{y_2})|}} \right| \\ &= \tanh(\tfrac12 \operatorname{dist}(iy_1, iy_2)).\end{aligned}$$

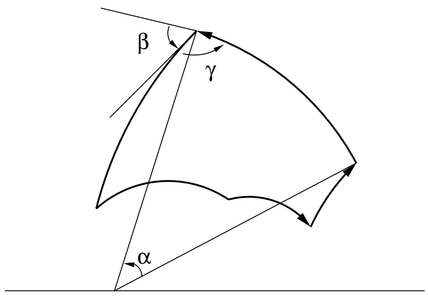
Since $SL(2,\mathbb{R})$ acts isometrically doubly transitively by (3) and since both sides are invariant, the result follows.

(5) *The geodesic exponential mapping.* We have $\exp_i(ti) = e^t.i$ since by (4) we have $\operatorname{dist}(i, e^t i) = \log \frac{e^t i}{i} = t$. Now let $X \in T_i(H^2_+)$ with $|X| = 1$. In (3) we saw that there exists φ with

$$m\big(\begin{smallmatrix}\cos\varphi & -\sin\varphi\\ \sin\varphi & \cos\varphi\end{smallmatrix}\big)'(i)i = \frac{i}{(i\sin\varphi+\cos\varphi)^2} = e^{-2i\varphi}.i = X, \quad \varphi = \frac{\pi}{4} - \frac{\arg(X)}{2} + \pi\mathbb{Z},$$

$$\exp_i(tX) = m\big(\begin{smallmatrix}\cos\varphi & -\sin\varphi\\ \sin\varphi & \cos\varphi\end{smallmatrix}\big)(e^t i) = \frac{\cos\varphi.e^t.i - \sin\varphi}{\sin\varphi.e^t i + \cos\varphi}.$$

(6) *Hyperbolic area of a geodesic polygon.* By (8.5) the density of the Riemann metric $g = \frac{1}{y^2}(dx^2+dy^2)$ is given by $\operatorname{vol}(g) = \sqrt{\det g_{ij}}\,dx\,dy = \frac{1}{y^2}dx\,dy$.



$$\operatorname{Vol}^{H^2_+}(P) = \int_P \frac{dx\wedge dy}{y^2} = \int_P d\left(\frac{dx}{y}\right)$$
$$= \int_{\partial P}\frac{dx}{y} = -\int_{\partial P} d\theta,$$

since each geodesic is part of a circle $z - a = re^{i\theta}$, $a\in\mathbb{R}$. On it we have

$$\frac{dx}{y} = \frac{d(r\cos\theta + a)}{r\sin\theta} = \frac{-r\sin\theta\,d\theta}{r\sin\theta} = -d\theta.$$

The integral is thus the total increase of the tangent angle. For a simply connected polygon the total increase of the tangent angle is 2π if we also add the exterior angles at the corners: $\int_{\partial P} d\theta + \sum_i \beta_i = \sum_i \alpha_i + \sum_i \beta_i = 2\pi$. We change to the inner angles $\gamma_i = \pi - \beta_i$ and get:

$$\operatorname{Vol}^{H^2_+}(P) = -\int_{\partial P} d\theta = -2\pi + \sum_i \beta_i = (n-2)\pi - \sum_i \gamma_i.$$

This is a particular instance of the theorem of Gauß-Bonnet.

16.8. The 3-sphere S^3. We use the following parametrization of $S^3 \subset \mathbb{R}^4$.

$$f(\varphi,\theta,\tau) = \begin{pmatrix} \cos\varphi\ \cos\theta\ \cos\tau \\ \sin\varphi\ \cos\theta\ \cos\tau \\ \sin\theta\ \cos\tau \\ \sin\tau \end{pmatrix}, \qquad \begin{array}{c} 0<\varphi<2\pi \\ -\frac{\pi}{2}<\theta<\frac{\pi}{2} \\ -\frac{\pi}{2}<\tau<\frac{\pi}{2}\end{array}$$

We write $f^1_1 = \partial_\varphi f^1$ etc. Then the induced metric is given by:

$$g_{11} = \langle f_1, f_1\rangle = f^1_1 f^1_1 + f^2_1 f^2_1 + f^3_1 f^3_1 + f^4_1 f^4_1 = \cos^2\theta\cos^2\tau,$$
$$g_{12} = \langle f_1, f_2\rangle = 0, \qquad g_{13} = 0, \qquad g_{22} = \cos^2\tau, \qquad g_{23} = 0 \qquad g_{33} = 1.$$
$$g = \cos^2\theta\ \cos^2\tau\ d\varphi\otimes d\varphi + \cos^2\tau\ d\theta\otimes d\theta + d\tau\otimes d\tau.$$
$$\sigma^1 = \cos\theta\ \cos\tau\ d\varphi, \qquad \sigma^2 = \cos\tau\ d\theta, \qquad \sigma^3 = d\tau.$$
$$d\sigma^1 = -\sin\theta\ \cos\tau\ d\theta\wedge d\varphi - \cos\theta\ \sin\tau\ d\tau\wedge d\varphi,$$
$$d\sigma^2 = -\sin\tau\ d\tau\wedge d\theta, \qquad d\sigma^3 = 0.$$

Now we use the first structure equation $d\sigma + \omega \wedge \sigma = 0$:

$$d\sigma^1 = -0 - \omega^1_2 \wedge \sigma^2 - \omega^1_3 \wedge \sigma^3 = \sin\theta\ \cos\tau\ d\varphi \wedge d\theta + \cos\theta\ \sin\tau\ d\varphi \wedge d\tau,$$
$$d\sigma^2 = -\omega^2_1 \wedge \sigma^1 - 0 - \omega^2_3 \wedge \sigma^3 = \sin\tau\ d\theta \wedge d\tau,$$
$$d\sigma^3 = -\omega^3_1 \wedge \sigma^1 - \omega^3_2 \wedge \sigma^2 - 0 = 0.$$
$$-\omega^1_2 \wedge \cos\tau\ d\theta - \omega^1_3 \wedge d\tau = \sin\theta\ \cos\tau\ d\varphi \wedge d\theta + \cos\theta\ \sin\tau\ d\varphi \wedge d\tau,$$
$$-\omega^2_1 \wedge \cos\theta\ \cos\tau\ d\varphi - \omega^2_3 \wedge d\tau = \sin\tau\ d\theta \wedge d\tau,$$
$$-\omega^3_1 \wedge \cos\theta\ \cos\tau\ d\varphi - \omega^3_2 \wedge \cos\tau\ d\theta = 0.$$

$$\begin{cases} \omega^1_3 = -\cos\theta\ \sin\tau\ d\varphi \\ \omega^2_3 = -\sin\tau\ d\theta \\ \omega^1_2 = -\sin\theta\ d\varphi \end{cases} \qquad \omega = \begin{pmatrix} 0 & -\sin\theta\ d\varphi & -\cos\theta\ \sin\tau\ d\varphi \\ \sin\theta\ d\varphi & 0 & -\sin\tau\ d\theta \\ \cos\theta\ \sin\tau\ d\varphi & \sin\tau\ d\theta & 0 \end{pmatrix}$$

From this we can compute the curvature:

$$\begin{aligned}
\Omega^1_2 &= d\omega^1_2 + 0 + 0 + \omega^1_3 \wedge \omega^3_2 = -\cos\theta\ d\theta \wedge d\varphi - \cos\theta\ \sin\tau\ d\varphi \wedge \sin\tau\ d\theta \\
&= \cos\theta\ \cos^2\tau\ d\varphi \wedge d\theta = \sigma^1 \wedge \sigma^2 \\
\Omega^1_3 &= d\omega^1_3 + 0 + \omega^1_2 \wedge \omega^2_3 + 0 = \sin\theta\ \sin\tau\ d\theta \wedge d\varphi - \cos\theta\ \cos\tau\ d\tau \wedge d\varphi + \\
&\quad + \sin\theta\ d\varphi \wedge \sin\tau\ d\theta = \cos\theta\ \cos\tau\ d\varphi \wedge d\tau = \sigma^1 \wedge \sigma^3 \\
\Omega^2_3 &= d\omega^2_3 + \omega^2_1 \wedge \omega^1_3 + 0 + 0 = -\cos\tau\ d\tau \wedge d\theta + 0 \\
&= \cos\tau\ d\theta \wedge d\tau = \sigma^2 \wedge \sigma^3 \\
\Omega &= \begin{pmatrix} 0 & \sigma^1 \wedge \sigma^2 & \sigma^1 \wedge \sigma^3 \\ -\sigma^1 \wedge \sigma^2 & 0 & \sigma^2 \wedge \sigma^3 \\ -\sigma^1 \wedge \sigma^3 & -\sigma^2 \wedge \sigma^3 & 0 \end{pmatrix} = \begin{pmatrix} \sigma^1 \\ \sigma^2 \\ \sigma^3 \end{pmatrix} \wedge (\sigma^1, \sigma^2, \sigma^3)
\end{aligned}$$

Another representation of the 3-sphere with radius $1/\sqrt{k}$. The induced metric is given by

$$g = \frac{1}{k}\big(\cos^2\theta\ \cos^2\tau\ d\varphi \otimes d\varphi + \cos^2\tau\ d\theta \otimes d\theta + d\tau \otimes d\tau\big),$$

where $0 < \varphi < 2\pi$, $-\frac{\pi}{2} < \theta < \frac{\pi}{2}$, and $-\frac{\pi}{2} < \tau < \frac{\pi}{2}$. Now we introduce the coordinate function r by $\cos^2\tau = k\,r^2$, more precisely by

$$r = \begin{cases} -\frac{1}{\sqrt{k}}\cos\tau & -\frac{\pi}{2} < \tau < 0 \\ \frac{1}{\sqrt{k}}\cos\tau & 0 < \tau < \frac{\pi}{2} \end{cases}, \qquad 0 < |r| < \tfrac{1}{\sqrt{k}}.$$

Then $\operatorname{sign}\tau\ \ \cos\tau = \sqrt{k}\,r$ thus $-\operatorname{sign}\tau\ \ \sin\tau\ \ d\tau = \sqrt{k}\,dr$, and since $\sin^2\tau = 1 - \cos^2\tau = 1 - k\,r^2$ we finally get $(1 - k\,r^2)\,d\tau \otimes d\tau = \sin^2\tau\ d\tau \otimes d\tau = k\,dr \otimes dr$. Furthermore we replace θ by $\theta + \frac{\pi}{2}$. Then the metric becomes:

$$\begin{aligned}
g &= \frac{1}{k}\left(\sin^2\theta\ k\,r^2\ d\varphi \otimes d\varphi + k\,r^2\ d\theta \otimes d\theta + \frac{k}{1-kr^2} dr \otimes dr\right) \\
&= \frac{1}{1-kr^2} dr \otimes dr + r^2\ d\theta \otimes d\theta + r^2\ \sin^2\theta\ d\varphi \otimes d\varphi, \qquad \text{where} \qquad (1) \\
&\quad 0 < \varphi < 2\pi, \qquad 0 < \theta < \pi, \qquad 0 < |r| < \frac{1}{\sqrt{k}}.
\end{aligned}$$

16.9. The Robertson-Walker metric in general relativity. This is the metric of signature $(+---)$ of the form

$$
\begin{aligned}
g &= dt\otimes dt - R(t)^2\left(\frac{1}{1-kr^2}dr\otimes dr + r^2\, d\theta\otimes d\theta + r^2\,\sin^2\theta\, d\varphi\otimes d\varphi\right)\\
&\qquad \text{for } 0<\varphi<2\pi,\quad 0<\theta<\pi,\quad 0<|r|<\frac{1}{\sqrt{k}};\\
&= \rho^0\otimes\rho^0 - \rho^1\otimes\rho^1 - \rho^2\otimes\rho^2 - \rho^3\otimes\rho^3\\
\rho^0 &= dt, \qquad \rho^1 = \frac{R}{w}\,dr, \quad \text{where } w := \sqrt{1-kr^2},\\
\rho^2 &= Rr\,d\theta, \qquad \rho^3 = Rr\,\sin\theta\,d\varphi.
\end{aligned}
$$

The differential of the coframe is:

$$
\begin{aligned}
d\rho^0 &= 0,\\
d\rho^1 &= \frac{\dot R}{w}\,dt\wedge dr = \frac{\dot R}{R}\rho^0\wedge\rho^1,\\
d\rho^2 &= \dot R r\,dt\wedge d\theta + R\,dr\wedge d\theta, = \frac{\dot R}{R}\,\rho^0\wedge\rho^2 + \frac{w}{Rr}\,\rho^1\wedge\rho^2\\
d\rho^3 &= \dot R r\,\sin\theta\,d\theta\wedge d\varphi + R\,\sin\theta\,dr\wedge d\varphi + Rr\,\cos\theta\,d\theta\wedge d\varphi\\
&= \frac{\dot R}{R}\rho^0\wedge\rho^3 + \frac{w}{Rr}\,\rho^1\wedge\rho^3 + \frac{\operatorname{cotan}\theta}{Rr}\rho^2\wedge\rho^3
\end{aligned}
$$

Now we use $d\rho+\omega\wedge\rho=0$, $\omega^i_j=-\omega^j_i$ for $1\le i,j\le 3$, $\omega^i_i=0$, and $\omega^0_i=\omega^i_0$:

$$
\begin{aligned}
d\rho^0 &= -\omega^0_1\wedge\rho^1 - \omega^0_2\wedge\rho^2 - \omega^0_3\wedge\rho^3 = 0,\\
d\rho^1 &= -\omega^1_0\wedge\rho^0 - \omega^1_2\wedge\rho^2 - \omega^1_3\wedge\rho^3 = \frac{\dot R}{R}\rho^0\wedge\rho^1,\\
d\rho^2 &= -\omega^2_0\wedge\rho^0 - \omega^2_1\wedge\rho^1 - \omega^2_3\wedge\rho^3 = \frac{\dot R}{R}\,\rho^0\wedge\rho^2 + \frac{w}{Rr}\,\rho^1\wedge\rho^2\\
d\rho^3 &= -\omega^3_0\wedge\rho^0 - \omega^3_1\wedge\rho^1 - \omega^3_2\wedge\rho^2\\
&= \frac{\dot R}{R}\rho^0\wedge\rho^3 + \frac{w}{Rr}\,\rho^1\wedge\rho^3 + \frac{\operatorname{cotan}\theta}{Rr}\rho^2\wedge\rho^3
\end{aligned}
$$

This is a linear system of equations with a unique solution for the ω^i_j. We solve this by trying. Guided by (16.8) we assume that ω^0_1 is a multiple of ρ^1, etc. and we get the solutions

$$
\begin{aligned}
\omega^1_0 &= \frac{\dot R}{R}\rho^1 = \frac{\dot R}{w}\,dr & \omega^2_0 &= \frac{\dot R}{R}\rho^2 = \dot R\,r\,d\theta\\
\omega^3_0 &= \frac{\dot R}{R}\rho^3 = \dot R\,r\,\sin\theta\,d\varphi & \omega^2_1 &= \frac{w}{Rr}\rho^2 = w\,d\theta\\
\omega^3_1 &= \frac{w}{Rr}\rho^3 = w\,\sin\theta\,d\varphi & \omega^3_2 &= \frac{\operatorname{cotan}\theta}{Rr}\rho^3 = \cos\theta\,d\varphi
\end{aligned}
$$

From these we can compute the curvature 2-forms, using $\Omega = d\omega + \omega \wedge \omega$:

$$\Omega^1_0 = -\frac{\ddot R}{R}\rho^1 \wedge \rho^0 \qquad \Omega^2_0 = -\frac{\ddot R}{R}\rho^2 \wedge \rho^0$$

$$\Omega^3_0 = -\frac{\ddot R}{R}\rho^3 \wedge \rho^0 \qquad \Omega^2_1 = \frac{k + \dot R^2}{R^2}\rho^2 \wedge \rho^1$$

$$\Omega^3_1 = -\frac{-k + \dot R^2}{R^2}\rho^3 \wedge \rho^1 \qquad \Omega^3_2 = \frac{k + \dot R^2}{R^2}\rho^3 \wedge \rho^2$$

17. Riemann immersions and submersions

17.1. Riemann submanifolds and isometric immersions. Let $(\bar{M}, \bar{g})$ be a Riemann manifold of dimension $m+p$, and let $M \xrightarrow{i} \bar{M}$ be a manifold of dimension m with an immersion i. Let $g := i^*\bar{g}$ be the induced Riemann metric on M. Let $\bar{\nabla}$ be the Levi-Civita covariant derivative on $\bar{M}$, and let ∇ be the Levi-Civita covariant derivative on M. We denote by $Ti^\perp = TM^\perp := \{X \in T_{i(x)}\bar{M}, x \in M, \bar{g}(X, Ti(T_xM)) = 0\}$ the normal bundle (over M) of the immersion i or the immersed submanifold M.

Let $X, Y \in \mathfrak{X}(M)$. We may regard $Ti.Y$ as vector field with values in $T\bar{M}$ defined along i and thus consider $\bar{\nabla}_X(Ti.Y) : M \to i^*T\bar{M}$.

Lemma. Gauß' formula. *If $X, Y \in \mathfrak{X}(M)$ then $\bar{\nabla}_X(Ti.Y) - Ti \circ \nabla_X Y =: S(X,Y)$ is normal to M, and $S : TM \times_M TM \to Ti^\perp$ is a symmetric tensor field, which is called the second fundamental form or the shape operator of M.*

Proof. For $X, Y, Z \in \mathfrak{X}(M)$ and a suitable open set $U \subset M$ we may choose an open subset $\bar{U} \subset \bar{M}$ with $i(U)$ closed in $\bar{U}$ such that $i : U \to \bar{U}$ is an embedding, and then extensions $\bar{X}, \bar{Y}, \bar{Z} \in \mathfrak{X}(\bar{U})$ with $\bar{X} \circ i|_U = Ti.X|_U$, etc. By (13.5.7) we have

$$\begin{aligned}2\bar{g}(\bar{\nabla}_{\bar{X}}\bar{Y}, \bar{Z}) &= \bar{X}(\bar{g}(\bar{Y}, \bar{Z})) + \bar{Y}(\bar{g}(\bar{Z}, \bar{X})) - \bar{Z}(\bar{g}(\bar{X}, \bar{Y})) \\ &\quad + \bar{g}([\bar{X}, \bar{Y}], \bar{Z}) + \bar{g}([\bar{Z}, \bar{X}], \bar{Y}) - \bar{g}([\bar{Y}, \bar{Z}], \bar{X}).\end{aligned}$$

Composing this formula with $i|_U$ we get on U

$$\begin{aligned}2\bar{g}(\bar{\nabla}_X(Ti.Y), Ti.Z) &= X(g(Y,Z)) + Y(g(Z,X)) - Z(g(X,Y)) \\ &\quad + g([X,Y],Z) + g([Z,X],Y) - g([Y,Z],X) = 2g(\nabla_X Y, Z),\end{aligned}$$

again by (13.5.7). Since this holds for all $Z \in \mathfrak{X}(U)$, the orthonormal projection of $\bar{\nabla}_X Y$ to TM is just $\nabla_X Y$. Thus $S(X,Y) := \bar{\nabla}_X(Ti.Y) - Ti.\nabla_X Y$ is a section of $Ti^\perp$, and it is symmetric in X, Y since

$$\begin{aligned}S(X,Y) &= \bar{\nabla}_X(Ti.Y) - Ti \circ \nabla_X Y = (\bar{\nabla}_{\bar{X}}\bar{Y}) \circ i - Ti \circ \nabla_X Y \\ &= (\bar{\nabla}_{\bar{Y}}\bar{X} + [\bar{X}, \bar{Y}]) \circ i - Ti.(\nabla_Y X + [X,Y]) = S(Y,X).\end{aligned}$$

For $f \in C^\infty(M)$ we have

$$S(fX, Y) = \bar{\nabla}_{fX}(Ti.Y) - Ti \circ \nabla_{fXY} = f\bar{\nabla}_X(Ti.Y) - fTi \circ \nabla_X Y = fS(X,Y),$$

and $S(X, fY) = fS(X,Y)$ follows by symmetry. $\square$

17.2. Corollary. *Let $c : [a, b] \to M$ be a smooth curve. Then we have*

$$\bar\nabla_{\partial_t}(Ti.c') = \bar\nabla_{\partial_t}(i \circ c)' = Ti \circ \nabla_{\partial_t} c' + S(c', c').$$

Consequently c is a geodesic in M if and only if $\bar\nabla_{\partial_t}(i \circ c)' = S(c', c') \in Ti^\perp$, i.e., the acceleration of $i \circ c$ in $\bar M$ is orthogonal to M.

Let $i : M \to \bar M$ be an isometric immersion. Then the following conditions are equivalent:

(1) *Any geodesic in $\bar M$ which starts in $i(M)$ in a direction tangent to $i(M)$ stays in $i(M)$; it is then a geodesic in $i(M)$. We call $i : M \to \bar M$ a totally geodesic immersion.*
(2) *The second fundamental form S of $i : M \to \bar M$ vanishes.* □

17.3. In the setting of (17.1) we now investigate $\bar\nabla_X \xi$ where $X \in \mathfrak{X}(M)$ and where $\xi \in \Gamma(Ti^\perp)$ is a normal field. We split it into tangential and normal components:

(1) $$\bar\nabla_X \xi = -Ti.L_\xi(X) + \nabla^\perp_X \xi \in \mathfrak{X}(M) \oplus \Gamma(Ti^\perp) \quad (\textit{Weingarten formula}).$$

Proposition.

(2) *The mapping $(\xi, X) \mapsto L_\xi(X)$ is $C^\infty(M)$-bilinear, thus $L : Ti^\perp \times_M TM \to TM$ is a tensor field, called the Weingarten mapping and we have:*

$$g(L_\xi(X), Y) = \bar g(S(X, Y), \xi), \quad \xi \in \Gamma(Ti^\perp), X, Y \in \mathfrak{X}(M).$$

By the symmetry of S, $L_\xi : TM \to TM$ is a symmetric endomorphism with respect to g, i.e. $g(L_\xi(X), Y) = g(X, L_\xi(Y))$.

(3) *The mapping $(X, \xi) \mapsto \nabla^\perp_X \xi$ is a covariant derivative in the normal bundle $Ti^\perp \to M$ which respects the metric $g^\perp := \bar g|Ti^\perp \times_M Ti^\perp$; i.e.:*

$$\begin{aligned}
&\nabla^\perp : \mathfrak{X}(M) \times \Gamma(Ti^\perp) \to \Gamma(Ti^\perp) \quad \textit{is } \mathbb{R}\textit{-bilinear},\\
&\nabla^\perp_{f.X}\xi = f.\nabla^\perp_X \xi, \qquad \nabla^\perp_X(f.\xi) = df(X).\xi + \nabla^\perp_X \xi,\\
&X(g^\perp(\xi, \eta)) = g^\perp(\nabla^\perp_X \xi, \eta) + g^\perp(\xi, \nabla^\perp_X \eta).
\end{aligned}$$

Note that there does not exist torsion for $\nabla^\perp$.

Proof. The mapping $(\xi, X) \mapsto L_\xi(X)$ is obviously $\mathbb{R}$-bilinear. Moreover,

$$\begin{aligned}
-Ti.L_\xi(f.X) + \nabla^\perp_{f.X}\xi &= \bar\nabla_{f.X}\xi = f.\bar\nabla_X \xi = -f.(Ti.L_\xi(X)) + f.\nabla^\perp_X \xi\\
&\Rightarrow \quad L_\xi(f.X) = f.L_\xi(X), \quad \nabla^\perp_{f.X}\xi = f.\nabla^\perp_X \xi.\\
-Ti.L_{f.\xi}(X) + \nabla^\perp_X(f.\xi) &= \bar\nabla_X(f.\xi) = df(X).\xi + f.\bar\nabla_X \xi =\\
&= -f.(Ti.L_\xi(X)) + (df(X).\xi + f.\nabla^\perp_X \xi)\\
&\Rightarrow \quad L_{f.\xi}(X) = f.L_\xi(X), \quad \nabla^\perp_X(f.\xi) = df(X).\xi + f.\nabla^\perp_X \xi.
\end{aligned}$$

For the rest we enlarge $X, Y \in \mathfrak{X}(M)$ and $\xi, \eta \in \Gamma(Ti^\perp)$ locally to vector fields $\bar X, \bar Y, \bar\xi, \bar\eta$ on $\bar M$. Then we have:

$$\begin{aligned}
X(g^\perp(\xi,\eta)) &= \bar X(\bar g(\bar\xi,\bar\eta))\circ i = \big(\bar g(\bar\nabla_{\bar X}\bar\xi,\bar\eta) + \bar g(\bar\xi,\bar\nabla_{\bar X}\bar\eta)\big)\circ i\\
&= \bar g(\bar\nabla_X\xi,\eta) + \bar g(\xi,\bar\nabla_X\eta)\\
&= \bar g(-Ti.L_\xi(X) + \nabla^\perp_X\xi,\eta) + \bar g(\xi, -Ti.L_\eta(X) + \nabla^\perp_X\eta)\\
&= g^\perp(\nabla^\perp_X\xi,\eta) + g^\perp(\xi,\nabla^\perp_X\eta)\\
\bar X(\bar g(\bar Y,\bar\xi)) &= \bar g(\bar\nabla_{\bar X}\bar Y,\bar\xi) + \bar g(\bar Y,\bar\nabla_{\bar X}\bar\xi). \qquad \text{Pull this back to } M:\\
0 = X(\bar g(Y,\xi)) &= \bar g(\bar\nabla_X(Ti.Y),\xi) + \bar g(Ti.Y,\bar\nabla_X\xi)\\
&= \bar g(Ti.\nabla_XY + S(X,Y),\xi) + \bar g(Ti.Y, -Ti.L_\xi(X) + \nabla^\perp_X\xi)\\
&= g^\perp(S(X,Y),\xi) + g(Y,-L_\xi(X)). \quad \square
\end{aligned}$$

17.4. Theorem. *Let $(M,g) \xrightarrow{i} (\bar M,\bar g)$ be an isometric immersion of Riemann manifolds with Riemann curvatures R and $\bar R$ respectively. Then we have:*

(1) *For $X_i \in \mathfrak{X}(M)$ or T_xM we have (Gauß' equation, 'theorema egregium'):*

$$\begin{aligned}
\bar g(\bar R(Ti.X_1,&Ti.X_2)(Ti.X_3), Ti.X_4) = g(R(X_1,X_2)X_3,X_4)+\\
&+ g^\perp(S(X_1,X_3),S(X_2,X_4)) - g^\perp(S(X_2,X_3),S(X_1,X_4)).
\end{aligned}$$

(2) *The tangential part of $\bar R(X_1,X_2)X_3$ is given by:*

$$(\bar R(Ti.X_1,Ti.X_2)(Ti.X_3))^\top = R(X_1,X_2)X_3 + L_{S(X_1,X_3)}(X_2) - L_{S(X_2,X_3)}(X_1).$$

(3) *The normal part of $\bar R(X_1,X_2)X_3$ is then given by (Codazzi-Mainardi equation):*

$$\begin{aligned}
&(\bar R(Ti.X_1,Ti.X_2)(Ti.X_3))^\perp =\\
&\quad = \big(\nabla^{Ti^\perp\otimes T^*M\otimes T^*M}_{X_1}S\big)(X_2,X_3) - \big(\nabla^{Ti^\perp\otimes T^*M\otimes T^*M}_{X_2}S\big)(X_1,X_3).
\end{aligned}$$

(4) *The tangential and the normal parts of $\bar R(Ti.X_1,Ti.X_2)\xi$ (where ξ is a normal field along i) are given by:*

$$\begin{aligned}
&(\bar R(Ti.X_1,Ti.X_2)\xi)^\top =\\
&\quad = Ti.\Big((\nabla^{TM\otimes(Ti^\perp)^*\otimes T^*M}_{X_2}L)_\xi(X_1) - (\nabla^{TM\otimes(Ti^\perp)^*\otimes T^*M}_{X_1}L)_\xi(X_2)\Big)\\
&(\bar R(Ti.X_1,Ti.X_2)\xi)^\perp = R^{\nabla^\perp}(X_1,X_2)\xi + S(L_\xi(X_1),X_2) - S(L_\xi(X_2),X_1).
\end{aligned}$$

Proof. Every $x \in M$ has an open neighborhood U such that $i : U \to \bar M$ is an embedding. Since the assertions are local, we may thus assume that i is an embedding, and we may suppress i in the following proof. For the proof we need vector fields $X_i \in \mathfrak{X}(M)$. We start from the Gauß formula (17.1).

$$\begin{aligned}
\bar\nabla_{X_1}(\bar\nabla_{X_2}X_3) &= \bar\nabla_{X_1}(\nabla_{X_2}X_3 + S(X_2,X_3))\\
&= \nabla_{X_1}\nabla_{X_2}X_3 + S(X_1,\nabla_{X_2}X_3) + \bar\nabla_{X_1}S(X_2,X_3)\\
\bar\nabla_{X_2}(\bar\nabla_{X_1}X_3) &= \nabla_{X_2}\nabla_{X_1}X_3 + S(X_2,\nabla_{X_1}X_3) + \bar\nabla_{X_2}S(X_1,X_3)\\
\bar\nabla_{[X_1,X_2]}X_3 &= \nabla_{[X_1,X_2]}X_3 + S([X_1,X_2],X_3)\\
&= \nabla_{[X_1,X_2]}X_3 + S(\nabla_{X_1}X_2,X_3) - S(\nabla_{X_2}X_1,X_3)
\end{aligned}$$

Inserting this we get for the part which is tangent to M:

$$\begin{aligned}
&\bar g(\bar R(X_1,X_2)X_3,X_4) = \bar g(\bar\nabla_{X_1}\bar\nabla_{X_2}X_3 - \bar\nabla_{X_2}\bar\nabla_{X_1}X_3 - \bar\nabla_{[X_1,X_2]}X_3, X_4)\\
&\quad = g(\nabla_{X_1}\nabla_{X_2}X_3 - \nabla_{X_2}\nabla_{X_1}X_3 - \nabla_{[X_1,X_2]}X_3,X_4)+\\
&\qquad + \bar g(S(X_1,\nabla_{X_2}X_3) - S(X_2,\nabla_{X_1}X_3) - S([X_1,X_2],X_3),X_4) \qquad \text{this term } = 0\\
&\qquad + \bar g(\bar\nabla_{X_1}S(X_2,X_3) - \bar\nabla_{X_2}S(X_1,X_3),X_4)\\
&\quad = g(R(X_1,X_2)X_3,X_4)\\
&\qquad + g^\perp(S(X_1,X_3),S(X_2,X_4)) - g^\perp(S(X_2,X_3),S(X_1,X_4)).
\end{aligned}$$

where we also used (17.3.1) and (17.3.2) in:

$$\begin{aligned}
\bar g(\bar\nabla_{X_1}S(X_2,X_3),X_4) &= \bar g(\nabla^\perp_{X_1}S(X_2,X_3) - L_{S(X_2,X_3)}(X_1),X_4)\\
&= 0 - g^\perp(S(X_1,X_4),S(X_2,X_3)).
\end{aligned}$$

So (1) and (2) follow. For equation (3) we have to compute the normal components of the $+--$ sum of the first three equations in this proof:

$$\begin{aligned}
&(\bar R(X_1,X_2)X_3)^\perp = 0 + S(X_1,\nabla_{X_2}X_3) + \big(\bar\nabla_{X_1}S(X_2,X_3)\big)^\perp - 0 - S(X_2,\nabla_{X_1}X_3)\\
&\qquad - \big(\bar\nabla_{X_2}S(X_1,X_3)\big)^\perp - 0 - S(\nabla_{X_1}X_2,X_3) + S(\nabla_{X_2}X_1,X_3)\\
&\quad = \big(\nabla^\perp_{X_1}S(X_2,X_3) - S(\nabla_{X_1}X_2,X_3) - S(X_2,\nabla_{X_1}X_3)\big)\\
&\qquad - \big(\nabla^\perp_{X_2}S(X_1,X_3) - S(\nabla_{X_2}X_1,X_3) - S(X_1,\nabla_{X_2}X_3)\big)\\
&\quad = \big(\nabla^{Ti^\perp\otimes T^*M\otimes T^*M}_{X_1}S\big)(X_2,X_3) - \big(\nabla^{Ti^\perp\otimes T^*M\otimes T^*M}_{X_2}S\big)(X_1,X_3).
\end{aligned}$$

For the proof of (4) we start from the Weingarten formula (17.3.1) and use (17.1):

$$\begin{aligned}
\bar\nabla_{X_1}(\bar\nabla_{X_2}\xi) &= \bar\nabla_{X_1}(\nabla^\perp_{X_2}\xi - L_\xi(X_2))\\
&= \nabla^\perp_{X_1}\nabla^\perp_{X_2}\xi - L_{\nabla^\perp_{X_2}\xi}(X_1) - \nabla_{X_1}(L_\xi(X_2)) - S(X_1,L_\xi(X_2))\\
\bar\nabla_{X_2}(\bar\nabla_{X_1}\xi) &= \nabla^\perp_{X_2}\nabla^\perp_{X_1}\xi - L_{\nabla^\perp_{X_1}\xi}(X_2) - \nabla_{X_2}(L_\xi(X_1)) - S(X_2,L_\xi(X_1))\\
\bar\nabla_{[X_1,X_2]}\xi &= \nabla^\perp_{[X_1,X_2]}\xi - L_\xi([X_1,X_2])\\
&= \nabla^\perp_{[X_1,X_2]}\xi - L_\xi(\nabla_{X_1}X_2) + L_\xi(\nabla_{X_2}X_1)
\end{aligned}$$

Inserting this we get for the tangential part:

$$\begin{aligned}(\bar R(X_1,X_2)\xi)^\top &= L_{\nabla^\perp_{X_1}\xi}(X_2) - L_{\nabla^\perp_{X_2}\xi}(X_1)\\ &\quad + \nabla_{X_2}(L_\xi(X_1)) - L_\xi(\nabla_{X_2}X_1) - \nabla_{X_1}(L_\xi(X_2)) + L_\xi(\nabla_{X_1}X_2)\\ &= -(\nabla^{TM\otimes(Ti^\perp)^*\otimes T^*M}_{X_1}L)_\xi(X_2) + (\nabla^{TM\otimes(Ti^\perp)^*\otimes T^*M}_{X_2}L)_\xi(X_1)\end{aligned}$$

For the normal part we get:

$$\begin{aligned}(\bar R(X_1,X_2)\xi)^\perp &= \nabla^\perp_{X_1}\nabla^\perp_{X_2}\xi - \nabla^\perp_{X_2}\nabla^\perp_{X_1}\xi - \nabla^\perp_{[X_1,X_2]}\xi\\ &\quad - S(X_1,L_\xi(X_2)) + S(X_2,L_\xi(X_1)). \quad\square\end{aligned}$$

17.5. Hypersurfaces. Let $i : (M,g) \to (\bar M,\bar g)$ be an isometrically embedded hypersurface, so that $\dim(\bar M) = \dim(M)+1$. Let ν be a local unit normal field along M, i.e., $\nu \in \Gamma(Ti^\perp|U)$ with $|\nu|_{\bar g} = 1$. There are two choices for ν.

Theorem. *In this situation we have:*

(1) $\bar\nabla_X\nu \in TM$ *for all* $X \in TM$.

(2) *For* $X,Y \in \mathfrak{X}(M)$ *we have (Weingarten equation):*

$$\bar g(\bar\nabla_X\nu,Y) = -\bar g(\nu,\bar\nabla_XY) = -g^\perp(\nu,S(X,Y)).$$

(3) $\bar g(\bar\nabla_X\nu,Y) = \bar g(\bar\nabla_Y\nu,X)$.

(4) *If we put* $s(X,Y) := g^\perp(\nu,S(X,Y))$ *then* s *is called the classical second fundamental form and the Weingarten equation* (2) *takes the following form:*

$$\bar g(\bar\nabla_X\nu,Y) = -s(X,Y).$$

(5) *For hypersurfaces the Codazzi Mainardi equation takes the following form:*

$$\bar g(\bar R(X_1,X_2)X_3,\nu) = (\nabla_{X_1}s)(X_2,X_3) - (\nabla_{X_2}s)(X_1,X_3).$$

Proof. (1) Since $1 = \bar g(\nu,\nu)$ we get $0 = X(\bar g(\nu,\nu)) = 2\bar g(\bar\nabla_X\nu,\nu)$, thus $\bar\nabla_X\nu$ is tangent to M.

(2) Since $0 = \bar g(\nu,Y)$ we get $0 = X(\bar g(\nu,Y)) = \bar g(\bar\nabla_X\nu,Y) + \bar g(\nu,\bar\nabla_XY)$ and thus $\bar g(\bar\nabla_X\nu,Y) = -\bar g(\nu,\bar\nabla_XY) = -\bar g(\nu,\nabla_XY + S(X,Y)) = -\bar g(\nu,S(X,Y))$.

(3) follows from (2) and symmetry of $S(X,Y)$. (4) is a reformulation.

(5) We put ourselves back into the proof of (17.4.3) and use $S(X,Y) = s(X,Y).\nu$ and the fact that $s \in \Gamma(S^2T^*M|U)$ is a $\binom{0}{2}$ tensorfield so that ∇_Xs makes sense. We have $\bar\nabla_{X_1}(S(X_2,X_3)) = \bar\nabla_{X_1}(s(X_2,X_3).\nu) = X_1(s(X_2,X_3).\nu + s(X_2,X_3).\bar\nabla_{X_1}\nu$, and by (1) $\bar\nabla_{X_1}\nu$ is tangential to M. Thus the normal part is:

$$\begin{aligned}\big(\bar\nabla_{X_1}(S(X_2,X_3))\big)^\perp &= X_1(s(X_2,X_3)).\nu\\ &= (\nabla_{X_1}s)(X_2,X_3).\nu + s(\nabla_{X_1}X_2,X_3).\nu + s(X_2,\nabla_{X_1}X_3).\nu.\end{aligned}$$

Now we put this into the formula of the proof of (17.4.3):

$$\begin{aligned}(\bar R(X_1,X_2)X_3)^\perp &= S(X_1,\nabla_{X_2}X_3) + \big(\bar\nabla_{X_1}(S(X_2,X_3))\big)^\perp - S(X_2,\nabla_{X_1}X_3)\\ &\quad - \big(\bar\nabla_{X_2}(S(X_1,X_3))\big)^\perp - S(\nabla_{X_1}X_2,X_3) + S(\nabla_{X_2}X_1,X_3)\\ &= \big((\nabla_{X_1}s)(X_2,X_3) - (\nabla_{X_2}s)(X_1,X_3)\big)\nu. \quad\square\end{aligned}$$

17.6. Remark. (*Theorema egregium proper*) Let M be a surface in $\mathbb{R}^3$, then $\bar{R} = 0$ and by (17.4.1) we have for $X, Y \in T_xM$:

$$0 = \langle \bar{R}(X,Y)X, Y\rangle = \langle R(X,Y)X, Y\rangle + s(X,X).s(Y,Y) - s(Y,X).s(X,Y).$$

Let us now choose a local coordinate system $(U, (x,y))$ on M and put

$$\begin{aligned}
g &= i^*\langle\quad,\quad\rangle =: E\,dx\otimes dx + F\,dx\otimes dy + F\,dy\otimes dx + G\,dy\otimes dy,\\
s &=: l\,dx\otimes dx + m\,dx\otimes dy + m\,dy\otimes dx + n\,dy\otimes dy, \qquad \text{then}\\
K &= \text{ Gauß' curvature } = \text{ sectional curvature } =\\
&= -\frac{\langle R(\partial_x,\partial_y)\,\partial_x,\partial_y\rangle}{|\,\partial_x\,|^2|\,\partial_y\,|^2 - \langle\partial_x,\partial_y\rangle^2} = \frac{s(\partial_x,\partial_x).s(\partial_y,\partial_y) - s(\partial_x,\partial_y)^2}{EG-F^2}\\
&= \frac{ln - m^2}{EG-F^2},
\end{aligned}$$

which is Gauß' formula for his curvature in his notation.

17.7. Adapted frames for isometric embeddings. All the following also holds for immersions. For notational simplicity we stick with embeddings. Let $e : (M,g) \to (\bar{M},\bar{g})$ be an isometric embedding of Riemann manifolds, let $\dim(\bar{M}) = m+p$ and $\dim(M) = m$. An *adapted orthonormal frame* $\bar{s} = (\bar{s}_1,\dots,\bar{s}_{m+p})$ is orthonormal frame for $\bar{M}$ over $\bar{U} \subset \bar{M}$ such that for $U = \bar{U} \cap M \subset M$ the fields $s_1 = \bar{s}_1|_U, \dots, s_m = \bar{s}_m|_U$ are tangent to M. Thus $s = (s_1,\dots,s_m)$ is an orthonormal frame for M over U. The orthonormal coframe

$$\bar{\sigma} = \begin{pmatrix} \bar{\sigma}^1 \\ \vdots \\ \bar{\sigma}^{m+p}\end{pmatrix} = (\bar{\sigma}^1,\dots,\bar{\sigma}^{m+p})^\top$$

for $\bar{M}$ over $\bar{U}$ dual to $\bar{s}$ is then given by $\bar{\sigma}^{\bar{\imath}}(\bar{s}_{\bar{\jmath}}) = \delta^{\bar{\imath}}_{\bar{\jmath}}$. We recall from (16.5):

(1)
$$\begin{aligned}
&\bar{g} = \textstyle\sum_{\bar{\imath}=1}^{m+p} \bar{\sigma}^{\bar{\imath}} \otimes \bar{\sigma}^{\bar{\imath}}.\\
&\bar{\nabla}\bar{s} = \bar{s}.\bar{\omega}, \quad \bar{\omega}^{\bar{\imath}}_{\bar{\jmath}} = -\bar{\omega}^{\bar{\jmath}}_{\bar{\imath}}, \quad \text{so } \bar{\omega} \in \Omega^1(\bar{U}, \mathfrak{so}(m+p)).\\
&d\bar{\sigma} + \bar{\omega}\wedge\bar{\sigma} = 0, \quad d\bar{\sigma}^{\bar{\imath}} + \textstyle\sum_{\bar{k}=1}^{m+p} \bar{\omega}^{\bar{\imath}}_{\bar{k}} \wedge \bar{\sigma}^{\bar{k}} = 0.\\
&\bar{R}\bar{s} = \bar{s}.\bar{\Omega}, \quad \bar{\Omega} = d\bar{\omega} + \bar{\omega}\wedge\bar{\omega} \in \Omega^2(\bar{U}, \mathfrak{so}(m+p)),\\
&\qquad \bar{\Omega}^{\bar{\imath}}_{\bar{\jmath}} = d\bar{\omega}^{\bar{\imath}}_{\bar{\jmath}} + \textstyle\sum_{\bar{k}=1}^{m+p} \bar{\omega}^{\bar{\imath}}_{\bar{k}} \wedge \bar{\omega}^{\bar{k}}_{\bar{\jmath}}.\\
&\bar{\Omega}\wedge\bar{\sigma} = 0, \quad \textstyle\sum_{\bar{k}=1}^{m+p} \bar{\Omega}^{\bar{\imath}}_{\bar{k}} \wedge \bar{\sigma}^{\bar{k}} = 0, \quad \text{first Bianchi identity.}\\
&d\bar{\Omega} + \bar{\omega}\wedge\bar{\Omega} - \bar{\Omega}\wedge\bar{\omega} = d\bar{\Omega} + [\bar{\omega},\bar{\Omega}]_\wedge = 0, \quad \text{second Bianchi identity.}
\end{aligned}$$

Likewise we have the orthonormal coframe $\sigma = (\sigma^1,\dots,\sigma^m)^\top$ for M over U dual to s is then given by $\sigma^i(s_j) = \delta^i_j$. Recall again from (16.5):

(2) $g = \sum_{i=1}^m \sigma^i \otimes \sigma^i$.

$\nabla s = s.\omega, \quad \omega^i_j = -\omega^j_i, \quad$ so $\omega \in \Omega^1(U, \mathfrak{so}(m))$.

$d\sigma + \omega \wedge \sigma = 0, \quad d\sigma^i + \sum_{k=1}^m \omega^i_k \wedge \sigma^k = 0.$

$Rs = s.\Omega, \quad \Omega = d\omega + \omega \wedge \omega \in \Omega^2(U, \mathfrak{so}(m)),$

$\Omega^i_j = d\omega^i_j + \sum_{k=1}^m \omega^i_k \wedge \omega^k_j.$

$\Omega \wedge \sigma = 0, \quad \sum_{k=1}^m \Omega^i_k \wedge \sigma^k = 0, \quad$ first Bianchi identity.

$d\Omega + \omega \wedge \Omega - \Omega \wedge \omega = d\Omega + [\omega, \Omega]_\wedge = 0, \quad$ second Bianchi identity.

Obviously we have $\bar\sigma^i|_U = \sigma^i$, more precisely $e^*\bar\sigma^i = \sigma^i$, for $i = 1, \dots, m$, and $e^*\bar\sigma^{\bar\imath} = 0$ for $\bar\imath = m+1, \dots, m+p$. We want to compute $e^*\bar\omega$. From $d\bar\sigma^{\bar\imath} + \sum_{\bar k=1}^{m+p} \bar\omega^{\bar\imath}_{\bar k} \wedge \bar\sigma^{\bar k} = 0$ we get

(3) $$d\sigma^i = -\sum_{\bar k=1}^{m+p} e^*\bar\omega^i_{\bar k} \wedge e^*\bar\sigma^{\bar k} = -\sum_{k=1}^m e^*\bar\omega^i_k \wedge \sigma^k \quad \text{for } i = 1, \dots, m.$$
$$0 = -\sum_{\bar k=1}^{m+p} e^*\bar\omega^{\bar\imath}_{\bar k} \wedge e^*\bar\sigma^{\bar k} = -\sum_{k=1}^m e^*\bar\omega^{\bar\imath}_k \wedge \sigma^k \quad \text{for } m+1 \le \bar\imath.$$

Since also $e^*\bar\omega^i_j = -e^*\bar\omega^j_i$, the forms $e^*\bar\omega^i_j$ for $1 \le i, j \le m$ satisfy the defining equations for ω^i_j; thus we have:

(4) $$\omega^i_j = e^*\bar\omega^i_j, \quad \text{for } 1 \le i, j \le m.$$

Since $\bar g(\bar\nabla_X s_i, s_j) = \bar\omega^j_i(X) = \omega^j_i(X) = g(\nabla_X s_i, s_j)$ for $X \in \mathfrak{X}(M)$, equation (4) also expresses the fact that the tangential part $(\bar\nabla_X s_i)^\top = \nabla_X s_i$.

Next we want to investigate the forms $e^*\bar\omega^i_{\bar\jmath} = -e^*\bar\omega^{\bar\jmath}_i$ for $1 \le i \le m$ and $m+1 \le \bar\jmath \le m+p$. We shall need the following result.

(5) **Lemma.** *(E. Cartan) For $\bar U$ open in $\bar M^{m+p}$, let $\lambda^1, \dots, \lambda^m \in \Omega^1(\bar U)$ be everywhere linearly independent, and consider 1-forms $\mu_1, \dots, \mu_m \in \Omega^1(\bar U)$ such that $\sum_{i=1}^m \mu_i \wedge \lambda^i = 0$. Then there exist unique smooth functions $f_{ij} \in C^\infty(\bar U)$ satisfying $\mu_i = \sum_{j=1}^m f_{ij}\lambda^j$ and $f_{ij} = f_{ji}$.*

Proof. Near each point we may find $\lambda^{m+1}, \dots, \lambda^{m+p}$ such that $\lambda^1, \dots, \lambda^{m+p}$ are everywhere linearly independent, thus they form a coframe. Then there exist unique f_{ij} such that $\mu_i = \sum_{\bar k=1}^{m+p} f_{i\bar\jmath}\lambda^{\bar\jmath}$. But we have

$$0 = \sum_{i=1}^m \mu_i \wedge \lambda^i = \sum_{i=1}^m \sum_{\bar k=1}^{m+p} f_{i\bar k}\, \lambda^{\bar k} \wedge \lambda^i$$
$$= \sum_{1 \le k < i \le m} (f_{ik} - f_{ki})\lambda^k \wedge \lambda^i + \sum_{i=1}^m \sum_{\bar k=m+1}^{m+p} f_{i\bar k}\, \lambda^{\bar k} \wedge \lambda^i.$$

Since the $\lambda^{\bar k} \wedge \lambda^{\bar\imath}$ for $\bar k < \bar\imath$ are linearly independent we conclude that $f_{ik} = f_{ki}$ for $1 \le i, k \le m$ and $f_{i\bar k} = 0$ for $1 \le i \le m < \bar k \le m+p$. $\square$

By (3) we have $0 = \sum_{k=1}^m e^*\bar\omega^{\bar\imath}_k \wedge \sigma^k$ for $\bar\imath = m+1\dots m+p$. By lemma (5) thus there exist unique functions $s^{\bar\imath}_{kj} \in C^\infty(U)$ for $1 \le j,k \le m$ and $\bar\imath = m+1,\dots,m+p$ with:

$$e^*\bar\omega^{\bar\imath}_k = \sum_{j=1}^m s^{\bar\imath}_{kj}\sigma^j, \qquad s^{\bar\imath}_{kj} = s^{\bar\imath}_{jk}. \tag{6}$$

This is equivalent to the Weingarten formula (17.3.1).

Since $\bar g(\bar\nabla_{s_k}s_j, \bar s_{\bar\imath}) = \bar\omega^{\bar\imath}_j(s_k) = (e^*\bar\omega^{\bar\imath}_j)(s_k) = s^{\bar\imath}_{jk}$ we have by (17.1)

$$S(s_i,s_j) = \sum_{\bar k=m+1}^{m+p} (\bar s_{\bar k}|U)(e^*\omega^{\bar k}_j)(s_i) = \sum_{\bar k=m+1}^{m+p} (\bar s_{\bar k}|U)s^{\bar k}_{ij} \tag{7}$$

Let us now investigate the second structure equation $\bar\Omega^{\bar\imath}_{\bar\jmath} = d\bar\omega^{\bar\imath}_{\bar\jmath} + \sum_{\bar k=1}^{m+p} \bar\omega^{\bar\imath}_{\bar k} \wedge \bar\omega^{\bar k}_{\bar\jmath}$. We look first at indices $1 \le i,j \le m$ and restrict it to M:

$$\begin{aligned}
e^*\bar\Omega^i_j &= de^*\bar\omega^i_j + \sum_{k=1}^m e^*\bar\omega^i_k \wedge e^*\bar\omega^k_j + \sum_{\bar k=m+1}^{m+p} e^*\bar\omega^i_{\bar k} \wedge e^*\bar\omega^{\bar k}_j\\
&= d\omega^i_j + \sum_{k=1}^m \omega^i_k \wedge \omega^k_j + \sum_{\bar k=m+1}^{m+p} e^*\bar\omega^i_{\bar k} \wedge e^*\bar\omega^{\bar k}_j
\end{aligned}$$

$$e^*\bar\Omega^i_j = \Omega^i_j + \sum_{\bar k=m+1}^{m+p} e^*\bar\omega^i_{\bar k} \wedge e^*\omega^{\bar k}_j = \Omega^i_j - \sum_{\bar k=m+1}^{m+p}\sum_{l,n=1}^m s^{\bar k}_{il}s^{\bar k}_{jn}\,\sigma^l\wedge\sigma^n \tag{8}$$

This is equivalent to the Gauß equation (17.4.1).

Then we look at the indices $1 \le j \le m < \bar\imath \le m+p$ and restrict the second structure equation to M:

$$\begin{aligned}
e^*\bar\Omega^{\bar\imath}_j &= de^*\bar\omega^{\bar\imath}_j + \sum_{k=1}^m e^*\bar\omega^{\bar\imath}_k \wedge e^*\bar\omega^k_j + \sum_{\bar k=m+1}^{m+p} e^*\bar\omega^{\bar\imath}_{\bar k} \wedge e^*\bar\omega^{\bar k}_j\\
&= de^*\bar\omega^{\bar\imath}_j + \sum_{k=1}^m e^*\bar\omega^{\bar\imath}_k \wedge \omega^k_j + \sum_{\bar k=m+1}^{m+p} e^*\bar\omega^{\bar\imath}_{\bar k} \wedge e^*\bar\omega^{\bar k}_j,
\end{aligned} \tag{9}$$

which is equivalent to the *Codazzi Mainardi equation.* In the case of a hypersurface this takes the simpler form:

$$e^*\bar\Omega^{m+1}_j = de^*\bar\omega^{m+1}_j + \sum_{k=1}^m e^*\bar\omega^{m+1}_k \wedge \omega^k_j$$

17.8. Resumee of computing with adapted frames. Let $e : (M, g) \to (\bar M, \bar g)$ be an isometric embedding between Riemann manifolds. Let $\bar s = (\bar s_1, \dots, \bar s_{m+p})$ be an orthonormal local frame on $\bar M$ over $\bar U \subset \bar M$ with connection 1-form $\bar\omega = (\bar\omega^{\bar\imath}_{\bar\jmath}) \in \Omega^1(U, \mathfrak{so}(m+p))$ and curvature 2-form $\bar\Omega = (\bar\Omega^{\bar\imath}_{\bar\jmath}) \in \Omega^2(U, \mathfrak{so}(m+p))$, such that the $s_i := \bar s_i | U$ form a local orthonormal frame $s = (s_1, \dots, s_m)$ of TM over $U = \bar U \cap M$, with connection 1-form $\omega = (\omega^i_j) \in \Omega^1(U, \mathfrak{so}(m))$ and curvature 2-form $\Omega = (\Omega^i_j) \in \Omega^2(U, \mathfrak{so}(m))$. Let

$$\bar\sigma = \begin{pmatrix} \bar\sigma^1 \\ \vdots \\ \bar\sigma^{m+p} \end{pmatrix}, \qquad \sigma = \begin{pmatrix} \sigma^1 \\ \vdots \\ \sigma^m \end{pmatrix}$$

be the dual coframes. Using the ranges of indices $1 \le i, j, k, l \le m$ and $m+1 \le \bar\imath, \bar\jmath, \bar k \le m+p$ we then have:

$$\begin{aligned}
&e^*\bar\sigma^i = \sigma^i, \qquad e^*\bar\sigma^{\bar\imath} = 0,\\
&e^*\bar\omega^i_j = \omega^i_j, \qquad e^*\bar\omega^{\bar\imath}_j = \textstyle\sum_{k\le m} s^{\bar\imath}_{jk}\sigma^k, \qquad s^{\bar\imath}_{jk} = s^{\bar\imath}_{kj},\\
&e^*\bar\Omega^i_j = \Omega^i_j + \textstyle\sum_{m<\bar k} e^*\bar\omega^i_{\bar k} \wedge e^*\bar\omega^{\bar k}_j = \Omega^i_j - \sum_{\bar k=m+1}^{m+p} \sum_{l,n=1}^m s^{\bar k}_{il} s^{\bar k}_{jn}\, \sigma^l \wedge \sigma^n,\\
&e^*\bar\Omega^{\bar\imath}_j = de^*\bar\omega^{\bar\imath}_j + \sum_{k=1}^m e^*\bar\omega^{\bar\imath}_k \wedge \omega^k_j + \sum_{\bar k=m+1}^{m+p} e^*\bar\omega^{\bar\imath}_{\bar k} \wedge e^*\bar\omega^{\bar k}_j.
\end{aligned}$$

17.9. Definitions. Let $p : E \to B$ be a submersion of smooth manifolds, that is $Tp : TE \to TB$ surjective. Then

$$V = V(p) = V(E) := \ker(Tp)$$

is called the *vertical subbundle* of E. If E is a Riemann manifold with metric g, then we can go on to define the *horizontal subbundle* of E.

$$\mathrm{Hor} = \mathrm{Hor}(p) = \mathrm{Hor}(E) = \mathrm{Hor}(E, g) := V(p)^\perp$$

If both (E, g_E) and (B, g_B) are Riemann manifolds, then we will call p a *Riemannian submersion*, if

$$T_x p : \mathrm{Hor}(p)_x \to T_{p(x)}B$$

is an isometric isomorphism for all $x \in E$.

Examples: For any two Riemann manifolds M, N, the projection $pr_1 : M \times N \to M$ is a Riemannian submersion. Here the Riemann metric on the product $M \times N$ is given by: $g_{M\times N}(X_M + X_N, Y_M + Y_N) := g_M(X_M, Y_M) + g_N(X_N, Y_N)$ using $T(M \times N) \cong TM \oplus TN$. In particular, $\mathbb{R}^{m+n} \to \mathbb{R}^m$ with the usual metric, or $pr_2 : S^n \times \mathbb{R}^+ \to \mathbb{R}^+$ are Riemannian submersions.

17.10. Definition. Let $p : E \to B$ be a Riemannian submersion. A vector field:
$\xi \in \mathfrak{X}(E)$ is called *vertical*, if $\xi(x) \in V_x(p)$ for all x (i.e., if $Tp\,\xi(x) = 0$).
$\xi \in \mathfrak{X}(E)$ is called *horizontal*, if $\xi(x) \in \mathrm{Hor}_x(p)$ for all x (i.e., if $\xi(x) \perp V_x(p)$).

$\xi \in \mathfrak{X}(E)$ is called *projectable*, if there is an $\eta \in \mathfrak{X}(B)$, such that $Tp.\xi = \eta \circ p$.
$\xi \in \mathfrak{X}(E)$ is called *basic*, if it is horizontal and projectable.

The orthogonal projection $\Phi : TE \to V(E)$ with respect to the Riemann metric is a (generalized) connection on the bundle (E, p) in the sense of section (20) below and defines a local parallel transport over each curve in B (denoted by $\operatorname{Pt}^\Phi(c, .)$) as well as the horizontal lift:

$$C : TB \underset{B}{\times} E \to TE : (X_b, e) \mapsto Y_e, \text{ where } Y_e \in \operatorname{Hor}_e(p) \text{ with } T_e p.Y_e = X_b$$

This map also gives us an isomorphism $C_* : \mathfrak{X}(B) \to \mathfrak{X}_{\text{basic}}(E)$ between the vector fields on B and the basic vector fields.

17.11. Lemma. *Consider a Riemannian submersion $p : (E, g_E) \to (B, g_B)$ with connection $\Phi : TE \to V(p)$, and $c : [0,1] \to B$, a geodesic. Then we have:*

(1) *The length $L_0^t(c) = L_0^t \operatorname{Pt}^\Phi(c, ., u)$, where $u \in E_{c(0)}$ is the starting point of the parallel transport. For the energy $E_0^t(c) = E_0^t(\operatorname{Pt}^\Phi(c, ., u))$.*
(2) $\operatorname{Pt}^\Phi(c, ., u) \perp E_{c(t)}$ *for all t.*
(3) *If c is a geodesic of minimal length in B, then we have $L_0^1(\operatorname{Pt}^\Phi(c, ., u)) =$ $\operatorname{dist}\big(E_{c(0)}, E_{c(1)}\big)$.*
(4) $t \mapsto \operatorname{Pt}^\Phi(c, t, u)$ *is a geodesic in E (again for any geodesic c in B).*

Proof. (1) Since $\partial_s \operatorname{Pt}^\Phi(c, s, u)$ is a horizontal vector and by the property of p as Riemannian submersion, we have

$$\begin{aligned} L_0^t(\operatorname{Pt}^\Phi(c, ., u)) &= \int_0^t g_E\left(\partial_s \operatorname{Pt}^\Phi(c, s, u), \partial_s \operatorname{Pt}^\Phi(c, s.u)\right)^{\frac{1}{2}} ds \\ &= \int_0^t g_B(c'(s), c'(s))^{\frac{1}{2}} ds = L_0^t(c), \\ E_0^t(\operatorname{Pt}^\Phi(c, ., u)) &= \frac{1}{2}\int_0^t g_E\left(\partial_s \operatorname{Pt}^\Phi(c, s, u), \partial_s \operatorname{Pt}^\Phi(c, s.u)\right) ds = E_0^t(c). \end{aligned}$$

(2) This is due to our choice of Φ as orthogonal projection onto the vertical bundle in terms of the given metric on E. By this choice, the parallel transport is the unique horizontal curve covering c, so it is orthogonal to each fiber $E_{c(t)}$ it meets.

(3) Consider a (piecewise) smooth curve $e : [0,1] \to E$ from $E_{c(0)}$ to $E_{c(1)}$, then $p \circ e$ is a (piecewise) smooth curve from $c(0)$ to $c(1)$. Since c is a minimal geodesic, we have $L_0^1(c) \le L_0^1(p \circ e)$. Furthermore, we can decompose the vectors tangent to e into horizontal and vertical components and use the fact that Tp is an isometry on horizontal vectors to show that $L_0^1(e) \ge L_0^1(p \circ e)$:

$$\begin{aligned} L_0^1(e) &= \int_0^1 |e'(t)^{\text{ver}} + e'(t)^{\text{hor}}|_{g_E} dt \\ &\ge \int_0^1 |e'(t)^{\text{hor}}|_{g_E} dt = \int_0^1 |(p \circ e)'(t)|_{g_M} dt = L_0^1(p \circ e). \end{aligned}$$

Now with (1) we can conclude:

$$L_0^1(e) \geq L_0^1(p \circ e) \geq L_0^1(c) = L_0^1(\mathrm{Pt}^\Phi(c, ., u))$$

for all (piecewise) smooth curves e from $E_{c(0)}$ to $E_{c(1)}$. Therefore, $L_0^1(\mathrm{Pt}^\Phi(c, ., u)) = \operatorname{dist}\big(E_{c(0)}, E_{c(1)}\big)$.

(4) This is a consequence of (3) and the observation from (13.4) that every curve which minimizes length or energy locally is a geodesic. □

17.12. Corollary. *Consider a Riemannian submersion $p : E \to B$, and let $c : [0,1] \to E$ be a geodesic in E with the property $c'(t_0) \perp E_{p(c(t_0))}$ for some t_0. Then $c'(t) \perp E_{p(c(t))}$ for all $t \in [0,1]$ and $p \circ c$ is a geodesic in B.*

Proof. Consider the curve $f : t \mapsto \exp^B_{p(c(t_0))}(tT_{c(t_0)}p.c'(t_0))$. It is a geodesic in B and therefore lifts to a geodesic $e(t) = \mathrm{Pt}^\Phi(f, t - t_0, c(t_0))$ in E by (17.11.4). Furthermore $e(t_0) = c(t_0)$ and $e'(t_0) = C(T_{c(t_0)}p.c'(t_0), c(t_0)) = c'(t_0)$ since $c'(t_0) \perp E_{p(c(t_0))}$ is horizontal. But geodesics are uniquely determined by their starting point and starting vector. Therefore $e = c$, thus e is orthogonal to each fiber it meets by (17.11.2) and it projects onto the geodesic f in B. □

17.13. Corollary. *Let $p : E \to B$ be a Riemannian submersion. If* $\mathrm{Hor}(E)$ *is integrable then:*

1. *Every leaf is totally geodesic in the sense of* (17.2).
2. *For each leaf L the restriction $p : L \to B$ is a local isometry.*

Proof. (1) follows from corollary (17.12), while (2) is just a direct consequence of the definitions. □

17.14. Remark. If $p : E \to B$ is a Riemannian submersion, then $\mathrm{Hor}(E)|_{E_b} = \mathrm{Nor}(E_b)$ for all $b \in B$ and p defines a global parallelism as follows. A section $\tilde v \in C^\infty(\mathrm{Nor}(E_b))$ is called p-parallel, if $T_e p.\tilde v(e) = v \in T_b B$ is the same point for all $e \in E_b$. There is also a second parallelism. It is given by the induced covariant derivative: A section $\tilde v \in C^\infty(\mathrm{Nor}(E_b))$ is called parallel if $\nabla^{\mathrm{Nor}}\tilde v = 0$. The p-parallelism is always flat and with trivial holonomy which is not generally true for ∇^{Nor}. Yet we will see later on that if $\mathrm{Hor}(E)$ is integrable then the two parallelisms coincide.

17.15. Definition. *A Riemannian submersion $p : E \to B$ is called integrable, if* $\mathrm{Hor}(E) = (\ker Tp)^\perp$ *is an integrable distribution.*

17.16. Local Theory of Riemannian Submersions. Let $p : (E, g_E) \to (B, g_B)$ be a Riemannian submersion. Choose for an open neighborhood U in E an orthonormal frame field $s = (s_1, \dots, s_{m+k}) \in \Gamma(TE|U)^{m+k}$ in such a way that $s_1, \dots, s_m$ are vertical and $s_{m+1}, \dots, s_{m+k}$ are basic (horizontal and projectable). That way, if we project $s_{m+1}, \dots, s_{m+k}$ onto $TB|p(U)$ we get another orthonormal frame field, $\bar s = (\bar s_{m+1}, \dots, \bar s_{m+k}) \in C^\infty(TB|p(U))^k$, since p, as Riemannian submersion, is isometric on horizontal vectors. The indices will always run in the domain indicated:

$$1 \le i, j, k \le m, \quad m+1 \le \bar a, \bar b, \bar c \le m+k, \quad 1 \le A, B, C \le m+k.$$

The orthonormal coframe dual to s is given by

$$\sigma^A(s_B) = \delta^A_B, \qquad \sigma = \begin{pmatrix} \sigma^1 \\ \vdots \\ \sigma^{m+k} \end{pmatrix} \in \Omega^1(U)^{m+k}.$$

Analogously, we have the orthonormal coframe $\bar\sigma^{\bar a} \in \Omega^1(p(U))$ on $p(U) \subseteq B$, with $\bar\sigma^{\bar a}(\bar s_{\bar b}) = \delta^{\bar a}_{\bar b}$. It is related to $\sigma^{\bar a}$ by $p^*\bar\sigma^{\bar a} = \sigma^{\bar a}$. By (16.5) we have on $(U \subset E, g_E)$

$$\begin{aligned}
&g_E|_U = \textstyle\sum_A \sigma^A \otimes \sigma^A.\\
&\nabla^E s = s.\omega \quad \text{where} \quad \omega^A_B = -\omega^B_A, \quad \text{so} \quad \omega \in \Omega^1(U, \mathfrak{so}(n+k)).\\
&d\sigma + \omega\wedge\sigma = 0, \quad \text{i.e.,} \quad d\sigma^A + \textstyle\sum_C \omega^A_C \wedge \sigma^C = 0.\\
&Rs = s.\Omega \quad \text{where} \quad \Omega = d\omega + \omega\wedge\omega \in \Omega^2(U, \mathfrak{so}(n+k)),\\
&\qquad\qquad\quad \text{or} \qquad \Omega^A_B = d\omega^A_B + \textstyle\sum_C \omega^A_C \wedge \omega^C_B.\\
&\Omega\wedge\sigma = 0 \quad \text{or} \quad \textstyle\sum_C \Omega^A_C \wedge \sigma^C = 0, \quad \text{the first Bianchi identity.}\\
&d\Omega + \omega\wedge\Omega - \Omega\wedge\omega = d\Omega + [\omega,\Omega]_\wedge = 0, \quad \text{the second Bianchi identity.}
\end{aligned}$$

and similarly on $(p(U) \subset B, g^B)$ with bars on all forms.

For the following it will be faster to rederive results as compiling some of them from (17.7) and (17.8). We start by pulling back the structure equation $d\bar\sigma + \bar\omega \wedge \bar\sigma = 0$ from B to E via p^*:

$$0 = p^*\left(d\bar\sigma^{\bar a} + \sum \bar\omega^{\bar a}_{\bar b} \wedge \bar\sigma^{\bar b}\right) = dp^*\bar\sigma^{\bar a} + \sum (p^*\bar\omega^{\bar a}_{\bar b}) \wedge (p^*\bar\sigma^{\bar b}) = d\sigma^{\bar a} + \sum (p^*\bar\omega^{\bar a}_{\bar b}) \wedge \sigma^{\bar b}$$

The $\bar a$-part of the structure equation on E, $d\sigma^{\bar a} + \sum \omega^{\bar a}_{\bar b} \wedge \sigma^{\bar b} + \sum \omega^{\bar a}_i \wedge \sigma^i = 0$, combines with this to

$$\sum (p^*\bar\omega^{\bar a}_{\bar b}) \wedge \sigma^{\bar b} = \sum \omega^{\bar a}_{\bar b} \wedge \sigma^{\bar b} + \sum \omega^{\bar a}_i \wedge \sigma^i \tag{1}$$

The left hand side of this equation contains no $\sigma^i \wedge \sigma^{\bar a}$- or $\sigma^i \wedge \sigma^j$-terms. Let us write out $\omega^{\bar a}_{\bar b}$ and $\omega^{\bar a}_i$ in this basis.

$$\omega^{\bar a}_{\bar b} = -\omega^{\bar b}_{\bar a} =: \sum q^{\bar a}_{\bar b\bar c}\sigma^{\bar c} + \sum b^{\bar a}_{\bar b i}\sigma^i, \qquad \omega^{\bar a}_i = -\omega^i_{\bar a} =: \sum a^{\bar a}_{i\bar b}\sigma^{\bar b} + \sum r^{\bar a}_{ij}\sigma^j.$$

This gives us for the righthand side of (1)

$$\begin{aligned}
\sum q^{\bar a}_{\bar b\bar c}\sigma^{\bar c}\wedge\sigma^{\bar b} &+ \sum b^{\bar a}_{\bar b i}\sigma^i \wedge \sigma^{\bar b} + \sum a^{\bar a}_{i\bar b}\sigma^{\bar b}\wedge\sigma^i + \sum r^{\bar a}_{ij}\sigma^j\wedge\sigma^i = \\
&= \sum q^{\bar a}_{\bar b\bar c}\sigma^{\bar c}\wedge\sigma^{\bar b} + \sum (b^{\bar a}_{\bar b i} - a^{\bar a}_{i\bar b})\sigma^i\wedge\sigma^{\bar b} + \tfrac12 \sum (r^{\bar a}_{ij} - r^{\bar a}_{ji})\sigma^j \wedge \sigma^i
\end{aligned}$$

So we have found $a^{\bar a}_{i\bar b} = b^{\bar a}_{\bar b i}$ and $r^{\bar a}_{ij} = r^{\bar a}_{ji}$ or, in other words, $\omega^{\bar a}_i(s_{\bar b}) = \omega^{\bar a}_{\bar b}(s_i)$ and $\omega^{\bar a}_i(s_j) = \omega^{\bar a}_j(s_i)$. That is: $\omega^{\bar a}_i(s_A) = \omega^{\bar a}_A(s_i)$, and this just means that the horizontal part of $[s_A, s_i]$ is 0, or $[s_A, s_i]$ is always vertical:

$$0 = \sum s_{\bar a}\omega^{\bar a}_i(s_A) - \sum s_{\bar a}\omega^{\bar a}_A(s_i) = (\nabla_{s_A} s_i - \nabla_{s_i} s_A)^{\text{hor}} = [s_A, s_i]^{\text{hor}}. \tag{2}$$

Now we will consider the second fundamental form $S^{E_b} : TE_b \times_{E_b} TE_b \to \operatorname{Hor}(E)$ of the submanifold $E_b := p^{-1}(b)$ in E. By (17.1) S^{E_b} is given as:

$$\begin{aligned}
S^{E_b}(X^{\text{ver}},Y^{\text{ver}}) &= \nabla^E_{X^{\text{ver}}} Y^{\text{ver}} - \nabla^{E_b}_{X^{\text{ver}}} Y^{\text{ver}} = \nabla^E_{X^{\text{ver}}} Y^{\text{ver}} - \big(\nabla^E_{X^{\text{ver}}} Y^{\text{ver}}\big)^{\text{ver}}\\
&= (\nabla^E_{X^{\text{ver}}} Y^{\text{ver}})^{\text{hor}} = \big(\nabla^E_{X^{\text{ver}}} Y^{\text{ver}}\big)^{\text{hor}}\\
&= \big(\nabla^E_{X^{\text{ver}}}(\textstyle\sum s_i\sigma^i(Y^{\text{ver}}))\big)^{\text{hor}}\\
&= \big(\textstyle\sum(\nabla^E_{X^{\text{ver}}} s_i)\sigma^i(Y^{\text{ver}}) + \sum s_i d(\sigma^i(Y^{\text{ver}})).X^{\text{ver}}\big)^{\text{hor}}\\
&= \big(\textstyle\sum s_A\omega^A_i(X^{\text{ver}})\sigma^i(Y^{\text{ver}})\big)^{\text{hor}} + 0 = \sum s_{\bar a}\omega^{\bar a}_i(X^{\text{ver}})\sigma^i(Y^{\text{ver}})\\
&= \textstyle\sum r^{\bar a}_{ij}\left(s_{\bar a}\otimes\sigma^j\otimes\sigma^i\right)(X^{\text{ver}}, Y^{\text{ver}})
\end{aligned}$$

So

$$\sum s_{\bar a}\sigma^{\bar a}(S^{E_b}) = \sum r^{\bar a}_{ij}\, s_{\bar a}\otimes\sigma^j\otimes\sigma^i.$$

Note that $r^{\bar a}_{ij} = r^{\bar a}_{ji}$ from above corresponds to symmetry of S. The covariant derivative on the normal bundle $\operatorname{Nor}(E_b) = \operatorname{Hor}(E)|_{E_b} \to E_b$ is given by the Weingarten formula (17.3) as the corresponding projection:

$$\begin{aligned}
\nabla^{\text{Nor}} &: \mathfrak{X}(E_b)\times\Gamma(\operatorname{Nor}(E_b)) \longrightarrow \Gamma(\operatorname{Nor}(E_b))\\
\nabla^{\text{Nor}}_{X^{\text{ver}}} Y^{\text{hor}} &= (\nabla^E_{X^{\text{ver}}} Y^{\text{hor}})^{\text{hor}} = \Big(\nabla^E_{X^{\text{ver}}}\Big(\textstyle\sum s_{\bar b}\sigma^{\bar b}(Y^{\text{hor}})\Big)\Big)^{\text{hor}} =\\
&= \Big(\textstyle\sum(\nabla^E_{X^{\text{ver}}} s_{\bar b})\sigma^{\bar b}(Y^{\text{hor}})\Big)^{\text{hor}} + \sum s_{\bar b} d\sigma^{\bar b}(Y^{\text{hor}}).X^{\text{ver}} =\\
&= \textstyle\sum s_{\bar a}\omega^{\bar a}_{\bar b}(X^{\text{ver}})\sigma^{\bar b}(Y^{\text{hor}}) + \sum s_{\bar b} d\sigma^{\bar b}(Y^{\text{hor}}).X^{\text{ver}} =\\
&= \textstyle\sum b^{\bar a}_{\bar b i} s_{\bar a}\otimes\sigma^i\otimes\sigma^{\bar b}(X^{\text{ver}}, Y^{\text{hor}}) + \sum s_{\bar a}\otimes d\sigma^{\bar a}(Y^{\text{hor}})(X^{\text{ver}})\\
\nabla^{\text{Nor}} Y^{\text{hor}} &= \textstyle\sum\Big(b^{\bar a}_{\bar b i}\sigma^{\bar b}(Y^{\text{hor}})\sigma^i + d\sigma^{\bar a}(Y^{\text{hor}})\Big)\otimes s_{\bar a}.
\end{aligned}$$

Yet in the decomposition

$$\nabla^E_X Y = \big(\nabla^E_{X^{\text{ver}}+X^{\text{hor}}}(Y^{\text{ver}} + Y^{\text{hor}})\big)^{\text{ver}+\text{hor}}$$

we can find two more tensor fields (besides S), the so called O'Neill-tensor fields. (see [O'Neill, 1966])

$$\begin{aligned}
&X, Y \in \mathfrak{X}(E)\\
&T(X,Y) := \big(\nabla^E_{X^{\text{ver}}} Y^{\text{ver}}\big)^{\text{hor}} + \big(\nabla^E_{X^{\text{ver}}} Y^{\text{hor}}\big)^{\text{ver}}\\
&A(X,Y) := \big(\nabla^E_{X^{\text{hor}}} Y^{\text{hor}}\big)^{\text{ver}} + \big(\nabla^E_{X^{\text{hor}}} Y^{\text{ver}}\big)^{\text{hor}}
\end{aligned} \tag{3}$$

Each of of these four terms making up A and T is a tensor field by itself - the first one restricting to S on E_b. Why they are combined to two tensors in just this way we will see once we have expressed them in our local frame. At the same time, we will see that they really are tensor fields.

$$\begin{aligned}A(X,Y) &= \big(\nabla^E_{X^{\text{hor}}}\big(\textstyle\sum s_{\bar a}\sigma^{\bar a}(Y)\big)\big)^{\text{ver}} + \big(\nabla^E_{X^{\text{hor}}}(\textstyle\sum s_i\sigma^i(Y))\big)^{\text{hor}} = \\ &= \textstyle\sum s_i\omega^i_{\bar a}(X^{\text{hor}})\sigma^{\bar a}(Y) + 0 + \sum s_{\bar a}\omega^{\bar a}_i(X^{\text{hor}})\sigma^i(Y) + 0 = \\ &= \textstyle\sum s_i(-a^{\bar a}_{i\bar b})\sigma^{\bar b}(X)\sigma^{\bar a}(Y) + \sum s_{\bar a}a^{\bar a}_{i\bar b}\sigma^{\bar b}(X)\sigma^i(Y) = \\ &= \textstyle\sum a^{\bar a}_{i\bar b}(\sigma^{\bar b}\otimes\sigma^i\otimes s_{\bar a} - \sigma^{\bar b}\otimes\sigma^{\bar a}\otimes s_i)(X,Y)\end{aligned}$$

Analogously:

$$T = \textstyle\sum r^{\bar a}_{ij}(\sigma^j\otimes\sigma^i\otimes s_{\bar a} - \sigma^j\otimes\sigma^{\bar a}\otimes s_i)$$

If $\operatorname{Hor}(E)$ is integrable, then every leaf L is totally geodesic by (17.13.1), and the $s_{\bar a}|_L$ are a local orthonormal frame field on L. The leaf L is totally geodesic if and only if its second fundamental form vanishes which is given by

$$S^L(X^{\text{hor}},Y^{\text{hor}}) := (\nabla^E_{X^{\text{hor}}}Y^{\text{hor}})^{\text{ver}}$$

So it is a necessary condition for the integrability of $\operatorname{Hor}(E)$ that $S^L = 0$, that is

$$0 = S^L(s_{\bar a},s_{\bar b}) = (\nabla_{s_{\bar a}}s_{\bar b})^{\text{ver}} = \textstyle\sum s_i\omega^i_{\bar b}(s_{\bar a}) = \sum s_i(-a^{\bar b}_{i\bar c})\sigma^{\bar c}(s_{\bar a}) = -\sum_i s_i a^{\bar b}_{i\bar a}$$

This is equivalent to the condition $a^{\bar a}_{i\bar b} = 0$ for all ${}^{\bar a}_{i\bar b}$ or to $A = 0$.

Let us now prove the converse: If A vanishes, then the horizontal distribution on E is integrable. In this case, we have $0 = A(s_{\bar a},s_{\bar b}) = (\nabla^E_{s_{\bar a}}s_{\bar b})^{\text{ver}} + 0$, as well as $0 = A(s_{\bar b},s_{\bar a}) = (\nabla^E_{s_{\bar b}}s_{\bar a})^{\text{ver}} + 0$. Therefore, $[s_{\bar a},s_{\bar b}] = \nabla^E_{s_{\bar a}}s_{\bar b} - \nabla^E_{s_{\bar b}}s_{\bar a}$ is horizontal, and the horizontal distribution is integrable.

17.17. Theorem. *Let $p : E \to B$ be a Riemannian submersion, then the following conditions are equivalent.*

(1) *p is integrable (that is $\operatorname{Hor}(p)$ is integrable).*
(2) *Every p-parallel normal field along E_b is ∇^{Nor}-parallel.*
(3) *The O'Neill tensor A is zero.*

Proof. We already saw (1) $\iff$ (3) above.

(3) $\implies$ (2) Take $s_{\bar a}$ for a p-parallel normal field X along E_b. $A = 0$ implies $A(s_{\bar a},s_i) = 0 + (\nabla_{s_{\bar a}}s_i)^{\text{hor}} = 0$. Recall that, as we showed in (17.16.1) above, $[s_i,s_{\bar a}]$ is vertical. Therefore,

$$\nabla^{\text{Nor}}_{s_i}s_{\bar a} = (\nabla^E_{s_i}s_{\bar a})^{\text{hor}} = ([s_i,s_{\bar a}] + \nabla^E_{s_{\bar a}}s_i)^{\text{hor}} = 0$$

Since for any $e \in E_b$, $T_ep|_{\operatorname{Nor}_b(E_b)}$ is an isometric isomorphism, a p-parallel normal field X along E_b is determined completely by the equation $X(e) = \sum X^{\bar a}(e)s_{\bar a}(e)$. Therefore it is always a linear combination of the $s_{\bar a}$ with constant coefficients and we are done.

(2) $\implies$ (3) By (2) $\nabla^{\text{Nor}}_{s_i}s_{\bar a} = (\nabla^E_{s_i}s_{\bar a})^{\text{hor}} = 0$. Therefore, as above, we have that $([s_i,s_{\bar a}] + \nabla^E_{s_{\bar a}}s_i)^{\text{hor}} = 0 + (\nabla^E_{s_{\bar a}}s_i)^{\text{hor}} = A(s_{\bar a},s_i) = 0$. Thus $\sigma^{\bar b}A(s_{\bar a},s_i) = a^{\bar b}_{\bar a i} = 0$, so A vanishes completely. □

18. Jacobi fields

18.1. Jacobi fields. Let (M, ∇) be a manifold with covariant derivative ∇, with curvature R and torsion Tor. Let us consider a smooth mapping $\gamma : (-\varepsilon, \varepsilon) \times [0,1] \to M$ such that $t \mapsto \gamma(s,t)$ is a geodesic for each $s \in (-\varepsilon, \varepsilon)$; we call this a *1-parameter variation through geodesics*. Let us write $\partial_s \gamma =: \gamma'$ and $\partial_t \gamma =: \dot\gamma$ in the following. Our aim is to investigate the variation vector field $\partial_s|_0 \gamma(s, \quad) = \gamma'(0, \quad)$.

We first note that by (13.10.4) we have

$$\begin{aligned} \nabla_{\partial_s}\dot\gamma &= \nabla_{\partial_s}(T\gamma.\partial_t) = \nabla_{\partial_t}(T\gamma.\partial_s) + T\gamma.[\partial_s,\partial_t] + \operatorname{Tor}(T\gamma.\partial_s, T\gamma.\partial_t) \\ &= \nabla_{\partial_t}\gamma' + \operatorname{Tor}(\gamma',\dot\gamma) \end{aligned} \tag{1}$$

We have $\nabla_{\partial_t}\dot\gamma = \nabla_{\partial_t}(\partial_t \gamma) = 0$ since $\gamma(s, \quad)$ is a geodesic for each s. Thus by using (15.5) we get

$$\begin{aligned} 0 = \nabla_{\partial_s}\nabla_{\partial_t}\dot\gamma &= R(T\gamma.\partial_s, T\gamma.\partial_t)\dot\gamma + \nabla_{\partial_t}\nabla_{\partial_s}\dot\gamma + \nabla_{[\partial_s,\partial_t]}\dot\gamma \\ &= R(\gamma',\dot\gamma)\dot\gamma + \nabla_{\partial_t}\nabla_{\partial_t}\gamma' + \nabla_{\partial_t}\operatorname{Tor}(\gamma',\dot\gamma). \end{aligned} \tag{2}$$

Inserting $s = 0$, along the geodesic $c = \gamma(0, \quad)$ we get the *Jacobi differential equation* for the variation vector field $Y = \partial_s|_0 \gamma = \gamma'(0, \quad)$:

$$\boxed{0 = R(Y,\dot c)\dot c + \nabla_{\partial_t}\nabla_{\partial_t} Y + \nabla_{\partial_t}\operatorname{Tor}(Y,\dot c)} \tag{3}$$

This is a linear differential equation of second order for vector fields Y along the fixed geodesic $c : [0,1] \to M$. Thus for any $t_0 \in [0,1]$ and any initial values $(Y(t_0), (\nabla_{\partial_t})(t_0)) \in T_{c(t_0)}M \times T_{c(t_0)}M$ there exists a unique global solution Y of (3) along c. These solutions are called *Jacobi fields* along c; they form a $2m$-dimensional vector space.

18.2. The Jacobi flow. Consider a linear connector $K : TTM \to M$ on the tangent bundle with its horizontal lift mapping $C : TM \times_M TM \to TTM$, see (13.8) its spray $S : TM \to TTM$ given by $S(X) := C(X,X)$, see (13.7) and its covariant derivative $\nabla_X Y = K \circ TY \circ X$, see (13.9).

Theorem. [Michor, 1996] *Let $S : TM \to TTM$ be a spray on a manifold M. Then $\kappa_{TM} \circ TS : TTM \to TTTM$ is a vector field. Consider a flow line*

$$J(t) = \operatorname{Fl}_t^{\kappa_{TM}\circ TS}(J(0))$$

of this field. Then we have:

$c := \pi_M \circ \pi_{TM} \circ J$ is a geodesic on M
$\dot c = \pi_{TM} \circ J$ is the velocity field of c
$Y := T(\pi_M) \circ J$ is a Jacobi field along c
$\dot Y = \kappa_M \circ J$ is the velocity field of Y
$\nabla_{\partial_t} Y = K \circ \kappa_M \circ J$ is the covariant derivative of Y

The Jacobi equation is given by:

$$\begin{aligned}0 &= \nabla_{\partial_t}\nabla_{\partial_t}Y + R(Y,\dot c)\dot c + \nabla_{\partial_t}\operatorname{Tor}(Y,\dot c)\\ &= K\circ TK\circ TS\circ J.\end{aligned}$$

This implies that in a canonical chart induced from a chart on M the curve $J(t)$ is given by

$$(c(t),\dot c(t);Y(t),\dot Y(t)).$$

Proof. Consider a curve $s\mapsto X(s)$ in TM. Then each $t\mapsto \pi_M(\operatorname{Fl}^S_t(X(s)))$ is a geodesic in M, and in the variable s it is a variation through geodesics. Thus $Y(t) := \partial_s|_0\pi_M(\operatorname{Fl}^S_t(X(s)))$ is a Jacobi field along the geodesic $c(t) := \pi_M(\operatorname{Fl}^S_t(X(0)))$ by (18.1), and each Jacobi field is of this form, for a suitable curve $X(s)$, see (18.5.4) below. We consider now the curve $J(t) := \partial_s|_0\operatorname{Fl}^S_t(X(s))$ in TTM. Then by (6.13.6) we have

$$\begin{aligned}\partial_t J(t) &= \partial_t\partial_s|_0\operatorname{Fl}^S_t(X(s)) = \kappa_{TM}\partial_s|_0\partial_t\operatorname{Fl}^S_t(X(s)) = \kappa_{TM}\partial_s|_0 S(\operatorname{Fl}^S_t(X(s)))\\ &= (\kappa_{TM}\circ TS)(\partial_s|_0\operatorname{Fl}^S_t(X(s))) = (\kappa_{TM}\circ TS)(J(t)),\end{aligned}$$

so that $J(t)$ is a flow line of the vector field $\kappa_{TM}\circ TS : TTM\to TTTM$. Moreover using the properties of κ from (6.13) and of S from (13.7) we get

$$\begin{aligned}T\pi_M.J(t) &= T\pi_M.\partial_s|_0\operatorname{Fl}^S_t(X(s)) = \partial_s|_0\pi_M(\operatorname{Fl}^S_t(X(s))) = Y(t),\\ \pi_M T\pi_M J(t) &= c(t),\ \text{ the geodesic},\\ \partial_t Y(t) &= \partial_t T\pi_M.\partial_s|_0\operatorname{Fl}^S_t(X(s)) = \partial_t\partial_s|_0\pi_M(\operatorname{Fl}^S_t(X(s))),\\ &= \kappa_M\partial_s|_0\partial_t\pi_M(\operatorname{Fl}^S_t(X(s))) = \kappa_M\partial_s|_0\partial_t\pi_M(\operatorname{Fl}^S_t(X(s)))\\ &= \kappa_M\partial_s|_0 T\pi_M.\partial_t\operatorname{Fl}^S_t(X(s)) = \kappa_M\partial_s|_0(T\pi_M\circ S)\operatorname{Fl}^S_t(X(s))\\ &= \kappa_M\partial_s|_0\operatorname{Fl}^S_t(X(s)) = \kappa_M J(t),\\ \nabla_{\partial_t}Y &= K\circ\partial_t Y = K\circ\kappa_M\circ J.\end{aligned}$$

Finally let us express the Jacobi equation (18.1.3). Put $\gamma(s,t) := \pi_M(\operatorname{Fl}^S_t(X(s)))$ for shortness' sake.

$$\begin{aligned}&\nabla_{\partial_t}\nabla_{\partial_t}Y + R(Y,\dot c)\dot c + \nabla_{\partial_t}\operatorname{Tor}(Y,\dot c) =\\ &\quad= \nabla_{\partial_t}\nabla_{\partial_t}.T\gamma.\partial_s + R(T\gamma.\partial_s,T\gamma.\partial_t)T\gamma.\partial_t + \nabla_{\partial_t}\operatorname{Tor}(T\gamma.\partial_s,T\gamma.\partial_t)\\ &\quad= K.T(K.T(T\gamma.\partial_s).\partial_t).\partial_t\\ &\qquad + (K.TK.\kappa_{TM} - K.TK).TT(T\gamma.\partial_t).T\partial_s.\partial_t\\ &\qquad + K.T((K.\kappa_M - K).TT\gamma.T\partial_s.\partial_t).\partial_t\end{aligned}$$

Note that for example for the term in the second summand we have

$$TTT\gamma.TT\partial_t.T\partial_s.\partial_t = T(T(\partial_t\gamma).\partial_s).\partial_t = \partial_t\partial_s\partial_t\gamma = \partial_t.\kappa_M.\partial_t.\partial_s\gamma = T\kappa_M.\partial_t.\partial_t.\partial_s\gamma$$

which at $s = 0$ equals $T\kappa_M \ddot{Y}$. Using this we get for the Jacobi equation at $s = 0$:

$$\begin{aligned}&\nabla_{\partial_t}\nabla_{\partial_t} Y + R(Y,\dot c)\dot c + \nabla_{\partial_t} \operatorname{Tor}(Y,\dot c)\\ &\quad= (K.TK + K.TK.\kappa_{TM}.T\kappa_M - K.TK.T\kappa_M + K.TK.T\kappa_M - K.TK).\partial_t\partial_t Y\\ &\quad= K.TK.\kappa_{TM}.T\kappa_M.\partial_t\partial_t Y = K.TK.\kappa_{TM}.\partial_t J = K.TK.TS.J,\end{aligned}$$

where we used $\partial_t\partial_t Y = \partial_t(\kappa_M.J) = T\kappa_M\partial_t J = T\kappa_M.\kappa_{TM}.TS.J$. Finally the validity of the Jacobi equation $0 = K.TK.TS.J$ follows trivially from $K \circ S = 0_{TM}$. □

Note that the system of Jacobi fields depends only on the geodesic structure, thus on the spray induced by the given covariant derivative. So we may assume that the covariant derivative is torsionfree without loss; we do this from now on.

18.3. Fermi charts. Let (M, g) be a Riemann manifold. Let $c : (-2\varepsilon, 1+2\varepsilon) \to M$ be a geodesic (for $\varepsilon > 0$). We will define the *Fermi chart* along c as follows.

Since $c([-\varepsilon, 1 + \varepsilon])$ is compact in M there exists $\rho > 0$ such that

$$\begin{aligned}&B^\perp_{c(0)}(\rho) := \{X \in T^\perp_{c(0)}c := \{Y \in T_{c(0)}M : g(Y, c'(0)) = 0\}, |X|_g < \rho\}\\ (1)\qquad &\exp\circ \operatorname{Pt}(c,\quad) : (-\varepsilon, 1 + \varepsilon) \times B^\perp_c(0)(\rho) \to M\\ &(t, X) \mapsto \exp_{c(t)}(\operatorname{Pt}(c, t)X)\end{aligned}$$

is everywhere defined. Since its tangent mapping along $(-\varepsilon, 1 + \varepsilon) \times \{0\}$,

$$\begin{aligned}T_{t,0}(\exp\circ \operatorname{Pt}(c,\quad)) : \mathbb{R} \times T^\perp_{c(0)}c \to T_c(t)M = T_{c(t)}(c([0, 1])) \times T^\perp_{c(t)}c\\ (s, Y) \mapsto s.c'(t) + \operatorname{Pt}(c, t)Y\end{aligned}$$

is a linear isomorphism we may assume (by choosing ρ smaller if necessary using (13.7.6)) that the mapping $\exp\circ \operatorname{Pt}(c,\quad)$ in (1) is a diffeomorphism onto its image. Its inverse,

$$\begin{aligned}(2)\qquad &u_{c,\rho} := (\exp\circ Pt(c,\quad))^{-1} : U_{c.\rho} \to (-\varepsilon, 1 + \varepsilon) \times B^\perp_{c(0)}(\rho)\\ &U_{c.\rho} := (\exp\circ \operatorname{Pt}(c,\quad))((-\varepsilon, 1 + \varepsilon) \times B^\perp_{c(0)}(\rho))\end{aligned}$$

is called the *Fermi chart* along c. Its importance is due to the following result.

18.4. Lemma. *Let X be a vector field along the geodesic c. For the Fermi chart along c put $T_{c(t)}(u_{c,\rho})^{-1}.X(t) =: (t, \bar X(t))$. Then we have*

$$T_{c(t)}u_{c,\rho}.(\nabla_{\partial_t} X)(t) = (t, \bar X'(t)).$$

So in the Fermi chart the covariant derivative ∇_{∂_t} along c is just the ordinary derivative. More is true: The Christoffel symbol in the Fermi chart vanishes along $(-\varepsilon, 1 + \varepsilon) \times \{0\}$.

The last statement is a generalization of the property of Riemann normal coordinates $\exp_x^{-1}$ that the Christoffel symbol vanishes at 0, see (13.7).

Proof. In terms of the Chritoffel symbol of the Fermi chart the geodesic equation is given by $\bar{c}''(t) = \Gamma_{\bar{c}(t)}(\bar{c}'(t), \bar{c}'(t))$, see (13.4). But in the Fermi chart the geodesic c is given by $u_{c,\rho}(c(t)) = (t, 0)$, so the geodesic equation becomes $0 = \Gamma_{\bar{c}(t)}((1,0),(1,0)) = \Gamma_{\bar{c}(t)}(\bar{c}'(t), \bar{c}'(t))$. For $Y_0 \in T^\perp_{c(0)}c$ the parallel vector field $Y(t) = \operatorname{Pt}(c,t)Y_0$ is represented by $(t,0;0,Y_0)$ in the Fermi chart; thus we get $0 = \Gamma_{\bar{c}(t)}(\bar{c}'(t), Y_0)$. The geodesic $s \mapsto \exp_{c(t)}(s.\operatorname{Pt}(c,t).Y)$ for $Y \in T^\perp_{c(0)}c$ is represented by $s \mapsto (t, s.Y)$ in the Fermi chart. The corresponding geodesic equation is $0 = \frac{\partial^2}{\partial s^2}(t, s.Y) = \Gamma_{(t,s.Y)}(Y,Y)$. By symmetry of $\Gamma_{(t,0)}$ these facts imply that $\Gamma_{(t,0)} = 0$. Finally, $Tu_{c,\rho}.(\nabla_{\partial_t}X)(t) = \bar{X}'(t) - \Gamma_{(t,0)}(\bar{c}'(t), \bar{X}(t)) = \bar{X}'(t)$. $\square$

18.5. Let (M^m, g) be a Riemann manifold, and let $c : [0,1] \to M$ be a geodesic which might be constant. Let us denote by $\mathcal{J}_c$ the $2m$-dimensional real vector space of all Jacobi fields along c, i.e., all vector fields Y along c satisfying $\nabla_{\partial_t}\nabla_{\partial_t}Y + R(Y,\dot{c})\dot{c} = 0$.

Theorem.

(1) *The vector space $\mathcal{J}_c$ is canonically isomorphic to the vector space $T_{c(t)}M \times T_{c(t)}M$ via $\mathcal{J}_c \ni Y \mapsto (Y(t), (\nabla_{\partial_t}Y)(t))$, for each $t \in [0,1]$.*

(2) *The vector space $\mathcal{J}_c$ carries a canonical symplectic structure (see* (23.4)*):*

$$\omega_c(Y,Z) = g(Y(t), (\nabla_{\partial_t}Z)(t)) - g(Z(t), (\nabla_{\partial_t}Y)(t)) = \text{ constant in } t$$

(3) *Now let $c' \neq 0$. Then $\mathcal{J}_c$ splits naturally into the direct sum $\mathcal{J}_c = \mathcal{J}_c^\top \oplus \mathcal{J}_c^\perp$. Here $\mathcal{J}_c^\top$ is the 2-dimensional ω_c-non-degenerate subspace of all Jacobi fields which are tangent to c. All these are of the form $t \mapsto (a+tb)c'(t)$ for $(a,b) \in \mathbb{R}^2$. Also, $\mathcal{J}_c^\perp$ is the $(2m-2)$-dimensional ω_c-non-degenerate subspace consisting of all Jacobi fields Y satisfying $g(Y(t), c'(t)) = 0$ for all t. Moreover, $\omega_c(\mathcal{J}_c^\top, \mathcal{J}_c^\perp) = 0$.*

(4) *Each Jacobi field $Y \in \mathcal{J}_c$ is the variation vector field of a 1-parameter variation of c through geodesics, and conversely.*

(5) *Let $\mathcal{J}_c^0$ be the m-dimensional vector space consisting of all Jacobifields Y with $Y(0) = 0$. Then $\omega_c(\mathcal{J}_c^0, \mathcal{J}_c^0) = 0$, so $\mathcal{J}_c^0$ is a Lagrangian subspace (see* (23.4)*).*

Proof. Let first $c'(t) = 0$ so $c(t) = c(0)$. Then $Y(t) \in T_{c(0)}M$ for all t. The Jacobi equation becomes $\nabla_t\nabla_t Y = Y''$ so $Y(t) = A + tB$ for $A, B \in T_{c(0)}M$. Then (1), (2), and (5) holds.

Let us now assume that $c' \neq 0$. (1) follows from (18.1).

(2) For $Y, Z \in \mathcal{J}_c$ consider:

$$\begin{aligned}
\omega_c(Y,Z)(t) &= g(Y(t), (\nabla_{\partial_t}Z)(t)) - g(Z(t), (\nabla_{\partial_t}Y)(t)) \\
\partial_t\, \omega_c(Y,Z) &= g(\nabla_{\partial_t}Y, \nabla_{\partial_t}Z) + g(Y, \nabla_{\partial_t}\nabla_{\partial_t}Z) - g(\nabla_{\partial_t}Z, \nabla_{\partial_t}Y) - g(Z, \nabla_{\partial_t}\nabla_{\partial_t}Y) \\
&= -g(Y, R(Z,c')c') + g(Z, R(Y,c')c') \\
&= -g(R(Z,c')c', Y) + g(R(Y,c')c', Z) \\
&= g(R(Z,c')Y, c') - g(R(Y,c')Z, c') = 0 \quad \text{ by (15.4.5) and (15.4.4)}
\end{aligned}$$

Thus $\omega_c(Y,Z)(t)$ is constant in t. Also it is the standard symplectic structure (see (23.5)) on $T_{c(t)}M \times T_{c(t)}M$ induced by $g_{c(t)}$ via (1).

(3) We have $c' \neq 0$. In the Fermi chart $(U_{c,\rho}, u_{c,\rho})$ along c we have $c' = e_1$, the first unit vector, and the Jacobi equation becomes

$$Y \in \mathcal{J}_c \iff Y''(t) + R(Y, e_1)e_1 = 0. \tag{6}$$

Consider first a Jacobi field $Y(t) = f(t).c'(t)$ which is tangential to c'. From (6) we get

$$0 = Y''(t) + R(Y(t), e_1)e_1 = f''(t).e_1 + f(t).R(e_1, e_1)e_1 = f''(t).e_1$$

so that $f(t) = a + tb$ for $a, b \in \mathbb{R}$. Let $g(t) = a' + tb'$. We use the symplectic structure at $t = 0$ to get $\omega_c(f.c', g.c') = g(a.c', b.c') - g(a'.c', b.c') = (ab' - a'b)|c'|^2$, a multiple of the canonical symplectic structure on $\mathbb{R}^2$.

For an arbitrary $Y \in \mathcal{J}_c$ we can then write $Y = Y_1 + Y_2$ uniquely where $Y_1 \in \mathcal{J}_c^\top$ is tangent to c' and where Y_2 is in the ω_c-orthogonal complement to $\mathcal{J}_c^\top$ in $\mathcal{J}_c$:

$$\begin{aligned}
0 &= \omega_c(c', Y_2) = g(c', \nabla_{\partial_t} Y_2) - g(\nabla_{\partial_t} c', Y_2) = g(c', \nabla_{\partial_t} Y_2) \quad \implies \nabla_{\partial_t} Y_2 \bot c' \\
0 &= \omega_c(t.c', Y_2) = g(t.c', \nabla_{\partial_t} Y_2) - g(c', Y_2) = -g(c', Y_2) \quad \implies Y_2 \bot c'
\end{aligned}$$

Conversely, $Y_2 \bot^g c'$ implies $0 = \partial_t\, g(c', Y_2) = g(c', \nabla_{\partial_t} Y_2)$ so that $Y_2 \in \mathcal{J}_c^\perp$ and $\mathcal{J}_c^\perp$ equals the ω_c-orthogonal complement of $\mathcal{J}_c^\top$. By symplectic linear algebra the latter space is ω_c-non-degenerate.

(4) for $\dot c \neq 0$ and $\dot c = 0$. Let $Y \in \mathcal{J}_c$ be a Jacobi field. Consider $b(s) := \exp_{c(0)}(s.Y(0))$. We look for a vector field X along b such that $(\nabla_{\partial_s} X)(0) = \nabla_{\partial_t} Y(0)$. We try

$$\begin{aligned}
X(s) :&= \operatorname{Pt}(c, s)(\dot c(0) + s.(\nabla_{\partial_t} Y)(0)) \\
X'(0) &= \partial_s|_0 \big(Pt(b, s)(\dot c(0) + s.(\nabla_{\partial_t} Y)(0))\big) \\
&= \partial_s|_0 \big(Pt(b, s)(\dot c(0)) + T(Pt(b, 0))\, \partial_s|_0\, (\dot c(0) + s.(\nabla_{\partial_t} Y)(0)\big) \\
&= C(b'(0), \dot c(0)) + \operatorname{vl}_{TM}(\dot c(0), (\nabla_{\partial_t} Y)(0)) \quad \text{ using (15.2).}
\end{aligned}$$

Now we put

$$\begin{aligned}
\gamma(s,t) :&= \exp_{b(s)}(t.X(s)), \quad \text{ then} \\
\gamma(0,t) &= \exp_{c(0)}(t.X(0)) = \exp_{c(0)}(t.\dot c(0)) = c(t).
\end{aligned}$$

Obviously, γ is a 1-parameter variation of c through geodesics, thus the variation vector field $Z(t) = \partial_s|_0\, \gamma(s,t)$ is a Jacobi vector field. We have

$$\begin{aligned}
Z(0) &= \partial_s|_0\, \gamma(s, 0) = \partial_s|_0\, \exp_{b(s)}(0_{b(s)}) = \partial_s|_0\, b(s) = Y(0), \\
(\nabla_{\partial_t} Z)(0) &= \nabla_{\partial_t}(T\gamma.\, \partial_s)|_{s=0,t=0} \\
&= \nabla_{\partial_s}(T\gamma.\, \partial_t)|_{s=0,t=0} \quad \text{ by (13.10.4) or (18.1.1)} \\
&= \nabla_{\partial_s}\big(\partial_t|_0\, \exp_{b(s)}(t.X(s))\big)|_{s=0} = \nabla_{\partial_s} X|_{s=0} \\
&= K(\partial_s|_0\, X(s)) = K\big(C(b'(0), \dot c(0)) + \operatorname{vl}(\dot c(0), (\nabla_{\partial_t} Y)(0))\big) \\
&= 0 + (\nabla_{\partial_t} Y)(0).
\end{aligned}$$

Thus $Z = Y$ by (1).

(5) follows from (1) and symplectic linear algebra, see (23.5). $\square$

18.6. Lemma. *Let c be a geodesic with $c' \neq 0$ in a Riemann manifold (M,g) and let $Y \in \mathcal{J}_c^0$ be a Jacobi field along c with $Y(0)=0$. Then we have*

$$Y(t) = T_{t.\dot c(0)}(\exp_{c(0)}) \operatorname{vl}\big(t.\dot c(0), t.(\nabla_{\partial_t} Y)(0)\big).$$

Proof. Let us step back into the proof of (18.5.4). There we had

$$\begin{aligned}
b(s) &= \exp_{c(0)}(s.Y(0)) = c(0),\\
X(s) &= \operatorname{Pt}(c,s)(\dot c(0) + s.(\nabla_{\partial_t} Y)(0)) = \dot c(0) + s.(\nabla_{\partial_t} Y)(0),\\
Y(t) &= \partial_s|_0\, \gamma(s,t) = \partial_s|_0\, \exp_{b(s)}(t.X(s)) = T_{t.\dot c(0)}(\exp_{c(0)})\, \partial_s|_0\, m_t X(s)\\
&= T_{t.\dot c(0)}(\exp_{c(0)}).T(m_t)\, \partial_s|_0\, (\dot c(0) + s.(\nabla_{\partial_t} Y)(0))\\
&= T_{t.\dot c(0)}(\exp_{c(0)}).T(m_t). \operatorname{vl}\big(\dot c(0), (\nabla_{\partial_t} Y)(0)\big)\\
&= T_{t.\dot c(0)}(\exp_{c(0)}). \operatorname{vl}\big(t.\dot c(0), t.(\nabla_{\partial_t} Y)(0)\big). \quad \square
\end{aligned}$$

18.7. Corollary. *On a Riemann manifold (M,g) consider $\exp_x : T_xM \to M$. Then for $X \in T_xM$ the kernel of $T_X(\exp_x) : T_X(T_xM) \to T_{\exp_x(X)}M$ is isomorphic to the linear space consisting of all Jacobi fields $Y \in \mathcal{J}_c^0$ for $c(t) = \exp|_x(tX)$ which satisfy $Y(0)=0$ and $Y(1)=0$.*

Proof. By (18.6), $Y(t) = T_{tX}(\exp_x). \operatorname{vl}(tX, t(\nabla_{\partial_t} Y)(0))$ is a Jacobi field with $Y(0)=0$. But then

$$0 = Y(1) = T_X(\exp_x) \operatorname{vl}\big(X, (\nabla_{\partial_t} Y)(0)\big) \iff (\nabla_{\partial_t} Y)(0) \in \ker(T_X(\exp_x)). \quad \square$$

18.8. Let (M,g) and $(\tilde M, \tilde g)$ be two Riemann manifolds of the same dimension. Let $c : [0,1] \to M$ and $\tilde c : [0,1] \to \tilde M$ be two geodesics of the same length. We choose a linear isometry $I_0 : (T_{c(0)}M, g_{c(0)}) \to (T_{\tilde c(0)}\tilde M, \tilde g_{\tilde c(0)})$ and define the linear isometries:

$$I_t := \tilde{\operatorname{Pt}}(\tilde c, t) \circ I_0 \circ \operatorname{Pt}(c,t)^{-1} : T_{c(t)}M \to T_{\tilde c(t)}\tilde M.$$

Lemma. *If Y is a vector field along c, then $t \mapsto (I_*Y)(t) = I_t\, Y(t)$ is a vector field along $\tilde c$ and we have $\tilde\nabla_{\partial_t}(I_*Y) = I_*(\nabla_{\partial_t} Y)$ so that $\tilde\nabla_{\partial_t} \circ I_* = I_* \circ \nabla_{\partial_t}$.*

Proof. We use Fermi charts (with the minimum of the two ρ;s)

$$\begin{array}{ccc}
M \supset U_{c,\rho} & \xrightarrow{u_{c,\rho}} & (-\varepsilon, 1+\varepsilon) \times B^\perp_{c(0)}(\rho)\\
 & & \Big\downarrow{\scriptstyle \operatorname{Id}\times I_0 \text{ linear}}\\
\tilde M \supset U_{\tilde c,\rho} & \xrightarrow{u_{\tilde c,\rho}} & (-\varepsilon, 1+\varepsilon) \times B^\perp_{\tilde c(0)}(\rho)
\end{array}$$

By construction of the Fermi charts we have $(I_*Y)(t) = T(u_{\tilde c,\rho}^{-1} \circ (\operatorname{Id}\times I_0) \circ u_{c,\rho}).Y(t)$. Thus

$$\begin{aligned}
\tilde\nabla_{\partial_t}(I_*Y)(t) &= \tilde\nabla_{\partial_t}(T(u_{\tilde c,\rho}^{-1} \circ (\operatorname{Id}\times I_0) \circ u_{c,\rho}).Y)(t)\\
&= T(u_{\tilde c,\rho})^{-1}\, \partial_t\big((\operatorname{Id}\times I_0) \circ T(u_{c,\rho}).Y(t)\big) \quad \text{by (18.4)}\\
&= T(u_{\tilde c,\rho})^{-1}.(\operatorname{Id}\times I_0).\, \partial_t\, T(u_{c,\rho}).Y(t)\\
&= T(u_{\tilde c,\rho})^{-1}.(\operatorname{Id}\times I_0).T(u_{c,\rho}).(\nabla_{\partial_t} Y)(t) \quad \text{by (18.4)}\\
&= I_*(\nabla_{\partial_t} Y)(t). \quad \square
\end{aligned}$$

18.9. Jacobi operators. On a Riemann manifold (M, g) with curvature R we consider for each vector field $X \in \mathfrak{X}(M)$ the corresponding *Jacobi operator* $R_X : TM \to TM$ which is given by $R_X(Y) = R(Y, X)X$. It turns out that each R_X is a *selfadjoint* endomorphism, $g(R_X(Y, Z)) = g(Y, R_X(Z))$, since we have $g(R(Y, X)X, Z) = g(R(X, Z)Y, X) = g(R(Z, X)X, Y)$ by (15.4.4) and (15.4.5). One can reconstruct the curvature R from the family of Jacobi operators R_X by polarization and the properties from (15.4).

18.10 Theorem. *(E. Cartan) Let (M, g) and $(\tilde M, \tilde g)$ be Riemann manifolds of the same dimension. Let $x \in M$, $\tilde x \in \tilde M$, and $\varepsilon > 0$ be such that $\exp_x : B_{0_x}(\varepsilon) \to M$ and $\exp_{\tilde x} : B_{0_{\tilde x}}(\varepsilon) \to \tilde M$ are both diffeomorphisms onto their images. Let $I_x : (T_xM, g_x) \to (T_{\tilde x}\tilde M, \tilde g_{\tilde x})$ be a linear isometry. Then the following holds:*

The mapping $\Phi := \exp_{\tilde x} \circ I_x \circ (\exp_x |B_{0_x}(\varepsilon))^{-1} : B_x(\varepsilon) \to B_{0_x}(\varepsilon) \to B_{0_{\tilde x}}(\varepsilon) \to B_{\tilde x}(\varepsilon)$ is a diffeomorphism which maps radial geodesics to radial geodesics. The tangent mapping $T\Phi$ maps Jacobi fields Y along radial geodesics with $Y(0) = 0$ to Jacobi fields $\tilde Y$ along radial geodesics with $\tilde Y(0) = 0$.

Suppose that moreover for all radial geodesics c in $B_x(\varepsilon)$ and their images $\tilde c = \Phi \circ c$ the property

$$I_t \circ R_{\dot c(t)} = \tilde R_{\dot{\tilde c}(t)} \circ I_t \tag{1}$$

holds where $I_t : T_{c(t)}M \to T_{\tilde c(t)}\tilde M$ is defined in (18.8). *Then Φ is an isometry. Conversely, if Φ is an isometry, then* (1) *holds.*

Proof. It is clear that Φ maps radial geodesics in $B_x(\varepsilon) \subset M$ to radial geodesics in $B_{\tilde x}(\varepsilon) \subset \tilde M$. Any Jacobi field Y along a radial geodesic c can be written as variation vector field $Y(t) = \partial_s|_0\, \gamma(s, t)$ where $\gamma(s, \quad)$ is a radial geodesic for all s and $\gamma(0, t) = c(t)$. Then $T\Phi.Y(t) = T\Phi.\, \partial_s|_0\, \gamma(s, t) = \partial_s|_0\, (\Phi\gamma(s, t))$, and any $\Phi\gamma(s, \quad)$ is a radial geodesic in $B_{\tilde x}(\varepsilon)$. Thus $T\Phi.Y$ is a Jacobi field along the radial geodesic $\Phi \circ c$ with $T\Phi.Y(0) = 0$. This proves the first assertion.

Now let Y be a Jacobi field along the radial geodesic c with $Y(0) = 0$. Then the Jacobi equation $0 = \nabla_{\partial_t}\nabla_{\partial_t}Y + R_{\dot c}(Y)$ holds. Consider $(I_*Y)(t) = I_t\, Y(t)$. By (18.8) and (1) we then have

$$\tilde\nabla_{\partial_t}\tilde\nabla_{\partial_t}(I_*Y) + \tilde R_{\dot{\tilde c}}(I_*Y) = I_*(\nabla_{\partial_t}\nabla_{\partial_t}Y + R_{\dot c}Y) = 0.$$

Thus I_*Y is again a Jacobi field along the radial geodesic $\tilde c$ with $(I_*Y)(0) = 0$. Since also $\tilde\nabla_{\partial_t}(I_*Y)(0) = I_*(\nabla_{\partial_t}Y)(0) = I_0\, (\nabla_{\partial_t}Y)(0) = T\Phi.(\nabla_{\partial_t}Y)(0)$ we get $I_*Y = T\Phi.Y$. Since the vectors $Y(t)$ for Jacobi fields Y along c with $Y(0) = 0$ span $T_{c(t)}M$ by (18.6), we may conclude that $T_{c(t)}\Phi = I_t : T_{c(t)}M \to T_{\tilde c(t)}\tilde M$ is an isometry. The converse statement is obvious since an isometry intertwines the curvatures. □

18.11. Conjugate points. Let $c : [0, a] \to M$ be a geodesic on a Riemann manifold (M, g) with $c(0) = x$. A parameter $t_0 \in [0, a]$ or its image $c(t_0) \in c([0, a])$ is called a *conjugate point* for $x = c(0)$ on $c([0, a])$ if the tangent mapping

$$T_{t_0\dot c(0)}(\exp_x) : T_{t_0\dot c(0)}(T_xM) \to T_{c(t_0)}M$$

is **not** an isomorphism. Then $t_0 > 0$. The *multiplicity* of the conjugate point is the dimension of the kernel of $T_{t_0\dot c(0)}(\exp_x)$ which equals the dimension of the subspace of all Jacobi fields Y along c with $Y(0) = 0$ and $Y(t_0) = 0$, by (18.7).

18.12. Example. Let $M = \rho \cdot S^m \subset \mathbb{R}^{M+1}$, the sphere of radius $\rho > 0$. Then any geodesic c with $|\dot c| = 1$ satisfies $c(\rho\pi) = -c(0)$, so $-c(0)$ is conjugate to $c(0)$ along c with multiplicity $m - 1$.

18.13. Lemma. *Let $c : [0, a] \to M$ be a geodesic in a Riemann manifold (M, g). Then the vector $\partial_t(t.\dot c(0))|_{t=t_0} = \operatorname{vl}(t_0.\dot c(0), \dot c(0)) \in T_{t_0.\dot c(0)}(T_{c(0)}M)$ is orthogonal to the kernel $\ker(T_{t_0\dot c(0)}(\exp_{c(0)}))$, for any $t_0 \in [0, a]$.*

Proof. If $c(t_0)$ is not a conjugate point to $x = c(0)$ of c this is clearly true. If it is, let Y be the Jacobi field along c with $Y(0) = 0$ and $(\nabla_{\partial_t} Y)(0) = X \neq 0$ where $\operatorname{vl}(t_0.\dot c(0), X) \in \ker(T_{t_0\dot c(0)}(\exp_x))$. Then we have $T_{t_0\dot c(0)}(\exp_x)\operatorname{vl}(t_0.\dot c(0), X) = Y(t_0) = 0$. Let $\hat c(t) = (t - t_0)\dot c(0) \in \mathcal{J}_c^\top$, a tangential Jacobi field along c. By (18.5.2) applied for $t = 0$ and for $t - t_0$ we get

$$\begin{aligned}\omega_c(\hat c, Y) &= g(\hat c(0), (\nabla_{\partial_t})Y(0)) - g(Y(0), (\nabla_{\partial_t}Y)(0)) = g(t_0.\dot c(0), X) - 0,\\ &= g(\hat c(t_0), (\nabla_{\partial_t})Y(t_0)) - g(Y(t_0), (\nabla_{\partial_t}Y)(t_0)) = 0.\end{aligned}$$

Thus $t_0.g(\dot c(0), X) = 0$ and since $t_0 > 0$ we get $X \perp \dot c(0)$. □

We can extract more information about the Jacobi field Y from this proof. We showed that then $(\nabla_{\partial_t}Y)(0) \perp^g \dot c(0)$. We use this in the following application of (18.5.2) for $t = 0$: now

$$\omega_c(\dot c, Y) = g(\dot c(0), (\nabla_{\partial_t}Y)(0)) - g(Y(0, (\nabla_{\partial_t}\dot c)(0))) = 0$$

Together with $\omega_c(\hat c, Y) = 0$ from the proof this says that $Y \in \mathcal{J}_c^\perp$, so by (18.5.3) $Y(t) \perp^g \dot c(t)$ for all t.

Let us denote by $\mathcal{J}_c^{\perp,0} = \mathcal{J}_c^\perp \cap \mathcal{J}_c^0$ the space of all Jacobi fields Y with $Y(0) = 0$ and $Y(t) \perp^g \dot c(t)$ for all t. Then the dimension of the kernel of $T_{t_0\dot c(0)}(\exp_x)$ equals the dimension of the space of all $Y \in \mathcal{J}_c^{\perp,0}$ which satisfy $Y(t_0) = 0$.

Thus, if $c(0)$ and $c(t_0)$ are conjugate then there are 1-parameter variations of c through geodesics which all start at $c(0)$ and end at $c(t_0)$, at least infinitesimally in the variation parameter. For this reason conjugate points are also called *focal points*. We will strenghen this later on.

18.14. The Hessian of the energy, alias second variation formulas. Let (M, g) be a Riemann manifold. Let $c : [0, a] \to M$ be a geodesic with $c(0) = x$ and $c(a) = y$. A smooth *variation* of c with fixed ends is a smooth mapping $F : (-\varepsilon, \varepsilon) \times [0, a] \to M$ with $F(0, t) = c(t)$, $F(s, 0) = x$, and $F(s, a) = y$. The variation vector field for F is the vector field $X = \partial_s|_0 F(s,\ \ )$ along c, with $X(0) = 0$ and $X(a) = 0$.

The space $C^\infty(([0, a], 0, a), (M, x, y))$ of all smooth curves $\gamma : [0, a] \to M$ with $c(0) = x$ and $c(a) = y$ is an infinite dimensional smooth manifold modelled on

Fréchet spaces. See [Kriegl, Michor, 1997] for a thorough account of this. c is in this inifinite dimensional manifold, and $T_c(C^\infty(([0,a],0,a),(M,x,y)))$ consists of all variations vector fields along c as above. We consider again the energy as a smooth function

$$E : C^\infty(([0,a],0,a),(M,x,y)) \to \mathbb{R}, \qquad E(\gamma) = \tfrac{1}{2}\int_0^a |\dot\gamma(t)|_g^2\,dt.$$

Let now F be a variation with fixed ends of the geodesic c. Then we have:

$$\begin{aligned}\partial_s\, E(F(s,\quad)) &= \tfrac12 \int_0^a \partial_s\, g(\partial_t F, \partial_t F)\,dt = \int_0^a g(\nabla_{\partial_s}\partial_t F, \partial_t F)\,dt \\ &= \int_0^a g(\nabla_{\partial_t}\partial_s F, \partial_t F)\,dt, \qquad \text{by (13.10.4) or (18.1.1).}\end{aligned}$$

Therefore,

$$\begin{aligned}\partial_s^2|_0 E(F(s,\quad)) &= \int_0^a \Big(g(\nabla_{\partial_s}\nabla_{\partial_t}\partial_s F, \partial_t F) + g(\nabla_{\partial_t}\partial_s F, \nabla_{\partial_s}\partial_t F)\Big)\Big|_{s=0}\,dt \\ &= \int_0^a \Big(g(\nabla_{\partial_t}\nabla_{\partial_s}\partial_s F, \partial_t F) + g(R(\partial_s F, \partial_t F)\,\partial_s F, \partial_t F) \\ &\qquad\qquad + g(\nabla_{\partial_t}\partial_s F, \nabla_{\partial_t}\partial_s F)\Big)\Big|_{s=0}\,dt \qquad \text{by (15.5) and (13.10.4)} \\ &= \int_0^a \Big(g(\nabla_{\partial_t}\partial_s F, \nabla_{\partial_t}\partial_s F) + g(R(\partial_s F, \partial_t F)\,\partial_s F, \partial_t F)\Big)\Big|_{s=0}\,dt \\ &\quad + \int_0^a \Big(g(\nabla_{\partial_t}\nabla_{\partial_s}\partial_s F, \partial_t F)|_{s=0} + g(\nabla_{\partial_s}\partial_s F|_{s=0}, \underbrace{\nabla_{\partial_t}\partial_t F|_{s=0}}_{\nabla_{\partial_t}\dot c = 0})\Big)\,dt.\end{aligned}$$

The last summand equals $\int_0^a \partial_t\, g(\nabla_{\partial_s}\partial_s F, \partial_t F)|_{s=0}\,dt$ which vanishes since we have a variation with fixed ends and thus $(\nabla_{\partial_s}\partial_s F)(s,0) = 0$ and $(\nabla_{\partial_s}\partial_s F)(s,a) = 0$. Recall $X = \partial_s|_0 F$, a vector field along c with $X(0) = 0$ and $X(a) = 0$. Thus

$$d^2E(c)(X,X) = \partial_s^2|_0 E(F(s,\quad)) = \int_0^a \big(g(\nabla_{\partial_t}X, \nabla_{\partial_t}X) + g(R(X,\dot c)X, \dot c)\big)\,dt.$$

If we polarize this we get the Hessian of the energy at a geodesic c as follows (the boundary terms vanish since X, Y vanish at the ends 0 and a):

$$dE(c)(X) = \int_0^a g(\nabla_{\partial_t}X, \dot c)\,dt = -\int_0^a g(X, \nabla_{\partial_t}\dot c)\,dt = 0$$

$$d^2E(c)(X,Y) = \int_0^a \big(g(\nabla_{\partial_t}X, \nabla_{\partial_t}Y) - g(R_{\dot c}(X), Y)\big)\,dt \tag{1}$$

$$d^2E(c)(X,Y) = -\int_0^a g\big(\nabla_{\partial_t}\nabla_{\partial_t}X + R_{\dot c}(X), Y\big)\,dt \tag{2}$$

We see that among all vector fields X along c with $X(0) = 0$ and $X(a) = 0$ those which satisfy $d^2E(c)(X,Y) = 0$ for all Y are exactly the Jacobi fields.

We shall need a slight generalization. Let X, Y be continuous vector fields along c which are smooth on $[t_i, t_{i+1}]$ for $0 = t_0 < t_1 < \dots < t_k = a$, and which vanish at 0 and a. These are tangent vectors at c to the smooth manifold of all curves from x to y which are piecewise smooth in the same manner. Then we take the following as a definition, which can be motivated by the computations above (with considerable care). We will just need that $d^2E(c)$ to be defined below is continuous in the natural uniform C^2-topology on the space of piecewise smooth vector fields so that later we can approximate a broken vector field by a smooth one.

$$
\begin{aligned}
d^2E(c)(X,Y) &= \int_0^a \big(g(\nabla_{\partial_t}X, \nabla_{\partial_t}Y) + g(R(X,\dot c)Y, \dot c)\big)\,dt \\
&= \sum_{i=0}^{k-1} \int_{t_i}^{t_{i+1}} \big(g(\nabla_{\partial_t}X, \nabla_{\partial_t}Y) + g(R(X,\dot c)Y, \dot c)\big)\,dt \\
&= \sum_{i=0}^{k-1} \int_{t_i}^{t_{i+1}} \Big(\partial_t\, g(\nabla_{\partial_t}X, Y) - g(\nabla_{\partial_t}\nabla_{\partial_t}X, Y) - g(R(X,\dot c)\dot c, Y)\Big)\,dt \\
&= -\int_0^a g\big(\nabla_{\partial_t}\nabla_{\partial_t}X + R_{\dot c}(X), Y\big)\,dt \qquad (3)\\
&\quad + \sum_{i=0}^{k-1} \Big(g\big((\nabla_{\partial_t}X)(t_{i+1}-), Y(t_{i+1})\big)) - g\big((\nabla_{\partial_t}X)(t_i+), Y(t_{i+1})\big))\Big).
\end{aligned}
$$

18.15. Theorem. *Let (M,g) be a Riemann manifold and let $c : [0,a] \to M$ be a geodesic with $c(0) = x$ and $c(a) = y$.*

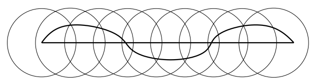
(1) If $T_{t\dot c(0)}(\exp_x) : T_{t\dot c(0)}(T_xM) \to T_{c(t)}M$ is an isomorphism for all $t \in [0,a]$, then for any smooth curve e from x to y which is near enough to c the length $L(e) \geq L(c)$ with equlity if and only if e is a reparameterization of c. Moreover, $d^2E(c)(X,X) \geq 0$ for each smooth vector field X along c which vanishes at the ends.

(2) If there are conjugate points $c(0)$, $c(t_1)$ along c with $0 < t_1 < a$, then there exists a smooth vector field X along c with $X(0) = 0$ and $X(a) = 0$ such that $d^2E(c)(X,X) < 0$. Thus for any smooth variation F of c with $\partial_s|_0 F(s, \quad) = X$ the curve $F(s, \quad)$ from x to y is shorter than c for all $0 < |s| < \varepsilon$.

Proof. (1) Since $T_{t\dot c(0)}(\exp_x) : T_{t\dot c(0)}(T_xM) \to T_{c(t)}M$ is an isomorphism, for each $t \in [0,a]$ there exist an open neighbourhood $U(t.\dot c(0)) \subset T_xM$ of $t\dot c(0)$ such that $\exp_x|U(t.\dot c(0))$ is a diffeomorphism onto its image. Since $[0,a].\dot c(0)$ is compact in T_xM there exists an $\varepsilon > 0$ such that $U(t.\dot c(0)) \supset B_{t\dot c(0)}(\varepsilon)$ for all t.

Now let $e : [0,a] \to M$ be a smooth curve with $e(0) = x$ and $e(a) = y$ which is near c in the sense that there exists a subdivision $0 = t_0 < t_1 < \dots < t_k = a$ with $e([t_i, t_{i+1}]) \subset \exp_x(B_{t_i\dot c(0)}(\varepsilon))$. We put:

$$\tilde e : [0,a] \to T_xM$$
$$\tilde e(t) := (\exp_x|B_{t_i\dot c(0)}(\varepsilon))^{-1}(e(t)), \quad t \in [t_i, t_{i+1}]$$



Then $\tilde e$ is smooth, $\tilde e(0) = 0_x$, $\tilde e(a) = a.\dot c(0)$, and $\exp_x(\tilde e(t)) = e(t)$. We consider the polar representation $\tilde e(t) = r(t).\varphi(t)$ in T_xM where $\varphi(t) = \frac{\tilde e(t)}{|\tilde e(t)|}$ and $r(t) = |\tilde e(t)|$. Let $r = |\tilde e(a)| = a|\dot c(0)|$. Then we put:

$$\gamma(s,t) = \exp_x(r.t.\varphi(s))$$

which implies

$$e(t) = \gamma(t, \tfrac{r(t)}{r}) = \exp_x(r(t).\varphi(t)), \quad \dot e(t) = \partial_s\gamma(t, \tfrac{r(t)}{r}) + \partial_t\gamma(t, \frac{r(t)}{r})\frac{\dot r(t)}{r}.$$

Note that $\nabla_{\partial_t}\partial_t\gamma = 0$ since $\gamma(s,\quad)$ is a geodesic. From

$$\begin{aligned}\partial_t\, g(\partial_s\gamma,\partial_t\gamma) &= g(\nabla_{\partial_t}\partial_s\gamma,\partial_t\gamma) + g(\partial_s\gamma,\nabla_{\partial_t}\partial_t\gamma)\\ &= g(\nabla_{\partial_s}\partial_t\gamma,\partial_t\gamma) + 0 \qquad \text{by (13.10.1)}\\ &= \tfrac12\partial_s\, g(\partial_t\gamma,\partial_t\gamma) = \tfrac12\partial_s\,|\,\partial_t\gamma(s,\quad)|^2 = \tfrac12\partial_s\, r^2|\varphi(s)|^2 = \tfrac12\partial_s\, r^2 = 0\end{aligned}$$

we get that $g(\partial_s\gamma(s,t),\partial_t\gamma(s,t)) = g(\partial_s\gamma(s,0),\partial_t\gamma(s,0)) = g(0, r.\varphi(s)) = 0$. Thus

$$g_{\gamma(s,t)}(\partial_s\gamma(s,t),\partial_t\gamma(s,t)) = 0 \quad \text{for all } s,t. \tag{3}$$

By Pythagoras

$$\begin{aligned}|\dot e(t)|_g^2 &= |\,\partial_s\gamma(t,\tfrac{r(t)}{r})|_g^2 + |\,\partial_t\gamma(t,\tfrac{r(t)}{r})|_g^2\frac{|\dot r(t)|^2}{r^2}\\ &= |\,\partial_s\gamma(t,\tfrac{r(t)}{r})|_g^2 + r^2|\varphi(t)|_g^2\frac{|\dot r(t)|^2}{r^2} \ge |\dot r(t)|^2\end{aligned}$$

with equality iff $\partial_s\gamma(t,\frac{r(t)}{r}) = 0$, i.e., $\varphi(t)$ is constant in t. So

$$L(e) = \int_0^a |\dot e(t)|_g\,dt \ge \int_0^a |\dot r(t)|\,dt \ge \int_0^a \dot r(t)\,dt = r(a) - r(0) = r = L(c) \tag{4}$$

with equality iff $\dot r(t) \ge 0$ and $\varphi(t)$ is constant, i.e., e is a reparameterization of c.

Note that (3) and (4) generalize Gauß' lemma (14.2) and its corollary (14.3) to more general assumptions.

Now consider a vector field X along c with $X(0) = 0$ and $X(a) = 0$ and let $F : (-\varepsilon,\varepsilon)\times[0,a]\to M$ be a smooth variation of c with $F(s,0) = x$, $F(s,a) = y$, and $\partial_s|_0\,F = X$. We have

$$\begin{aligned}2E(F(s,\quad)).a &= \int_0^a |\,\partial_tF|_g^2\,dt\cdot\int_0^a 1^2\,dt \ge \Big(\int_0^a |\,\partial_tF|_g.1\,dt\Big)^2\\ &= L(F(s,\quad))^2 \ge L(c)^2 \qquad \text{by (4)}\\ &= \Big(\int_0^a |\dot c(0)|_g\,dt\Big)^2 = |\dot c(0)|^2.a^2 = \int_0^a |\dot c(0)|^2\,dt\cdot a = 2E(c).a.\end{aligned} \tag{5}$$

Moreover, $\partial_s|_0\,E(F(s,\quad)) = 0$ since c is a geodesic. Thus we get $d^2E(c)(X,X) = \partial_s^2|_0\,E(F(s,\quad)) \ge 0$.

(2) Let $c(0)$, $c(t_1)$ be conjugate points along c with $0 < t_1 < a$. By (18.11) there exists a Jacobi field $Y \neq 0$ along c with $Y(0) = 0$ and $Y(t_1) = 0$. Choose $0 < t_0 < t_1 < t_2 < a$ and a vector field Z along c with $Z|[0, t_0] = 0$, $Z|[t_2, a] = 0$, and $Z(t_1) = -(\nabla_{\partial_t} Y)(t_1) \neq 0$ (since $Y \neq 0$). Let $\tilde{Y}$ be the continuous piecewise smooth vector field along c which is given by $\tilde{Y}|[0, t_1] = Y|[0, t_1]$ and $\tilde{Y}|[t_1, a] = 0$. Then $\tilde{Y} + \eta Z$ is a continuous piecewise smooth vector field along c which is broken at t_1 and vanishes at 0 and at a. Then we have

$$d^2E(c)(\tilde{Y} + \eta Z, \tilde{Y} + \eta Z) = d^2E(c)(\tilde{Y}, \tilde{Y}) + \eta^2\, d^2E(c)(Z, Z) + 2\eta\, d^2E(c)(\tilde{Y}, Z)$$

and by (13.12.3)

$$\begin{aligned}
d^2E(c)(\tilde{Y}, \tilde{Y}) &= -\int_0^{t_1} g\big(\nabla_{\partial_t}\nabla_{\partial_t} Y + R_{\dot c}(Y), Y\big) - \int_{t_1}^{a} g\big(\nabla_{\partial_t}\nabla_{\partial_t} 0 + R_{\dot c}(0), 0\big)\\
&\quad + g((\nabla_{\partial_t} Y)(t_1-), 0) - g((\nabla_{\partial_t} Y)(0+), 0)\\
&\quad + g((\nabla_{\partial_t} \tilde{Y})(a-), 0) - g((\nabla_{\partial_t} \tilde{Y})(t_1+), 0) = 0,\\
d^2E(c)(\tilde{Y}, \tilde{Z}) &= -\int_0^{t_1} g\big(\nabla_{\partial_t}\nabla_{\partial_t} Y + R_{\dot c}(Y), Z\big) - \int_{t_1}^{a} g\big(\nabla_{\partial_t}\nabla_{\partial_t} 0 + R_{\dot c}(0), Z\big)\\
&\quad + g((\nabla_{\partial_t} Y)(t_1-), Z(t_1)) - g((\nabla_{\partial_t} Y)(0+), 0)\\
&\quad + g((\nabla_{\partial_t} \tilde{Y})(a-), 0) - g((\nabla_{\partial_t} 0)(t_1+), Z(t_1))\\
&= g((\nabla_{\partial_t} Y)(t_1), Z(t_1)) = -g((\nabla_{\partial_t} Y)(t_1), (\nabla_{\partial_t} Y)(t_1))\\
&= -|(\nabla_{\partial_t} Y)(t_1)|_g^2 < 0.\\
d^2E(c)(\tilde{Y} + \eta Z, \tilde{Y} + \eta Z) &= \eta^2\, d^2E(c)(Z, Z) - 2\eta\, |(\nabla_{\partial_t} Y)(t_1)|_g^2
\end{aligned}$$

The last expression will be negative for η small enough. Since $d^2E(c)$ is continuous in the C^2-topology for continuous piecewise smooth vector fields along c, we can approximate $\tilde{Y} + \eta Z$ by a smooth vector field X vanishing at the ends such that still $d^2E(c)(X, X) < 0$.

Finally, let $F : (-\varepsilon, \varepsilon) \times [0, a] \to M$ be any smooth variation of c with fixed ends and $\partial_s|_0 F = X$. Consider the Taylor expansion

$$E(F(s, \quad)) = E(c) + s\, dE(c)(X) + \tfrac{s^2}{2} d^2E(c)(X, X) + s^3 h(s)$$

where $h(s) = \int_0^1 \frac{(1-u)^2}{2}\, \partial_v^3\, E(F(v, \quad))|_{v=us}\, du$. Since $dE(c)(X) = 0$ this implies $E(F(s, \quad)) < E(c)$ for $s \neq 0$ small enough. Using the two halves of (5) this implies $L(F(s, \quad))^2 \leq 2E(F(s, \quad))\, a < 2E(c)\, a = L(c)^2$. □

18.16. Theorem. *Let (M, g) be a Riemann manifold with sectional curvature $k \geq k_0 > 0$. Then for any geodesic c in M the distance between two conjugate points along c is $\leq \frac{\pi}{\sqrt{k_0}}$.*

Proof. Let $c : [0, a] \to M$ be a geodesic with $|\dot c| = 1$ such that $c(a)$ is the first point which is conjugate to $c(0)$ along c. We choose a parallel unit vector field Z along c, $Z(t) = \mathrm{Pt}(c, t).Z(0)$, $|Z(0)|_g = 1$, $Z(t) \perp^g \dot c(t)$, so that $\nabla_{\partial_t} Z = 0$. Consider

$f \in C^\infty([0,a],\mathbb{R})$ with $f(0)=0$ and $f(a)=0$, and let $0<b<a$. By (18.15.1) we have $d^2E_0^b(c)(fZ,fZ)\ge 0$. By (18.14.1) we have

$$\begin{aligned} d^2E_0^b(c)(fZ,fZ) &= \int_0^b \big(g(\nabla_{\partial_t}(fZ),\nabla_{\partial_t}(fZ)) - g(R(fZ,\dot c)\dot c, fZ)\big)\,dt \\ &= \int_0^b \big(f'^2 - f^2 k(Y\wedge \dot c)\big)\,dt \le \int_0^b (f'^2 - f^2 k_0)\,dt \end{aligned}$$

since $Y, \dot c$ form an orthonormal basis. Now we choose $f(t)=\sin(\pi t b)$ so that $\int_0^b f^2\,dt = \frac{b}{2}$ and $\int_0^b f'^2\,dt = \frac{\pi^2}{2b}$. Thus $0 \le \int_0^b (f'^2 - f^2k_0)\,dt = \frac{\pi^2}{2b} - \frac{b}{2}k_0$ which implies $b \le \frac{\pi}{\sqrt{k_0}}$. Since b was arbitrary $<a$ we get $a\le \frac{\pi}{\sqrt{k_0}}$. □

18.17. Corollary. *(Myers, 1935) If M is a complete connected Riemann manifold with sectional curvature $k \ge k_0 > 0$. Then the diameter of M is bounded:*

$$\operatorname{diam}(M) := \sup\{\operatorname{dist}(x,y) : x,y\in M\} \le \frac{\pi}{\sqrt{k_0}}.$$

Thus M is compact and each covering space of M is also compact, so the the fundamental group $\pi_1(M)$ is finite.

Proof. By (14.6.6) any two points $x,y\in M$ can be connected by a geodesic c of minimal length. Assume for contradiction that $\operatorname{dist}(x,y) > \frac{\pi}{\sqrt{k_0}}$ then by (18.16) there exist an interior point z on the geodesic c which is conjugate to x. By (18.15.2) there exist smooth curves in M from x to y which are shorter than c, contrary to the minimality of c □

18.18. Theorem. *Let M be a connected complete Riemann manifold with sectional curvature $k\le 0$. Then $\exp_x : T_xM \to M$ is a covering mapping for each $x\in M$. If M is also simply connected then $\exp_x : T_xM\to M$ is a diffeomorphism.*

This result is due to [Hadamard, 1898] for surfaces, and to E. Cartan 1928 in the general case.

Proof. Let $c:[0,\infty)\to M$ be a geodesic with $c(0)=x$. If $c(a)$ is a point conjugate to $c(0)$ along c then by (18.11) and (18.7) there exists a Jacobi field $Y\ne 0$ along c with $Y(0)=0$ and $Y(a)=0$. By (18.13) we have $Y(t)\perp^g \dot c(t)$ for all t. Now use (18.14.2) and (18.14.1) to get

$$\begin{aligned} d^2E(c)(Y,Y) &= -\int_0^a g\big(\nabla_{\partial_t}\nabla_{\partial_t}Y + R_{\dot c}(Y), Y\big)\,dt = 0, \\ d^2E_0^a(c)(Y,Y) &= \int_0^a \big(g(\nabla_{\partial_t}Y,\nabla_{\partial_t}Y) - g(R(Y,\dot c)\dot c, Y)\big)\,dt \\ &= \int_0^a \big(|\nabla_{\partial_t}Y|_g^2 - k(Y\wedge\dot c)(|Y|^2|\dot c|^2 - g(Y,\dot c))\big)\,dt > 0, \end{aligned}$$

a contradiction. Thus there are no conjugate points. Thus the surjective (by (14.6)) mapping $\exp_x : T_xM\to M$ is a local diffeomorphism by (18.11). Lemma (18.20) below then finishes the proof. □

18.19. A smooth mapping $f : (M, g) \to (\bar M, \bar g)$ between Riemann manifolds is called *distance increasing* if $f^*\bar g \ge g$; in detail, $\bar g_{f(x)}(T_xf.X, T_xf.X) \ge g_x(X, X)$ for all $X \in T_xM$, all $x \in M$.

Lemma. *Let (M, g) be a connected complete Riemann manifold. If $f : (M, g) \to (\bar M, \bar g)$ is surjective and distance increasing then f is a covering mapping.*

Proof. Obviously, f is locally injective thus T_xf is injective for all x and $\dim(M) \le \dim(\bar M)$. Since f is surjective, $\dim(M) \ge \dim(\bar M)$ by the theorem of Sard (10.12).

For each curve $c : [0, 1] \to M$ we have $L_g(c) = \int_0^1 |c'|_g\,dt \le \int_0^1 |c'|_{f^*\bar g}\,dt = L_{f^*\bar g}(c)$ thus $\text{dist}_g(x, y) \le \text{dist}_{f^*\bar g}(x, y)$ for $x, y \in M$. So $(M, \text{dist}_{f^*\bar g})$ is a complete metric space and $(M, f^*\bar g)$ is a complete Riemann manifold also. Without loss we may thus assume that $g = f^*\bar g$, so that f is a local isometry. Then $(\bar M = f(M), \bar g)$ is also complete.

For fixed $\bar x \in \bar M$ let $r > 0$ such that $\exp_{\bar x} : B_{0_{\bar x}}(2r) \to B_{\bar x}(2r) \subset \bar M$ is a diffeomorphism. Let $f^{-1}(\bar x) = \{x_1, x_2, \dots\}$. All the following diagrams commute:

$$\begin{array}{ccccccc}
T_{x_i}M & \hookleftarrow & B_{0_{x_i}}(2r) & \xrightarrow{\exp_{x_i}} & B_{x_i}(2r) & \hookrightarrow & M \\
 & & \downarrow{\scriptstyle T_{x_i}f} & & \downarrow{\scriptstyle f} & & \\
T_{\bar x}\bar M & \hookleftarrow & B_{0_{\bar x}}(2r) & \xrightarrow{\exp_{\bar x}} & B_{\bar x}(2r) & \hookrightarrow & \bar M
\end{array}$$

We claim (which finishes the proof):

(1) $f : B_{x_i}(2r) \to B_{\bar x}(2r)$ is a diffeomorphism for each i
(2) $f^{-1}(B_{\bar x}(r)) = \bigcup_i B_{x_i}(r)$
(3) $B_{x_i}(r) \cup B_{x_j}(r) = \emptyset$ for $i \ne j$.

(1) From the diagram we conclude that there $\exp_{x_i}$ is injective and f is surjective. Since $\exp_{x_i} : B_{0_{x_i}}(r) \to B_{x_i}(r)$ is also surjective (by completeness), $f : B_{x_i}(r) \to B_{\bar x}(r)$ is injective too and thus a diffeomorphism.

(2) From the diagram (with $2r$ replaced by r) we see that $f^{-1}(B_{\bar x}(r)) \supseteq B_{x_i}(r)$ for all i. If conversely $y \in f^{-1}(B_{\bar x}(r))$ let $\bar c : [0, s] \to B_{\bar x}(r)$ be the minimal geodesic from $f(y)$ to $\bar x$ in $\bar M$ where $s = \text{dist}_{\bar g}(f(y), \bar x)$. Let c be the geodesic in M which starts at y and satisfies $T_yf.c'(0) = \bar c'(0)$. Since f is an infinitesimal isometry, $f \circ c = \bar c$ and thus $f(c(s)) = \bar x$. So $c(s) = x_i$ for some i. Since $\text{dist}_g(y, x_i) \le s < r$ we have $y \in B_{0_{x_i}}(r)$. Thus $f^{-1}(B_{\bar x}(r)) \subseteq \bigcup_i B_{x_i}(r)$.

(3) If $y \in B_{x_i}(r) \cup B_{x_j}(r)$ then $x_j \in B_{x_i}(2r)$ and by (1) we get $x_j = x_i$. □

18.20. Lemma. [Kobayashi, 1961] *If M is a connected complete Riemann manifold without conjugate points, then $\exp_x : T_xM \to M$ is a covering mapping.*

Proof. Since (M, g) is complete and connected $\exp_x : T_xM \to M$ is surjective; and it is also a local diffeomorphism by (18.11) since M has no conjugate points. We will construct a complete Riemann metric $\tilde g$ on T_xM such that $\exp_x : (T_xM, \tilde g) \to (M, g)$ is distance increasing. By (18.19) this finishes the proof.

Define the continuous function $h : T_xM \to \mathbb{R}_{>0}$ by

$$\begin{aligned} h(X) &= \sup\{r : |T_X(\exp_x).\xi|^2_{g_{\exp_x(X)}} \geq r|\xi|^2_{g_x} \text{ for all } \xi \in T_xM\} \\ &= \min\{|T_X(\exp_x).\xi|^2_{g_{\exp_x(X)}} : |\xi|_{g_x} = 1\} \\ &= 1\Big/\sqrt{\text{operator norm}(T_X(\exp_x)^{-1} : T_{\exp_x(X)}M \to T_xM)} \end{aligned}$$

We use polar coordinates $\varphi : \mathbb{R}_{>0} \times S^{m-1} \to T_xM \setminus \{0_x\}$ given by $\varphi(r,\theta) = r.\theta$ and express the metric by $\varphi^*(g_x) = dr^2 + r^2 g^S$ where g^S is the metric on the sphere. Now we choose an even smooth function $f : \mathbb{R} \to \mathbb{R}$ which satisfies $0 < f(r(X)) \leq h(X)$. Consider the Riemann metric $\tilde g = dr^2 + r^2 f(r)$ on T_xM.

For every $R > 0$ we have

$$\overline{B}^{\tilde g}_{0_x}(R) = \{X \in T_xM : \operatorname{dist}_{\tilde g}(X, 0_x) \leq R\} \subseteq \{X \in T_xM : r(X) \leq R\}$$

which is compact, thus $(T_xM, \tilde g)$ is complete.

It remains to check that $\exp_x : (T_xM, \tilde g) \to (M, g)$ is distance increasing. Let $\xi \in T_X(T_xM)$. If $X = 0_x$ then $T_{0_x}(\exp_x).\xi = \xi$, so $\exp_x$ is distance increasing at 0_x since $f(0) \leq 1$.

So let $X \neq 0_x$. Then $\xi = \xi_1 + \xi_2$ where $dr(\xi_2) = 0$, thus ξ_2 tangent to the sphere through X, and $\xi_1 \perp \xi_2$ (with respect to both g_x and $\tilde g_X$). Then

$$|\xi|^2_{g_x} = |\xi_1|^2_{g_x} + |\xi_2|^2_{g_x}, \quad |\xi|^2_{\tilde g} = |\xi_1|^2_{\tilde g} + |\xi_2|^2_{\tilde g}, \quad |\xi|_{g_x} = |\xi|_{\tilde g} = |dr(\xi_1)| = |dr(\xi)|.$$

By the generalized version of the Gauß lemma in (18.15.3) the vector $T_X(\exp_x).\xi_1 \in T_{\exp_x(X)}M$ is tangent to the geodesic $t \mapsto \exp_x(t.X)$ in (M, g) and $T_X(\exp_x).\xi_2$ is normal to it. Thus $|T_X(\exp_x).\xi_1|_g = |\xi_1|_g = |\xi_1|_{\tilde g}$ and

$$\begin{aligned} |T_X(\exp_x).\xi|^2_g = |T_X(\exp_x).\xi_1|^2_g + |T_X(\exp_x).\xi_2|^2_g = |\xi_1|_{\tilde g} + |T_X(\exp_x).\xi_2|^2_g \\ |T_X(\exp_x).\xi|^2_g - |\xi|^2_{\tilde g} = |T_X(\exp_x).\xi_2|^2_g - |\xi_2|^2_{\tilde g} \end{aligned}$$

In order to show that that $|T_X(\exp_x).\xi|_g \geq |\xi|_{\tilde g}$ we can thus assume that $\xi = \xi_2$ is normal to the ray $t \mapsto t.X$. But for these ξ we have $|\xi|^2_{\tilde g} = f(r(X))|\xi|^2_{g_x}$ by construction of $\tilde g$ and

$$|T_X(\exp_x).\xi|^2_g \geq h(X)\,|\xi|^2_{g_x} \geq f(r(X))\,|\xi|^2_{g_x} = |\xi|^2_{\tilde g}.$$

So $\exp_x : (T_xM, \tilde g) \to (M, g)$ is distance increasing. □

H. Hodge theory

H.1. The Hodge $*$-operator. Let (M, g) be a oriented pseudo Riemann manifold of signature (p, q). Viewing $g : TM \to T^*M$, we let $g^{-1} : T^*M \to TM$ denote the dual bundle metric on T^*M. Then g^{-1} induces a symmetric non-degenerate bundle metric on the the bundle $\bigwedge^k T^*M$ of k-forms which is given by

$$g^{-1}(\varphi_1 \wedge \dots \wedge \varphi_k, \psi_1 \wedge \dots \wedge \psi_k) = \det(g^{-1}(\varphi_i, \psi_j)_{i,j=1}^k), \quad \varphi_i, \psi_j \in \Omega^1(M).$$

Let $\eta_{ij} = g(s_i, s_j) = \operatorname{diag}(1, \dots, 1, -1, \dots, -1)$ be the standard inner product matrix of the same signature (p, q), and let $s = (s_1, \dots, s_m)$ be an orthonormal frame on $U \subseteq M$ with orthonormal coframe $\sigma = (\sigma_1, \dots, \sigma_m)$ as in (16.5) so that $g = \sum_i \eta_{ii} \sigma^i \otimes \sigma^i$, then for $\varphi^k, \psi^k \in \Omega^k(M)$ we have

$$g^{-1}(\varphi^k, \psi^k) = \sum_{\substack{i_1 < \dots < i_k \\ j_1 < \dots < j_k}} \varphi^k(s_{i_1}, \dots, s_{i_k}) \psi^k(s_{j_1}, \dots, s_{j_k}) \eta^{i_1 j_1} \dots \eta^{i_k j_k}.$$

Note that $g^{-1}(\sigma^1 \wedge \dots \wedge \sigma^m, \sigma^1 \wedge \dots \wedge \sigma^m) = (-1)^q$. If M is also oriented then the volume form $\operatorname{vol}(g)$ from (8.5) agrees with the positively oriented m-form of length ± 1. We have $\operatorname{vol}(g) = \sigma^1 \wedge \dots \sigma^m$ if the frame $s = (s_1, \dots, s_m)$ is positively oriented.

We shall use the following notation: If $I = (i_1 < \dots < i_k)$ and $I' = (j_1 < \dots < j_{m-k})$ are the ordered tuples with $I \cap I' = \emptyset$ and $I \sqcup I' = \{1, \dots, m\}$ then we put $\sigma^I := \sigma^{i_1} \wedge \dots \wedge \sigma^{i_k}$.

Exercise. The k-forms σ^I for all I as above of length k give an orthonormal basis of g^{-1} on $\Omega^k(U)$. The signature of g^{-1} on $\bigwedge^k T_x^* M$ is

$$(P_+(p, q, k), P_-(p, q, k)) = \Big(\textstyle\sum_{j=0, j \text{ even}}^k \binom{p}{k-j}\binom{q}{j}, \sum_{j=0, j \text{ odd}}^k \binom{p}{k-j}\binom{q}{j}\Big)$$

On an oriented pseudo Riemann manifold (M, g) of dimension m and signature (p, q) we have the *Hodge isomorphism* with its elementary properties:

$$\begin{aligned}
&* : \Lambda^k T^*M \to \Lambda^{m-k} T^*M \\
(1) \qquad &(*\varphi^k)(X_{k+1}, \dots, X_m) \operatorname{vol}(g) = \varphi \wedge g(X_{k+1}) \wedge \dots \wedge g(X_m) \\
&\varphi^k \wedge \psi^{m-k} = g^{-1}(*\varphi^k, \psi^{m-k}) \operatorname{vol}(g). \\
&g^{-1}(*\varphi^k, *\psi^k) = (-1)^q g^{-1}(\varphi^k, \psi^k) \\
&**\varphi^k = (-1)^{k(m-k)+q} \varphi^k \\
&(*\varphi^k) \wedge \psi^k = (*\psi^k) \wedge \varphi^k
\end{aligned}$$

In the local orthonormal frame we get

$$\begin{aligned}
(*\sigma^I)(s_{j_1}, \dots, s_{j_{m-k}}) \operatorname{vol}(g) &= \sigma^I \wedge g(s_{j_1}) \wedge \dots \wedge g(s_{j_{m-k}}) \\
&= \sigma^I \wedge g(s_{j_1}) \wedge \dots \wedge g(s_{j_{m-k}}) = \sigma^I \wedge \eta_{j_1 j_1} \sigma^{j_1} \wedge \dots \wedge \eta_{j_{m-k} j_{m-k}} \sigma^{j_{m-k}} \\
*\sigma^I &= \operatorname{sign}\begin{pmatrix} 1 \dots m \\ I \quad I' \end{pmatrix} \eta_{j_1 j_1} \dots \eta_{j_{m-k} j_{m-k}} \sigma^{I'}
\end{aligned}$$

To get a geometric interpretation of $*\varphi^k$ we consider

$$\begin{aligned} i(X)(*\varphi^k)(X_{k+2},\dots,X_m)\operatorname{vol}(g) &= (*\varphi^k)(X,X_{k+2},\dots,X_m)\operatorname{vol}(g)\\ &= \varphi^k\wedge g(X)\wedge g(X_{k+2})\wedge\dots\wedge g(X_m) = *(\varphi^k\wedge g(X))(X_{k+2},\dots,X_m)\operatorname{vol}(g)\end{aligned}$$

so that

$$\begin{aligned} i(X)(*\varphi^k) &= *(\varphi^k\wedge g(X)),\\ \{X : i_X\varphi^k=0\}^{\perp,g} &= \{Y : i_Y(*\varphi^k)=0\}. \end{aligned} \tag{2}$$

H.2. Relations to vector analysis. We consider an oriented pseudo Riemann manifold (M,g) of signature (p,q). For functions $f\in C^\infty(M,\mathbb{R})$ and vector fields $X\in\mathfrak{X}(M)$ we have the following operations, *gradient* and *divergence*, and their elementary properties:

$$\begin{aligned}
&\operatorname{grad}^g(f) = g^{-1}\circ df\in\mathfrak{X}(M)\\
&g(X)\in\Omega^1(M),\qquad *g(X) = (-1)^q i_X\operatorname{vol}(g)\\
&*\,df = *g(\operatorname{grad}^g(f)) = (-1)^q i_{\operatorname{grad}^g(f)}\operatorname{vol}(g)\\
&\operatorname{div}^g(X).\operatorname{vol}(g) = (-1)^q d i_X\operatorname{vol}(g) = d*g(X)\\
&\operatorname{grad}^g(f\cdot h) = f\cdot\operatorname{grad}^g(h)+h\cdot\operatorname{grad}^g(f)\\
&\operatorname{div}^g(f\cdot X) = f\operatorname{div}^g(X)+(-1)^q df(X)\\
&\operatorname{grad}^g(f)|_U = \textstyle\sum_i \eta_{ii}s_i(f)\cdot s_i\\
&\operatorname{div}^g(X) = \operatorname{trace}(\nabla X).
\end{aligned}$$

Some authors take the negative of our definition of the divergence, so that later the Laplace-Beltrami operator $\Delta f = (-\operatorname{div}^g)\operatorname{grad}^g(f)$ is positive definite on any oriented Riemann manifold.

H.3. In dimension three.

On an oriented 3-dimensional pseudo Riemann manifold we have another operator on vector fields, *curl*, given by

$$\begin{aligned}
&*\,g(\operatorname{curl}^g(X)) = (-1)^q i_{\operatorname{curl}^g(X)}\operatorname{vol}(g) = dg(X),\\
&\operatorname{curl}^g(X) = (-1)^q g^{-1}*dg(X),
\end{aligned}$$

and from $d^2=0$ we have $\operatorname{curl}^g\operatorname{grad}^g=0$ and $\operatorname{div}^g\operatorname{curl}^g=0$.

On the oriented Euclidean space $\mathbb{R}^3$ we have

$$\begin{aligned}
\operatorname{grad}(f) &= \frac{\partial f}{\partial x^1}\frac{\partial}{\partial x^1}+\frac{\partial f}{\partial x^2}\frac{\partial}{\partial x^2}+\frac{\partial f}{\partial x^3}\frac{\partial}{\partial x^3}\\
\operatorname{curl}(X) &= \left(\frac{\partial X^3}{\partial x^2}-\frac{\partial X^2}{\partial x^3}\right)\frac{\partial}{\partial x^1}+\left(\frac{\partial X^1}{\partial x^3}-\frac{\partial X^3}{\partial x^1}\right)\frac{\partial}{\partial x^2}+\left(\frac{\partial X^2}{\partial x^1}-\frac{\partial X^1}{\partial x^2}\right)\frac{\partial}{\partial x^3}\\
\operatorname{div}(X) &= \frac{\partial X^1}{\partial x^1}+\frac{\partial X^2}{\partial x^2}+\frac{\partial X^3}{\partial x^3}
\end{aligned}$$

Note also that $\operatorname{curl}(f\cdot X) = f\cdot\operatorname{rot}(X)+\operatorname{grad}(f)\times X$ where $\times$ denotes the vector product in $\mathbb{R}^3$.

H.4 The Maxwell equations. Let $U \subset \mathbb{R}^3$ be an open set in the oriented Euclidean 3-space. We will later assume that $H^1(U) = 0$. We consider three time dependent vector fields and a function,

$$\begin{aligned}
&E : U \times \mathbb{R} \to \mathbb{R}^3, && \text{the electric field,}\\
&B : U \times \mathbb{R} \to \mathbb{R}^3, && \text{the magnetic field,}\\
&J : U \times \mathbb{R} \to \mathbb{R}^3, && \text{the current field,}\\
&\rho : U \times \mathbb{R} \to \mathbb{R}, && \text{the density function of the electric charge.}
\end{aligned}$$

Then the *Maxwell equations* are (where c is the speed of light)

$$\begin{aligned}
\operatorname{curl}(E) &= -\frac{1}{c}\frac{d}{dt}B, && \operatorname{div}(B) = 0,\\
\operatorname{curl}(B) &= \frac{1}{c}\frac{d}{dt}E + \frac{4\pi}{c}J, && \operatorname{div}(E) = 4\pi\rho.
\end{aligned}$$

Now let η be the standard positive definite inner product on $\mathbb{R}^3$. From (H.3) we see that the Maxwell equations can be written as

$$\begin{aligned}
*d\,\eta(E) &= -\frac{1}{c}\frac{d}{dt}\eta(B), && d * \eta(B) = 0,\\
*d\,\eta(B) &= \frac{1}{c}\frac{d}{dt}\eta(E) + \frac{4\pi}{c}\eta(J), && d * \eta(E) = 4\pi\rho\cdot\operatorname{vol}(\eta).
\end{aligned}$$

Now we assume that $H^1(U) = 0$. Since $d * \eta(B) = 0$, we have

$$*\eta(B) = dA \qquad \text{for a function } A, \qquad \textit{the magnetic potential.}$$

Then the first Maxwell equation can be written as

$$d\left(\eta(E) + \frac{1}{c}\frac{d}{dt}A\right) = 0.$$

Using again $H^1(U) = 0$, there exists a function $\Phi : U \times \mathbb{R} \to \mathbb{R}$, called the *electric potential*, such that

$$\eta(E) = -\frac{1}{c}\frac{d}{dt}A - d\Phi.$$

Starting from the magnetic and electric potentials $A, \Phi : U \times \mathbb{R} \to \mathbb{R}$, the electric and magnetic fields are given by

$$\eta(E) = -\frac{1}{c}\frac{d}{dt}A - d\Phi, \qquad \eta(B) = *dA,$$

where all terms are viewed as time dependent functions of forms on $\mathbb{R}^3$. Then the first row of the Maxwell equations is automatically satisfied. The second row then looks like

$$- * d * dA = -\frac{1}{c^2}\frac{d^2}{dt^2}A - \frac{1}{c}\frac{d}{dt}d\Phi + \frac{4\pi}{c}\eta(J), \quad \frac{1}{c}\frac{d}{dt}(*d * A) - \Delta\Phi = 4\pi\rho.$$

CHAPTER V
Bundles and Connections

19. Derivations on the Algebra of Differential Forms and the Frölicher-Nijenhuis Bracket

19.1. Derivations. In this section let M be a smooth manifold. We consider the graded commutative algebra $\Omega(M) = \bigoplus_{k=0}^{\dim M} \Omega^k(M) = \bigoplus_{k=-\infty}^{\infty} \Omega^k(M)$ of differential forms on M, where we put $\Omega^k(M) = 0$ for $k < 0$ and $k > \dim M$. We denote by $\operatorname{Der}_k \Omega(M)$ the space of all *(graded) derivations* of degree k, i.e. all linear mappings $D : \Omega(M) \to \Omega(M)$ with $D(\Omega^\ell(M)) \subset \Omega^{k+\ell}(M)$ and $D(\varphi \wedge \psi) = D(\varphi) \wedge \psi + (-1)^{k\ell} \varphi \wedge D(\psi)$ for $\varphi \in \Omega^\ell(M)$.

Lemma. *Then the space* $\operatorname{Der} \Omega(M) = \bigoplus_k \operatorname{Der}_k \Omega(M)$ *is a graded Lie algebra with the graded commutator* $[D_1, D_2] := D_1 \circ D_2 - (-1)^{k_1 k_2} D_2 \circ D_1$ *as bracket. This means that the bracket is graded anticommutative, and satisfies the graded Jacobi identity*

$$[D_1, D_2] = -(-1)^{k_1 k_2}[D_2, D_1],$$
$$[D_1, [D_2, D_3]] = [[D_1, D_2], D_3] + (-1)^{k_1 k_2}[D_2, [D_1, D_3]]$$

(so that $ad(D_1) = [D_1, \quad]$ *is itself a derivation of degree* k_1*).*

Proof. Plug in the definition of the graded commutator and compute. □

In section (7) we have already met some graded derivations: for a vector field X on M the derivation i_X is of degree -1, $\mathcal{L}_X$ is of degree 0, and d is of degree 1. Note also that the important formula $\mathcal{L}_X = d\, i_X + i_X\, d$ translates to $\mathcal{L}_X = [i_X, d]$.

19.2. Algebraic derivations. A derivation $D \in \operatorname{Der}_k \Omega(M)$ is called *algebraic* if $D \mid \Omega^0(M) = 0$. Then $D(f.\omega) = f.D(\omega)$ for $f \in C^\infty(M)$, so D is of tensorial character by (7.3). So D induces a derivation $D_x \in \operatorname{Der}_k \Lambda T_x^* M$ for each $x \in M$. It is uniquely determined by its restriction to 1-forms $D_x | T_x^* M : T_x^* M \to \Lambda^{k+1} T^* M$ which we may view as an element $K_x \in \Lambda^{k+1} T_x^* M \otimes T_x M$ depending smoothly on $x \in M$. To express this dependence we write $D = i_K = i(K)$, where $K \in \Gamma(\Lambda^{k+1} T^* M \otimes TM) =: \Omega^{k+1}(M; TM)$. Note the defining equation: $i_K(\omega) = \omega \circ K$ for $\omega \in \Omega^1(M)$. We call $\Omega(M, TM) = \bigoplus_{k=0}^{\dim M} \Omega^k(M, TM)$ the space of all *vector valued differential forms.*

Theorem. (1) *For $K \in \Omega^{k+1}(M,TM)$ the formula*

$$(i_K\omega)(X_1,\dots,X_{k+\ell}) = \\ = \tfrac{1}{(k+1)!\,(\ell-1)!}\sum_{\sigma\in\mathcal{S}_{k+\ell}} \operatorname{sign}\sigma\,.\omega(K(X_{\sigma 1},\dots,X_{\sigma(k+1)}),X_{\sigma(k+2)},\dots)$$

for $\omega \in \Omega^\ell(M)$, $X_i \in \mathfrak{X}(M)$ (or T_xM) defines an algebraic graded derivation $i_K \in \operatorname{Der}_k\Omega(M)$ and any algebraic derivation is of this form.

(2) *By $i([K,L]^\wedge) := [i_K, i_L]$ we get a bracket $[\ \ ,\ \ ]^\wedge$ on $\Omega^{*+1}(M,TM)$ which defines a graded Lie algebra structure with the grading as indicated, and for $K \in \Omega^{k+1}(M,TM)$, $L \in \Omega^{\ell+1}(M,TM)$ we have*

$$[K,L]^\wedge = i_K L - (-1)^{k\ell} i_L K$$

where $i_K(\omega\otimes X) := i_K(\omega)\otimes X$.

$[\ \ ,\ \ ]^\wedge$ is called the *algebraic bracket* or the *Nijenhuis-Richardson bracket*, see [Nijenhuis-Richardson, 1967].

Proof. Since ΛT_x^*M is the free graded commutative algebra generated by the vector space T_x^*M any $K \in \Omega^{k+1}(M,TM)$ extends to a graded derivation. By applying it to an exterior product of 1-forms one can derive the formula in (1). The graded commutator of two algebraic derivations is again algebraic, so the injection $i : \Omega^{*+1}(M,TM) \to \operatorname{Der}_*(\Omega(M))$ induces a graded Lie bracket on $\Omega^{*+1}(M,TM)$ whose form can be seen by applying it to a 1-form. $\square$

19.3. Lie derivations. The exterior derivative d is an element of $\operatorname{Der}_1\Omega(M)$. In view of the formula $\mathcal{L}_X = [i_X, d] = i_X\,d + d\,i_X$ for vector fields X, we define for $K \in \Omega^k(M;TM)$ the *Lie derivation* $\mathcal{L}_K = \mathcal{L}(K) \in \operatorname{Der}_k\Omega(M)$ by $\mathcal{L}_K := [i_K, d] = i_K\,d - (-1)^{k-1} d\,i_K$.

Then the mapping $\mathcal{L} : \Omega(M,TM) \to \operatorname{Der}\Omega(M)$ is injective, since $\mathcal{L}_K f = i_K df = df \circ K$ for $f \in \mathcal{C}^\infty(M)$.

Theorem. *For any graded derivation $D \in \operatorname{Der}_k\Omega(M)$ there are unique $K \in \Omega^k(M;TM)$ and $L \in \Omega^{k+1}(M;TM)$ such that*

$$D = \mathcal{L}_K + i_L.$$

We have $L = 0$ if and only if $[D,d] = 0$. D is algebraic if and only if $K = 0$.

Proof. Let $X_i \in \mathfrak{X}(M)$ be vector fields. Then $f \mapsto (Df)(X_1,\dots,X_k)$ is a derivation $C^\infty(M) \to C^\infty(M)$, so there exists a vector field $K(X_1,\dots,X_k) \in \mathfrak{X}(M)$ by (3.3) such that

$$(Df)(X_1,\dots,X_k) = K(X_1,\dots,X_k)f = df(K(X_1,\dots,X_k)).$$

Clearly $K(X_1,\dots,X_k)$ is $C^\infty(M)$-linear in each X_i and alternating, so K is tensorial by (7.3), $K \in \Omega^k(M;TM)$.

The defining equation for K is $Df = df \circ K = i_K df = \mathcal{L}_K f$ for $f \in C^\infty(M)$. Thus $D - \mathcal{L}_K$ is an algebraic derivation, so $D - \mathcal{L}_K = i_L$ by (19.2) for unique $L \in \Omega^{k+1}(M;TM)$.

Since we have $[d,d] = 2d^2 = 0$, by the graded Jacobi identity, we obtain $0 = [i_K,[d,d]] = [[i_K,d],d] + (-1)^{k-1}[d,[i_K,d]] = 2[\mathcal{L}_K,d]$. The mapping $K \mapsto [i_K,d] = \mathcal{L}_K$ is injective, so the last assertions follow. $\square$

19.4. Applying $i(Id_{TM})$ on a k-fold exterior product of 1-forms we get $i(Id_{TM})\omega = k\omega$ for $\omega \in \Omega^k(M)$. Thus we have $\mathcal{L}(Id_{TM})\omega = i(Id_{TM})d\omega - d\,i(Id_{TM})\omega = (k+1)d\omega - kd\omega = d\omega$. Thus $\mathcal{L}(Id_{TM}) = d$.

19.5. Let $K \in \Omega^k(M;TM)$ and $L \in \Omega^\ell(M;TM)$. Then clearly $[[\mathcal{L}_K,\mathcal{L}_L],d] = 0$, so we have

$$[\mathcal{L}(K),\mathcal{L}(L)] = \mathcal{L}([K,L])$$

for a uniquely defined $[K,L] \in \Omega^{k+\ell}(M;TM)$. This vector valued form $[K,L]$ is called the *Frölicher-Nijenhuis bracket* of K and L.

Theorem. *The space $\Omega(M;TM) = \bigoplus_{k=0}^{\dim M} \Omega^k(M;TM)$ with its usual grading is a graded Lie algebra for the Frölicher-Nijenhuis bracket. So we have*

$$[K,L] = -(-1)^{k\ell}[L,K]$$
$$[K_1,[K_2,K_3]] = [[K_1,K_2],K_3] + (-1)^{k_1k_2}[K_2,[K_1,K_3]]$$

$Id_{TM} \in \Omega^1(M;TM)$ is in the center, i.e. $[K,Id_{TM}] = 0$ for all K.

$\mathcal{L} : (\Omega(M;TM),[\quad,\quad]) \to \operatorname{Der}\Omega(M)$ is an injective homomorphism of graded Lie algebras. For vector fields the Frölicher-Nijenhuis bracket coincides with the Lie bracket.

Proof. $df \circ [X,Y] = \mathcal{L}([X,Y])f = [\mathcal{L}_X,\mathcal{L}_Y]f$. The rest is clear. $\square$

19.6. Lemma. *For $K \in \Omega^k(M;TM)$ and $L \in \Omega^{\ell+1}(M;TM)$ we have*

$$[\mathcal{L}_K,i_L] = i([K,L]) - (-1)^{k\ell}\mathcal{L}(i_LK), \text{ or}$$
$$[i_L,\mathcal{L}_K] = \mathcal{L}(i_LK) - (-1)^k\, i([L,K]).$$

This generalizes (7.7.3).

Proof. For $f \in C^\infty(M)$ we have $[i_L,\mathcal{L}_K]f = i_L\, i_K\, df - 0 = i_L(df \circ K) = df \circ (i_LK) = \mathcal{L}(i_LK)f$. So $[i_L,\mathcal{L}_K] - \mathcal{L}(i_LK)$ is an algebraic derivation.

$$\begin{aligned}[][[i_L,\mathcal{L}_K],d] &= [i_L,[\mathcal{L}_K,d]] - (-1)^{k\ell}[\mathcal{L}_K,[i_L,d]] = \\ &= 0 - (-1)^{k\ell}\mathcal{L}([K,L]) = (-1)^k[i([L,K]),d].\end{aligned}$$

Since $[\quad,d]$ kills the '$\mathcal{L}$'s' and is injective on the 'i's', the algebraic part of $[i_L,\mathcal{L}_K]$ is $(-1)^k\, i([L,K])$. $\square$

19.7. Module structure. The space $\operatorname{Der}\Omega(M)$ is a graded module over the graded algebra $\Omega(M)$ with the action $(\omega\wedge D)\varphi = \omega\wedge D(\varphi)$, because $\Omega(M)$ is graded commutative.

Theorem. *Let the degree of ω be q, of φ be k, and of ψ be ℓ. Let the other degrees be as indicated. Then we have:*

$$(1)\qquad [\omega\wedge D_1, D_2] = \omega\wedge[D_1,D_2] - (-1)^{(q+k_1)k_2} D_2(\omega)\wedge D_1.$$

$$(2)\qquad i(\omega\wedge L) = \omega\wedge i(L)$$

$$(3)\qquad \omega\wedge\mathcal{L}_K = \mathcal{L}(\omega\wedge K) + (-1)^{q+k-1} i(d\omega\wedge K).$$

$$(4)\qquad \begin{aligned}&[\omega\wedge L_1, L_2]^\wedge = \omega\wedge[L_1,L_2]^\wedge -\\ &\qquad - (-1)^{(q+\ell_1-1)(\ell_2-1)} i(L_2)\omega\wedge L_1.\end{aligned}$$

$$(5)\qquad \begin{aligned}&[\omega\wedge K_1, K_2] = \omega\wedge[K_1,K_2] - (-1)^{(q+k_1)k_2}\mathcal{L}(K_2)\omega\wedge K_1\\ &\qquad + (-1)^{q+k_1} d\omega\wedge i(K_1)K_2.\end{aligned}$$

$$(6)\qquad \begin{aligned}&[\varphi\otimes X, \psi\otimes Y] = \varphi\wedge\psi\otimes[X,Y]\\ &\qquad - \big(i_Y d\varphi\wedge\psi\otimes X - (-1)^{k\ell} i_X d\psi\wedge\varphi\otimes Y\big)\\ &\qquad - \big(d(i_Y\varphi\wedge\psi)\otimes X - (-1)^{k\ell} d(i_X\psi\wedge\varphi)\otimes Y\big)\\ &\qquad = \varphi\wedge\psi\otimes[X,Y] + \varphi\wedge\mathcal{L}_X\psi\otimes Y - \mathcal{L}_Y\varphi\wedge\psi\otimes X\\ &\qquad + (-1)^k\left(d\varphi\wedge i_X\psi\otimes Y + i_Y\varphi\wedge d\psi\otimes X\right).\end{aligned}$$

Proof. For (1) , (2) , (3) write out the definitions. For (4) compute $i([\omega\wedge L_1, L_2]^\wedge)$. For (5) compute $\mathcal{L}([\omega\wedge K_1, K_2])$. For (6) use (5) . $\square$

19.8. Theorem. *For $K\in\Omega^k(M;TM)$ and $\omega\in\Omega^\ell(M)$ the Lie derivative of ω along K is given by the following formula, where the X_i are vector fields on M.*

$$\begin{aligned}&(\mathcal{L}_K\omega)(X_1,\dots,X_{k+\ell}) =\\ &\quad = \tfrac{1}{k!\,\ell!}\sum_\sigma \operatorname{sign}\sigma\ \mathcal{L}(K(X_{\sigma1},\dots,X_{\sigma k}))(\omega(X_{\sigma(k+1)},\dots,X_{\sigma(k+\ell)}))\\ &\qquad + \tfrac{-1}{k!\,(\ell-1)!}\sum_\sigma \operatorname{sign}\sigma\ \omega([K(X_{\sigma1},\dots,X_{\sigma k}), X_{\sigma(k+1)}], X_{\sigma(k+2)},\dots)\\ &\qquad + \tfrac{(-1)^{k-1}}{(k-1)!\,(\ell-1)!\,2!}\sum_\sigma \operatorname{sign}\sigma\ \omega(K([X_{\sigma1},X_{\sigma2}],X_{\sigma3},\dots),X_{\sigma(k+2)},\dots).\end{aligned}$$

Proof. It suffices to consider $K=\varphi\otimes X$. Then by (19.7.3) we have $\mathcal{L}(\varphi\otimes X) = \varphi\wedge\mathcal{L}_X - (-1)^{k-1} d\varphi\wedge i_X$. Now use the global formulas of section (7) to expand this. $\square$

19.9. Theorem. *For $K\in\Omega^k(M;TM)$ and $L\in\Omega^\ell(M;TM)$ we have for the Frölicher-Nijenhuis bracket $[K,L]$ the following formula, where the X_i are vector fields on M.*

$$[K,L](X_1,\dots,X_{k+\ell}) =$$

$$
\begin{aligned}
&= \tfrac{1}{k!\,\ell!}\sum_\sigma \operatorname{sign}\sigma\,[K(X_{\sigma1},\dots,X_{\sigma k}),L(X_{\sigma(k+1)},\dots,X_{\sigma(k+\ell)})]\\
&\quad+\tfrac{-1}{k!\,(\ell-1)!}\sum_\sigma \operatorname{sign}\sigma\,L([K(X_{\sigma1},\dots,X_{\sigma k}),X_{\sigma(k+1)}],X_{\sigma(k+2)},\dots)\\
&\quad+\tfrac{(-1)^{k\ell}}{(k-1)!\,\ell!}\sum_\sigma \operatorname{sign}\sigma\,K([L(X_{\sigma1},\dots,X_{\sigma\ell}),X_{\sigma(\ell+1)}],X_{\sigma(\ell+2)},\dots)\\
&\quad+\tfrac{(-1)^{k-1}}{(k-1)!\,(\ell-1)!\,2!}\sum_\sigma \operatorname{sign}\sigma\,L(K([X_{\sigma1},X_{\sigma2}],X_{\sigma3},\dots),X_{\sigma(k+2)},\dots)\\
&\quad+\tfrac{(-1)^{(k-1)\ell}}{(k-1)!\,(\ell-1)!\,2!}\sum_\sigma \operatorname{sign}\sigma\,K(L([X_{\sigma1},X_{\sigma2}],X_{\sigma3},\dots),X_{\sigma(\ell+2)},\dots).
\end{aligned}
$$

Proof. It suffices to consider $K=\varphi\otimes X$ and $L=\psi\otimes Y$, then for $[\varphi\otimes X,\psi\otimes Y]$ we may use (19.7.6) and evaluate that at $(X_1,\dots,X_{k+\ell})$. After some combinatorial computation we get the right hand side of the above formula for $K=\varphi\otimes X$ and $L=\psi\otimes Y$. $\square$

There are more illuminating ways to prove this formula, see [Michor, 1987].

19.10. Local formulas. In a local chart (U,u) on the manifold M we put $K\mid U=\sum K^i_\alpha d^\alpha\otimes\partial_i$, $L\mid U=\sum L^j_\beta d^\beta\otimes\partial_j$, and $\omega\mid U=\sum\omega_\gamma d^\gamma$, where $\alpha=(1\le\alpha_1<\alpha_2<\dots<\alpha_k\le\dim M)$ is a form index, $d^\alpha=du^{\alpha_1}\wedge\ldots\wedge du^{\alpha_k}$, $\partial_i=\frac{\partial}{\partial u^i}$ and so on.

Plugging $X_j=\partial_{i_j}$ into the global formulas (19.2), (19.8), and (19.9), we get the following local formulas:

$$
\begin{aligned}
i_K\omega\mid U &= \sum K^i_{\alpha_1\dots\alpha_k}\omega_{i\alpha_{k+1}\dots\alpha_{k+\ell-1}}\,d^\alpha\\
[K,L]^\wedge\mid U &= \sum\Big(K^i_{\alpha_1\dots\alpha_k}\,L^j_{i\alpha_{k+1}\dots\alpha_{k+\ell}}\\
&\qquad -(-1)^{(k-1)(\ell-1)}L^i_{\alpha_1\dots\alpha_\ell}\,K^j_{i\alpha_{\ell+1}\dots\alpha_{k+\ell}}\Big)\,d^\alpha\otimes\partial_j\\
\mathcal{L}_K\omega\mid U &= \sum\Big(K^i_{\alpha_1\dots\alpha_k}\,\partial_i\omega_{\alpha_{k+1}\dots\alpha_{k+\ell}}\\
&\qquad +(-1)^k(\partial_{\alpha_1}K^i_{\alpha_2\dots\alpha_{k+1}})\,\omega_{i\alpha_{k+2}\dots\alpha_{k+\ell}}\Big)d^\alpha\\
[K,L]\mid U &= \sum\Big(K^i_{\alpha_1\dots\alpha_k}\,\partial_iL^j_{\alpha_{k+1}\dots\alpha_{k+\ell}}\\
&\qquad -(-1)^{k\ell}L^i_{\alpha_1\dots\alpha_\ell}\,\partial_iK^j_{\alpha_{\ell+1}\dots\alpha_{k+\ell}}\\
&\qquad -kK^j_{\alpha_1\dots\alpha_{k-1}i}\,\partial_{\alpha_k}L^i_{\alpha_{k+1}\dots\alpha_{k+\ell}}\\
&\qquad +(-1)^{k\ell}\ell L^j_{\alpha_1\dots\alpha_{\ell-1}i}\,\partial_{\alpha_\ell}K^i_{\alpha_{\ell+1}\dots\alpha_{k+\ell}}\Big)\,d^\alpha\otimes\partial_j
\end{aligned}
$$

19.11. Theorem. *For $K_i\in\Omega^{k_i}(M;TM)$ and $L_i\in\Omega^{k_i+1}(M;TM)$ we have*

(1) $$
\begin{aligned}
[\mathcal{L}_{K_1}+i_{L_1},\mathcal{L}_{K_2}+i_{L_2}] &= \mathcal{L}\left([K_1,K_2]+i_{L_1}K_2-(-1)^{k_1k_2}i_{L_2}K_1\right)\\
&\quad+i\left([L_1,L_2]^\wedge+[K_1,L_2]-(-1)^{k_1k_2}[K_2,L_1]\right).
\end{aligned}
$$

Each summand of this formula looks like a semidirect product of graded Lie algebras, but the mappings

$$\begin{aligned} i &: \Omega(M;TM) \to \operatorname{End}(\Omega(M;TM),[\quad,\quad]) \\ ad &: \Omega(M;TM) \to \operatorname{End}(\Omega(M;TM),[\quad,\quad]^\wedge) \end{aligned}$$

do not take values in the subspaces of graded derivations. We have instead for $K \in \Omega^k(M;TM)$ *and* $L \in \Omega^{\ell+1}(M;TM)$ *the following relations:*

$$\begin{aligned} i_L[K_1,K_2] &= [i_L K_1, K_2] + (-1)^{k_1\ell}[K_1, i_L K_2] \\ &\quad - \Big((-1)^{k_1\ell} i([K_1,L])K_2 - (-1)^{(k_1+\ell)k_2} i([K_2,L])K_1\Big) \end{aligned} \tag{2}$$

$$\begin{aligned} [K,[L_1,L_2]^\wedge] &= [[K,L_1],L_2]^\wedge + (-1)^{kk_1}[L_1,[K,L_2]]^\wedge - \\ &\quad - \Big((-1)^{kk_1}[i(L_1)K, L_2] - (-1)^{(k+k_1)k_2}[i(L_2)K, L_1]\Big) \end{aligned} \tag{3}$$

The algebraic meaning of the relations of this theorem and its consequences in group theory have been investigated in [Michor, 1989]. The corresponding product of groups is well known to algebraists under the name 'Zappa-Szep'-product.

Proof. Equation (1) is an immediate consequence of (19.6). Equations (2) and (3) follow from (1) by writing out the graded Jacobi identity, or as follows: Consider $\mathcal{L}(i_L[K_1,K_2])$ and use (19.6) repeatedly to obtain $\mathcal{L}$ of the right hand side of (2). Then consider $i([K,[L_1,L_2]^\wedge])$ and use again (19.6) several times to obtain i of the right hand side of (3). □

19.12. Corollary (of 8.9**).** *For* K, $L \in \Omega^1(M;TM)$ *we have*

$$\begin{aligned} [K,L](X,Y) &= [KX,LY] - [KY,LX] \\ &\quad - L([KX,Y] - [KY,X]) \\ &\quad - K([LX,Y] - [LY,X]) \\ &\quad + (LK + KL)[X,Y]. \end{aligned}$$

19.13. Curvature. Let $P \in \Omega^1(M;TM)$ be a fiber projection, i.e. $P \circ P = P$. This is the most general case of a (first order) *connection*. We may call $\ker P$ the *horizontal space* and $\operatorname{im} P$ the *vertical space* of the connection. If P is of constant rank, then both are sub vector bundles of TM. If $\operatorname{im} P$ is some primarily fixed sub vector bundle or (tangent bundle of) a foliation, P can be called a connection for it. Special cases of this will be treated extensively later on. The following result is immediate from (19.12).

Lemma. *We have*

$$[P,P] = 2R + 2\bar{R},$$

where R, $\bar{R} \in \Omega^2(M;TM)$ *are given by* $R(X,Y) = P[(Id-P)X,(Id-P)Y]$ *and* $\bar{R}(X,Y) = (Id-P)[PX,PY]$.

If P has constant rank, then R is the obstruction against integrability of the horizontal bundle $\ker P$, and $\bar{R}$ is the obstruction against integrability of the vertical bundle $\operatorname{im} P$. Thus we call R the *curvature* and $\bar{R}$ the *cocurvature* of the connection P. We will see later, that for a principal fiber bundle R is just the negative of the usual curvature.

19.14. Lemma (Bianchi identity). *If $P \in \Omega^1(M;TM)$ is a connection (fiber projection) with curvature R and cocurvature $\bar{R}$, then we have*

$$[P, R + \bar{R}] = 0$$
$$[R, P] = i_R \bar{R} + i_{\bar{R}} R.$$

Proof. We have $[P,P] = 2R + 2\bar{R}$ by (19.13) and $[P,[P,P]] = 0$ by the graded Jacobi identity. So the first formula follows. We have $2R = P \circ [P,P] = i_{[P,P]}P$. By (19.11.2) we get $i_{[P,P]}[P,P] = 2[i_{[P,P]}P, P] - 0 = 4[R,P]$. Therefore $[R,P] = \frac{1}{4} i_{[P,P]}[P,P] = i(R+\bar{R})(R+\bar{R}) = i_R\bar{R} + i_{\bar{R}}R$ since R has vertical values and kills vertical vectors, so $i_R R = 0$; likewise for $\bar{R}$. □

19.15. Naturality of the Frölicher-Nijenhuis bracket. Let $f : M \to N$ be a smooth mapping between manifolds. Two vector valued forms $K \in \Omega^k(M;TM)$ and $K' \in \Omega^k(N;TN)$ are called *f-related* or *f-dependent*, if for all $X_i \in T_xM$ we have

$$K'_{f(x)}(T_xf \cdot X_1, \dots, T_xf \cdot X_k) = T_xf \cdot K_x(X_1, \dots, X_k). \tag{1}$$

Theorem.

(2) *If K and K' as above are f-related then $i_K \circ f^* = f^* \circ i_{K'} : \Omega(N) \to \Omega(M)$.*
(3) *If $i_K \circ f^* \mid B^1(N) = f^* \circ i_{K'} \mid B^1(N)$, then K and K' are f-related, where B^1 denotes the space of exact 1-forms.*
(4) *If K_j and K'_j are f-related for $j = 1, 2$, then $i_{K_1}K_2$ and $i_{K'_1}K'_2$ are f-related, and also $[K_1, K_2]^\wedge$ and $[K'_1, K'_2]^\wedge$ are f-related.*
(5) *If K and K' are f-related then $\mathcal{L}_K \circ f^* = f^* \circ \mathcal{L}_{K'} : \Omega(N) \to \Omega(M)$.*
(6) *If $\mathcal{L}_K \circ f^* \mid \Omega^0(N) = f^* \circ \mathcal{L}_{K'} \mid \Omega^0(N)$, then K and K' are f-related.*
(7) *If K_j and K'_j are f-related for $j = 1, 2$, then their Frölicher-Nijenhuis brackets $[K_1, K_2]$ and $[K'_1, K'_2]$ are also f-related.*

Proof. (2) By (19.2) we have for $\omega \in \Omega^q(N)$ and $X_i \in T_xM$:

$$\begin{aligned}
&(i_K f^*\omega)_x(X_1, \dots, X_{q+k-1}) = \\
&\quad = \tfrac{1}{k!\,(q-1)!} \sum_\sigma \operatorname{sign}\sigma\, (f^*\omega)_x(K_x(X_{\sigma 1}, \dots, X_{\sigma k}), X_{\sigma(k+1)}, \dots) \\
&\quad = \tfrac{1}{k!\,(q-1)!} \sum_\sigma \operatorname{sign}\sigma\, \omega_{f(x)}(T_xf \cdot K_x(X_{\sigma 1}, \dots), T_xf \cdot X_{\sigma(k+1)}, \dots) \\
&\quad = \tfrac{1}{k!\,(q-1)!} \sum_\sigma \operatorname{sign}\sigma\, \omega_{f(x)}(K'_{f(x)}(T_xf \cdot X_{\sigma 1}, \dots), T_xf \cdot X_{\sigma(k+1)}, \dots) \\
&\quad = (f^* i_{K'}\omega)_x(X_1, \dots, X_{q+k-1})
\end{aligned}$$

(3) follows from this computation, since the df, $f \in C^\infty(M)$ separate points.

(4) follows from the same computation for K_2 instead of ω, the result for the bracket then follows from (19.2.2).

(5) The algebra homomorphism f^* intertwines the operators i_K and $i_{K'}$ by (2), and f^* commutes with the exterior derivative d. Thus f^* intertwines the commutators $[i_K, d] = \mathcal{L}_K$ and $[i_{K'}, d] = \mathcal{L}_{K'}$.

(6) For $g \in \Omega^0(N)$ we have $\mathcal{L}_K\, f^*\, g = i_K\, d\, f^*\, g = i_K\, f^*\, dg$ and $f^*\, \mathcal{L}_{K'}\, g = f^*\, i_{K'}\, dg$. By (3) the result follows.

(7) The algebra homomorphism f^* intertwines $\mathcal{L}_{K_j}$ and $\mathcal{L}_{K'_j}$, so also their graded commutators which equal $\mathcal{L}([K_1, K_2])$ and $\mathcal{L}([K'_1, K'_2])$, respectively. Now use (6). □

19.16. Let $f : M \to N$ be a local diffeomorphism. Then we can consider the pullback operator $f^* : \Omega(N; TN) \to \Omega(M; TM)$, given by

$$(1) \qquad (f^*K)_x(X_1, \dots, X_k) = (T_xf)^{-1}K_{f(x)}(T_xf \cdot X_1, \dots, T_xf \cdot X_k).$$

Note that this is a special case of the pullback operator for sections of natural vector bundles in (6.16). Clearly K and f^*K are then f-related.

Theorem. *In this situation we have:*

(2) $f^*\,[K, L] = [f^*K, f^*L]$.
(3) $f^*\, i_K L = i_{f^*K} f^*L$.
(4) $f^*\,[K, L]^\wedge = [f^*K, f^*L]^\wedge$.
(5) *For a vector field $X \in \mathfrak{X}(M)$ and $K \in \Omega(M; TM)$ by* (6.16) *the Lie derivative $\mathcal{L}_X K = \frac{\partial}{\partial t}\big|_0 (\mathrm{Fl}^X_t)^* K$ is defined. Then we have $\mathcal{L}_X K = [X, K]$, the Frölicher-Nijenhuis-bracket.*

We may say that the Frölicher-Nijenhuis bracket, $[\quad,\quad]^\wedge$, etc. are *natural bilinear mappings.*

Proof. (2) – (4) are obvious from (19.15). (5) Obviously $\mathcal{L}_X$ is $\mathbb{R}$-linear, so it suffices to check this formula for $K = \psi \otimes Y$, $\psi \in \Omega(M)$ and $Y \in \mathfrak{X}(M)$. But then

$$\begin{aligned} \mathcal{L}_X(\psi \otimes Y) &= \mathcal{L}_X\psi \otimes Y + \psi \otimes \mathcal{L}_X Y \quad \text{by (6.17)} \\ &= \mathcal{L}_X\psi \otimes Y + \psi \otimes [X, Y] \\ &= [X, \psi \otimes Y] \quad \text{by (19.7.6).} \quad \square \end{aligned}$$

19.17. Remark. At last we mention the best known application of the Frölicher-Nijenhuis bracket, which also led to its discovery. A vector valued 1-form $J \in \Omega^1(M; TM)$ with $J \circ J = -Id$ is called a *almost complex structure*; if it exists, $\dim M$ is even and J can be viewed as a fiber multiplication with $\sqrt{-1}$ on TM. By (19.12) we have

$$[J, J](X, Y) = 2([JX, JY] - [X, Y] - J[X, JY] - J[JX, Y]).$$

The vector valued form $\frac{1}{2}[J,J]$ is also called the *Nijenhuis tensor* of J. For it the following result is true:

A manifold M with a almost complex structure J is a complex manifold (i.e., there exists an atlas for M with holomorphic chart-change mappings) if and only if $[J,J]=0$. See [Newlander-Nirenberg, 1957].

20. Fiber Bundles and Connections

20.1. Definition. A *(fiber) bundle* (E,p,M,S) consists of manifolds E, M, S, and a smooth mapping $p : E \to M$; furthermore each $x \in M$ has an open neighborhood U such that $E \mid U := p^{-1}(U)$ is diffeomorphic to $U \times S$ via a fiber respecting diffeomorphism:

$$\begin{array}{ccc} E \mid U & \xrightarrow{\quad\psi\quad} & U \times S \\ & {\scriptstyle p}\searrow \quad \swarrow{\scriptstyle pr_1} & \\ & U & \end{array}$$

E is called the *total space*, M is called the *base space* or *basis*, p is a surjective submersion, called the *projection*, and S is called *standard fiber*. (U,ψ) as above is called a *fiber chart*.

A collection of fiber charts (U_α,ψ_α), such that (U_α) is an open cover of M, is called a *"fiber bundle atlas"*. If we fix such an atlas, then $\psi_\alpha \circ {\psi_\beta}^{-1}(x,s) = (x, \psi_{\alpha\beta}(x,s))$, where $\psi_{\alpha\beta} : (U_\alpha \cap U_\beta) \times S \to S$ is smooth and $\psi_{\alpha\beta}(x,\ )$ is a diffeomorphism of S for each $x \in U_{\alpha\beta} := U_\alpha \cap U_\beta$. We may thus consider the mappings $\psi_{\alpha\beta} : U_{\alpha\beta} \to \operatorname{Diff}(S)$ with values in the group $\operatorname{Diff}(S)$ of all diffeomorphisms of S; their differentiability is a subtle question, which will not be discussed in this book, but see [Michor, 1988]. In either form these mappings $\psi_{\alpha\beta}$ are called the *transition functions* of the bundle. They satisfy the *cocycle condition*: $\psi_{\alpha\beta}(x) \circ \psi_{\beta\gamma}(x) = \psi_{\alpha\gamma}(x)$ for $x \in U_{\alpha\beta\gamma}$ and $\psi_{\alpha\alpha}(x) = Id_S$ for $x \in U_\alpha$. Therefore the collection $(\psi_{\alpha\beta})$ is called a *cocycle of transition functions*.

Given an open cover (U_α) of a manifold M and a cocycle of transition functions $(\psi_{\alpha\beta})$ we may construct a fiber bundle (E,p,M,S) similarly as in (6.3).

20.2. Lemma.

(1) *Let $p : N \to M$ be a surjective submersion such that each fiber is compact and connected. Then p is proper.*

(2) *Let $p : N \to M$ be a surjective submersion (a fibered manifold) which is proper, so that $p^{-1}(K)$ is compact in N for each compact $K \subset M$, and let M be connected. Then (N,p,M) is a fiber bundle.*

Proof. (1) We have to show that for compact $K \subset M$ the inverse image $p^{-1}(K) \subset N$ is also compact.

Let (V_α) be an open cover of $p^{-1}(K)$. For $x \in K$ the fiber $N_x = p^{-1}(x)$ is compact, thus are open sets $V_{\alpha(x,1)} \supset V_{x,1}, \dots, V_{\alpha(x,n_x)} \supset V_{x,n_x}$ in N which cover N_x and which are fiberwise diffeomorphic as follows: $V_{x,i} \cong U_{x,i} \times \tilde{V}_{x,i}$ where $U_{x,i}$ is an open neighborhood of x in M. Then $\bigcap_{i=1}^{n_x} U_{x,i} =: U_x$ is still an open neighborhood of x in N, and these open sets cover the compact set K. Thus there is a finite subcover $U_{x_1}, \dots, U_{x_m}$. But then

$$\{V_{\alpha(x_j,k)} : k = 1, \dots, n_{x_j}, j = 1, \dots, m\}$$

is a finite subcover.

(2) We have to produce a fiber chart at each $x_0 \in M$. So let (U,u) be a chart centered at x_0 on M such that $u(U) \cong \mathbb{R}^m$. For each $x \in U$ let $\xi_x(y) := (T_y u)^{-1}.u(x)$, then we have $\xi_x \in \mathfrak{X}(U)$ which depends smoothly on $x \in U$, such that $u(\mathrm{Fl}_t^{\xi_x} u^{-1}(z)) = z + t.u(x)$, thus each ξ_x is a complete vector field on U. Since p is a submersion, with the help of a partition of unity on $p^{-1}(U)$ we may construct vector fields $\eta_x \in \mathfrak{X}(p^{-1}(U))$ which depend smoothly on $x \in U$ and are p-related to ξ_x: $Tp.\eta_x = \xi_x \circ p$. Thus $p \circ \mathrm{Fl}_t^{\eta_x} = \mathrm{Fl}_t^{\xi_x} \circ p$ by (3.14), so $\mathrm{Fl}_t^{\eta_x}$ is fiber respecting, and since p is proper and ξ_x is complete, η_x has a global flow too. Denote $p^{-1}(x_0)$ by S. Then $\varphi : U \times S \to p^{-1}(U)$, defined by $\varphi(x,y) = \mathrm{Fl}_1^{\eta_x}(y)$, is a diffeomorphism and is fiber respecting, so (U, φ^{-1}) is a fiber chart. Since M is connected, the fibers $p^{-1}(x)$ are all diffeomorphic.

20.3. Let (E,p,M,S) be a fiber bundle; we consider the fiber linear tangent mapping $Tp : TE \to TM$ and its kernel $\ker Tp =: VE$ which is called the *vertical bundle* of E. The following is special case of (19.13).

Definition. A *connection* on the fiber bundle (E,p,M,S) is a vector valued 1-form $\Phi \in \Omega^1(E;VE)$ with values in the vertical bundle VE such that $\Phi \circ \Phi = \Phi$ and $\mathrm{Im}\Phi = VE$; so Φ is just a projection $TE \to VE$.

Then $\ker \Phi$ is of constant rank, so by (6.7) $\ker \Phi$ is a sub vector bundle of TE, it is called the space of *horizontal vectors* or the *horizontal bundle* and it is denoted by $HE = \ker \Phi$. Clearly $TE = HE \oplus VE$ and $T_uE = H_uE \oplus V_uE$ for $u \in E$.

Now we consider the mapping $(Tp, \pi_E) : TE \to TM \times_M E$. Then by definition $(Tp,\pi_E)^{-1}(0_{p(u)}, u) = V_uE$, so $(Tp,\pi_E) \mid HE : HE \to TM \times_M E$ is fiber linear over E and injective, so by reason of dimensions it is a fiber linear isomorphism: Its inverse is denoted by

$$C := ((Tp,\pi_E) \mid HE)^{-1} : TM \times_M E \to HE \hookrightarrow TE.$$

So $C : TM \times_M E \to TE$ is fiber linear over E and is a right inverse for (Tp,π_E). C is called the *horizontal lift* associated to the connection Φ.

Note the formula $\Phi(\xi_u) = \xi_u - C(Tp.\xi_u, u)$ for $\xi_u \in T_uE$. So we can equally well describe a connection Φ by specifying C. Then we call Φ the *vertical projection* (no confusion with (6.12) will arise) and $\chi := \mathrm{id}_{TE} - \Phi = C \circ (Tp,\pi_E)$ will be called the *horizontal projection*.

20.4. Curvature. If $\Phi : TE \to VE$ is a connection on the bundle (E, p, M, S), then as in (19.13) the curvature R of Φ is given by

$$2R = [\Phi, \Phi] = [Id - \Phi, Id - \Phi] = [\chi, \chi] \in \Omega^2(E; VE)$$

(The cocurvature $\bar{R}$ vanishes since the vertical bundle VE is integrable). We have $R(X, Y) = \frac{1}{2}[\Phi, \Phi](X, Y) = \Phi[\chi X, \chi Y]$, so R is an obstruction against integrability of the horizontal subbundle. Note that for vector fields $\xi, \eta \in \mathfrak{X}(M)$ and their horizontal lifts $C\xi, C\eta \in \mathfrak{X}(E)$ we have $R(C\xi, C\eta) = [C\xi, C\eta] - C([\xi, \eta])$. Since the vertical bundle VE is integrable, by (19.14) we have the *Bianchi identity* $[\Phi, R] = 0$.

20.5. Pullback. Let (E, p, M, S) be a fiber bundle and consider a smooth mapping $f : N \to M$. Since p is a submersion, f and p are transversal in the sense of (2.16) and thus the pullback $N \times_{(f,M,p)} E$ exists. It will be called the *pullback* of the fiber bundle E by f and we will denote it by f^*E. The following diagram sets up some further notation for it:

$$\begin{array}{ccc} f^*E & \xrightarrow{p^*f} & E \\ {\scriptstyle f^*p}\downarrow & & \downarrow{\scriptstyle p} \\ N & \xrightarrow{f} & M. \end{array}$$

Proposition. *In the situation above we have:*

(1) (f^*E, f^*p, N, S) *is again a fiber bundle, and* p^*f *is a fiber wise diffeomorphism.*

(2) *If* $\Phi \in \Omega^1(E; VE) \subset \Omega^1(E; TE)$ *is a connection on the bundle* E*, then the vector valued form* $f^*\Phi$*, given by* $(f^*\Phi)_u(X) := V_u(p^*f)^{-1}.\Phi.T_u(p^*f).X$ *for* $X \in T_uE$*, is a connection on the bundle* f^*E*. The forms* $f^*\Phi$ *and* Φ *are* p^*f*-related in the sense of* (19.15).

(3) *The curvatures of* $f^*\Phi$ *and* Φ *are also* p^*f*-related.*

Proof. (1). If (U_α, ψ_α) is a fiber bundle atlas of (E, p, M, S) in the sense of (20.1), then $(f^{-1}(U_\alpha), (f^*p, pr_2 \circ \psi_\alpha \circ p^*f))$ is a fiber bundle atlas for (f^*E, f^*p, N, S), by the formal universal properties of a pullback (2.17). (2) is obvious. (3) follows from (2) and (19.15.7). □

20.6. Let us suppose that a connection Φ on the bundle (E, p, M, S) has zero curvature. Then by (20.4) the horizontal bundle is integrable and gives rise to the *horizontal foliation* by (3.28.2). Each point $u \in E$ lies on a unique leaf $L(u)$ such that $T_vL(u) = H_vE$ for each $v \in L(u)$. The restriction $p \mid L(u)$ is locally a diffeomorphism, but in general it is neither surjective nor is it a covering onto its image. This is seen by devising suitable horizontal foliations on the trivial bundle $\mathrm{pr}_2 : \mathbb{R} \times S^1 \to S^1$, or $\mathrm{pr}_2\, \mathbb{R} \times \mathbb{R} \to \mathbb{R}$, like $L(0, t) = \{(\tan(s - t), s) : s \in \mathbb{R}\}$.

20.7. Local description. Let Φ be a connection on (E, p, M, S). Let us fix a fiber bundle atlas (U_α) with transition functions $(\psi_{\alpha\beta})$, and let us consider the connection $((\psi_\alpha)^{-1})^*\Phi \in \Omega^1(U_\alpha \times S; U_\alpha \times TS)$, which may be written in the form

$$((\psi_\alpha)^{-1})^*\Phi)(\xi_x, \eta_y) =: -\Gamma^\alpha(\xi_x, y) + \eta_y \text{ for } \xi_x \in T_xU_\alpha \text{ and } \eta_y \in T_yS,$$

since it reproduces vertical vectors. The Γ^α are given by

$$(0_x, \Gamma^\alpha(\xi_x, y)) := -T(\psi_\alpha).\Phi.T(\psi_\alpha)^{-1}.(\xi_x, 0_y).$$

We consider Γ^α as an element of the space $\Omega^1(U_\alpha; \mathfrak{X}(S))$, a 1-form on U^α with values in the infinite dimensional Lie algebra $\mathfrak{X}(S)$ of all vector fields on the standard fiber. The Γ^α are called the *Christoffel forms* of the connection Φ with respect to the bundle atlas (U_α, ψ_α).

Lemma. *The transformation law for the Christoffel forms is*

$$T_y(\psi_{\alpha\beta}(x, \quad)).\Gamma^\beta(\xi_x, y) = \Gamma^\alpha(\xi_x, \psi_{\alpha\beta}(x, y)) - T_x(\psi_{\alpha\beta}(\quad, y)).\xi_x.$$

The curvature R of Φ satisfies

$$(\psi_\alpha^{-1})^* R = d\Gamma^\alpha + [\Gamma^\alpha, \Gamma^\alpha]_{\mathfrak{X}(S)}.$$

Here $d\Gamma^\alpha$ is the exterior derivative of the 1-form $\Gamma^\alpha \in \Omega^1(U_\alpha; \mathfrak{X}(S))$ with values in the complete locally convex space $\mathfrak{X}(S)$. We will later also use the Lie derivative of it and the usual formulas apply: consult [Frölicher, Kriegl, 1988] for calculus in infinite dimensional spaces.

The formula for the curvature is the *Maurer-Cartan* formula which in this general setting appears only in the level of local description.

Proof. From $(\psi_\alpha \circ (\psi_\beta)^{-1})(x, y) = (x, \psi_{\alpha\beta}(x, y))$ we get that $T(\psi_\alpha \circ (\psi_\beta)^{-1}).(\xi_x, \eta_y) = (\xi_x, T_{(x,y)}(\psi_{\alpha\beta}).(\xi_x, \eta_y))$ and thus:

$$\begin{aligned}
&T(\psi_\beta^{-1}).(0_x, \Gamma^\beta(\xi_x, y)) = -\Phi(T(\psi_\beta^{-1})(\xi_x, 0_y)) = \\
&= -\Phi(T(\psi_\alpha^{-1}).T(\psi_\alpha \circ \psi_\beta^{-1}).(\xi_x, 0_y)) = \\
&= -\Phi(T(\psi_\alpha^{-1})(\xi_x, T_{(x,y)}(\psi_{\alpha\beta})(\xi_x, 0_y))) = \\
&= -\Phi(T(\psi_\alpha^{-1})(\xi_x, 0_{\psi_{\alpha\beta}(x,y)})) - \Phi(T(\psi_\alpha^{-1})(0_x, T_{(x,y)}\psi_{\alpha\beta}(\xi_x, 0_y)) = \\
&= T(\psi_\alpha^{-1}).(0_x, \Gamma^\alpha(\xi_x, \psi_{\alpha\beta}(x, y))) - T(\psi_\alpha^{-1})(0_x, T_x(\psi_{\alpha\beta}(\quad, y)).\xi_x).
\end{aligned}$$

This implies the transformation law.

For the curvature R of Φ we have by (20.4) and (20.5.3)

$$\begin{aligned}
&(\psi_\alpha^{-1})^* R\,((\xi^1, \eta^1), (\xi^2, \eta^2)) = \\
&\quad = (\psi_\alpha^{-1})^*\Phi\,[(Id - (\psi_\alpha^{-1})^*\Phi)(\xi^1, \eta^1), (Id - (\psi_\alpha^{-1})^*\Phi)(\xi^2, \eta^2)] = \\
&\quad = (\psi_\alpha^{-1})^*\Phi[(\xi^1, \Gamma^\alpha(\xi^1)), (\xi^2, \Gamma^\alpha(\xi^2))] = \\
&\quad = (\psi_\alpha^{-1})^*\Phi\left([\xi^1, \xi^2], \xi^1\Gamma^\alpha(\xi^2) - \xi^2\Gamma^\alpha(\xi^1) + [\Gamma^\alpha(\xi^1), \Gamma^\alpha(\xi^2)]\right) = \\
&\quad = -\Gamma^\alpha([\xi^1, \xi^2]) + \xi^1\Gamma^\alpha(\xi^2) - \xi^2\Gamma^\alpha(\xi^1) + [\Gamma^\alpha(\xi^1), \Gamma^\alpha(\xi^2)] = \\
&\quad = d\Gamma^\alpha(\xi^1, \xi^2) + [\Gamma^\alpha(\xi^1), \Gamma^\alpha(\xi^2)]_{\mathfrak{X}(S)}. \quad \square
\end{aligned}$$

20.8. Theorem (Parallel transport). *Let Φ be a connection on a bundle (E, p, M, S) and let $c : (a, b) \to M$ be a smooth curve with $0 \in (a, b)$, $c(0) = x$.*

Then there is a neighborhood U of $E_x \times \{0\}$ in $E_x \times (a, b)$ and a smooth mapping $\operatorname{Pt}_c : U \to E$ such that:

(1) *$p(\operatorname{Pt}(c, u_x, t)) = c(t)$ if defined, and $\operatorname{Pt}(c, u_x, 0) = u_x$.*
(2) *$\Phi(\frac{d}{dt} \operatorname{Pt}(c, u_x, t)) = 0$ if defined.*
(3) *Reparametrisation invariance: If $f : (a', b') \to (a, b)$ is smooth with $0 \in (a', b')$, then $\operatorname{Pt}(c, u_x, f(t)) = \operatorname{Pt}(c \circ f, \operatorname{Pt}(c, u_x, f(0)), t)$ if defined.*
(4) *U is maximal for properties (1) and (2).*
(5) *In a certain sense Pt depends smoothly also on c.*

First proof. In local bundle coordinates $\Phi(\frac{d}{dt} \operatorname{Pt}(c, u_x, t)) = 0$ is an ordinary differential equation of first order, nonlinear, with initial condition $\operatorname{Pt}(c, u_x, 0) = u_x$. So there is a maximally defined local solution curve which is unique. All further properties are consequences of uniqueness.

Second proof. Consider the pullback bundle $(c^*E, c^*p, (a, b), S)$ and the pullback connection $c^*\Phi$ on it. It has zero curvature, since the horizontal bundle is 1-dimensional. By (20.6) the horizontal foliation exists and the parallel transport just follows a leaf and we may map it back to E, in detail:
$\operatorname{Pt}(c, u_x, t) = p^*c((c^*p \mid L(u_x))^{-1}(t))$.

Third proof. Consider a fiber bundle atlas (U_α, ψ_α) as in (20.7). Then we have $\psi_\alpha(\operatorname{Pt}(c, \psi_\alpha^{-1}(x, y), t)) = (c(t), \gamma(y, t))$, where

$$0 = \left((\psi_\alpha^{-1})^*\Phi\right)\left(\tfrac{d}{dt}c(t), \tfrac{d}{dt}\gamma(y, t)\right) = -\Gamma^\alpha\left(\tfrac{d}{dt}c(t), \gamma(y, t)\right) + \tfrac{d}{dt}\gamma(y, t),$$

so $\gamma(y, t)$ is the integral curve (evolution line) through $y \in S$ of the time dependent vector field $\Gamma^\alpha\left(\frac{d}{dt}c(t)\right)$ on S. This vector field visibly depends smoothly on c. Clearly local solutions exist and all properties follow, even (5). For more detailed information on (5) we refer to [Michor, 1983] or [Kriegl, Michor, 1997]. □

20.9. A connection Φ on (E, p, M, S) is called a *complete connection*, if the parallel transport Pt_c along any smooth curve $c : (a, b) \to M$ is defined on the whole of $E_{c(0)} \times (a, b)$. The third proof of theorem (20.8) shows that on a fiber bundle with compact standard fiber any connection is complete.

The following is a sufficient condition for a connection Φ to be complete:

> There exists a fiber bundle atlas (U_α, ψ_α) and complete Riemannian metrics g_α on the standard fiber S such that each Christoffel form $\Gamma^\alpha \in \Omega^1(U_\alpha, \mathfrak{X}(S))$ takes values in the linear subspace of g_α-bounded vector fields on S

For in the third proof of theorem (20.8) above the time dependent vector field $\Gamma^\alpha(\frac{d}{dt}c(t))$ on S is g_α-bounded for compact time intervals. By (14.9) this vector field is complete. So by continuation the solution exists globally.

A complete connection is called an *Ehresmann connection* in [Greub - Halperin - Vanstone I, p 314], where the following result is given as an exercise.

Theorem. *Each fiber bundle admits complete connections.*

Proof. Let $\dim M = m$. Let (U_α, ψ_α) be a fiber bundle atlas as in (20.1). By topological dimension theory [Nagata, 1965] the open cover (U_α) of M admits a refinement such that any $m+2$ members have empty intersection, see also (1.1). Let (U_α) itself have this property. Choose a smooth partition of unity (f_α) subordinated to (U_α). Then the sets $V_\alpha := \{ x : f_\alpha(x) > \frac{1}{m+2} \} \subset U_\alpha$ form still an open cover of M since $\sum f_\alpha(x) = 1$ and at most $m+1$ of the $f_\alpha(x)$ can be nonzero. By renaming assume that each V_α is connected. Then we choose an open cover (W_α) of M such that $\overline{W_\alpha} \subset V_\alpha$.

Now let g_1 and g_2 be complete Riemannian metrics on M and S, respectively (see (14.8)). For not connected Riemannian manifolds complete means that each connected component is complete. Then $g_1|U_\alpha \times g_2$ is a Riemannian metric on $U_\alpha \times S$ and we consider the metric $g := \sum f_\alpha \psi_\alpha^*(g_1|U_\alpha \times g_2)$ on E. Obviously $p : E \to M$ is a Riemannian submersion for the metrics g and g_1: this means that $T_u p : (T_u(E_{p(u)})^\perp, g_u) \to (T_{p(u)}M, (g_1)_{p(u)})$ is an isometry for each $u \in E$. We choose now the connection $\Phi : TE \to VE$ as the orthonormal projection with respect to the Riemannian metric g.

Claim. Φ is a complete connection on E.
Let $c : [0,1] \to M$ be a smooth curve. We choose a partition $0 = t_0 < t_1 < \dots < t_k = 1$ such that $c([t_i, t_{i+1}]) \subset V_{\alpha_i}$ for suitable α_i. It suffices to show that $\operatorname{Pt}(c(t_i + \quad), u_{c(t_i)}, t)$ exists for all $0 \le t \le t_{i+1} - t_i$ and all $u_{c(t_i)}$, for all i, since then we may piece them together. So we may assume that $c : [0,1] \to V_\alpha$ for some α. Let us now assume that for for $x = c(0)$ and some $y \in S$ the parallel transport $\operatorname{Pt}(c, \psi_\alpha(x,y), t)$ is defined only for $t \in [0, t')$ for some $0 < t' < 1$. By the third proof of (20.8) we have $\operatorname{Pt}(c, \psi_\alpha^{-1}(x,y), t) = \psi_\alpha^{-1}(c(t), \gamma(t))$, where $\gamma : [0, t') \to S$ is the maximally defined integral curve through $y \in S$ of the time dependent vector field $\Gamma^\alpha(\frac{d}{dt}c(t), \quad)$ on S. We put $g_\alpha := (\psi_\alpha^{-1})^* g$, then $(g_\alpha)_{(x,y)} = (g_1)_x \times (\sum_\beta f_\beta(x) \psi_{\beta\alpha}(x, \quad)^* g_2)_y$. Since $pr_1 : (V_\alpha \times S, g_\alpha) \to (V_\alpha, g_1|V_\alpha)$ is a Riemannian submersion and since the connection $(\psi_\alpha^{-1})^*\Phi$ is also given by orthonormal projection onto the vertical bundle, we get

$$\infty > g_1\text{-length}_0^{t'}(c) = g_\alpha\text{-length}(c,\gamma) = \int_0^{t'} |(c'(t), \tfrac{d}{dt}\gamma(t))|_{g_\alpha}\, dt =$$
$$= \int_0^{t'} \sqrt{|c'(t)|_{g_1}^2 + \textstyle\sum_\beta f_\beta(c(t)) (\psi_{\alpha\beta}(c(t), -)^* g_2)(\tfrac{d}{dt}\gamma(t), \tfrac{d}{dt}\gamma(t))}\, dt \ge$$
$$\ge \int_0^{t'} \sqrt{f_\alpha(c(t))}\, |\tfrac{d}{dt}\gamma(t)|_{g_2}\, dt \ge \frac{1}{\sqrt{m+2}} \int_0^{t'} |\tfrac{d}{dt}\gamma(t)|_{g_2} dt.$$

So g_2-length(γ) is finite and since the Riemannian metric g_2 on S is complete, $\lim_{t \to t'} \gamma(t) =: \gamma(t')$ exists in S and the integral curve γ can be continued. □

20.10. Holonomy groups and Lie algebras. Let (E, p, M, S) be a fiber bundle with a complete connection Φ, and let us assume that M is connected. We choose a fixed base point $x_0 \in M$ and we identify E_{x_0} with the standard fiber S. For each closed piecewise smooth curve $c : [0,1] \to M$ through x_0 the parallel transport $\operatorname{Pt}(c, \quad, 1) =: \operatorname{Pt}(c,1)$ (pieced together over the smooth parts of c) is a diffeomorphism of S. All these diffeomorphisms form together the group $\operatorname{Hol}(\Phi, x_0)$, the *holonomy group* of Φ at x_0, a subgroup of the diffeomorphism group $\operatorname{Diff}(S)$. If we consider only those piecewise smooth curves which are homotopic to zero, we get a subgroup $\operatorname{Hol}_0(\Phi, x_0)$, called the *restricted holonomy group* of the connection Φ at x_0.

Now let $C : TM \times_M E \to TE$ be the horizontal lifting as in (20.3), and let R be the curvature ((20.4)) of the connection Φ. For any $x \in M$ and $X_x \in T_xM$ the horizontal lift $C(X_x) := C(X_x, \quad) : E_x \to TE$ is a vector field along E_x. For X_x and $Y_x \in T_xM$ we consider $R(CX_x, CY_x) \in \mathfrak{X}(E_x)$. Now we choose any piecewise smooth curve c from x_0 to x and consider the diffeomorphism $\operatorname{Pt}(c,t) : S = E_{x_0} \to E_x$ and the pullback $\operatorname{Pt}(c,1)^* R(CX_x, CY_x) \in \mathfrak{X}(S)$. Let us denote by $\operatorname{hol}(\Phi, x_0)$ the closed linear subspace, generated by all these vector fields (for all $x \in M$, X_x, $Y_x \in T_xM$ and curves c from x_0 to x) in $\mathfrak{X}(S)$ with respect to the compact C^∞-topology, and let us call it the *holonomy Lie algebra* of Φ at x_0.

Lemma. $\operatorname{hol}(\Phi, x_0)$ *is a Lie subalgebra of* $\mathfrak{X}(S)$.

Proof. For $X \in \mathfrak{X}(M)$ we consider the local flow Fl^{CX}_t of the horizontal lift of X. It restricts to parallel transport along any of the flow lines of X in M. Then for vector fields on M the expression

$$\begin{aligned}
&\tfrac{d}{dt}|_0 (\operatorname{Fl}^{CX}_s)^* (\operatorname{Fl}^{CY}_t)^* (\operatorname{Fl}^{CX}_{-s})^* (\operatorname{Fl}^{CZ}_z)^* R(CU, CV) \restriction E_{x_0} \\
&\quad = (\operatorname{Fl}^{CX}_s)^* [CY, (\operatorname{Fl}^{CX}_{-s})^* (\operatorname{Fl}^{CZ}_z)^* R(CU, CV)] \restriction E_{x_0} \\
&\quad = [(\operatorname{Fl}^{CX}_s)^* CY, (\operatorname{Fl}^{CZ}_z)^* R(CU, CV)] \restriction E_{x_0}
\end{aligned}$$

is in $\operatorname{hol}(\Phi, x_0)$, since it is closed in the compact C^∞-topology and the derivative can be written as a limit. Thus

$$[(\operatorname{Fl}^{CX}_s)^* [CY_1, CY_2], (\operatorname{Fl}^{CZ}_z)^* R(CU, CV)] \restriction E_{x_0} \in \operatorname{hol}(\Phi, x_0)$$

by the Jacobi identity and

$$[(\operatorname{Fl}^{CX}_s)^* C[Y_1, Y_2], (\operatorname{Fl}^{CZ}_z)^* R(CU, CV)] \restriction E_{x_0} \in \operatorname{hol}(\Phi, x_0),$$

so also their difference

$$[(\operatorname{Fl}^{CX}_s)^* R(CY_1, CY_2), (\operatorname{Fl}^{CZ}_z)^* R(CU, CV)] \restriction E_{x_0}$$

is in $\operatorname{hol}(\Phi, x_0)$. □

20.11. The following theorem is a generalization of the theorem of Nijenhuis and Ambrose-Singer on principal connections. The reader who does not know principal connections is advised to read parts of sections (21) and (22) first. We include this result here in order not to disturb the development in section (22) later.

Theorem. *Let Φ be a complete connection on the fibre bundle (E,p,M,S) and let M be connected. Suppose that for some (hence any) $x_0 \in M$ the holonomy Lie algebra* $\operatorname{hol}(\Phi,x_0)$ *is finite dimensional and consists of complete vector fields on the fiber E_{x_0}*

Then there is a principal bundle (P,p,M,G) with finite dimensional structure group G, an connection ω on it and a smooth action of G on S such that the Lie algebra $\mathfrak{g}$ of G equals the holonomy Lie algebra $\operatorname{hol}(\Phi,x_0)$*, the fibre bundle E is isomorphic to the associated bundle $P[S]$, and Φ is the connection induced by ω. The structure group G equals the holonomy group* $\operatorname{Hol}(\Phi,x_0)$*. P and ω are unique up to isomorphism.*

By a theorem of [Palais, 1957] a finite dimensional Lie subalgebra of $\mathfrak{X}(E_{x_0})$ like $\operatorname{hol}(\Phi,x_0)$ consists of complete vector fields if and only if it is generated by complete vector fields as a Lie algebra.

Proof. Let us again identify E_{x_0} and S. Then $\mathfrak{g} := \operatorname{hol}(\Phi,x_0)$ is a finite dimensional Lie subalgebra of $\mathfrak{X}(S)$, and since each vector field in it is complete, there is a finite dimensional connected Lie group G_0 of diffeomorphisms of S with Lie algebra $\mathfrak{g}$, by theorem (5.15).

Claim 1. G_0 contains $\operatorname{Hol}_0(\Phi,x_0)$, the restricted holonomy group.
Let $f \in \operatorname{Hol}_0(\Phi,x_0)$, then $f = \operatorname{Pt}(c,1)$ for a piecewise smooth closed curve c through x_0, which is nullhomotopic. Since the parallel transport is essentially invariant under reparametrisation, (20.8), we can replace c by $c\circ g$, where g is smooth and flat at each corner of c. So we may assume that c itself is smooth. Since c is homotopic to zero, by approximation we may assume that there is a smooth homotopy $H:\mathbb{R}^2\to M$ with $H_1|[0,1] = c$ and $H_0|[0,1] = x_0$. Then $f_t := \operatorname{Pt}(H_t,1)$ is a curve in $\operatorname{Hol}_0(\Phi,x_0)$ which is smooth as a mapping $\mathbb{R}\times S\to S$; this can be seen by using the proof of claim 2 below or as in the proof of (22.7.4). We will continue the proof of claim 1 below.

Claim 2. $(\frac{d}{dt}f_t)\circ f_t^{-1} =: Z_t$ is in $\mathfrak{g}$ for all t.
To prove claim 2 we consider the pullback bundle $H^*E\to\mathbb{R}^2$ with the induced connection $H^*\Phi$. It is sufficient to prove claim 2 there. Let $X = \frac{d}{ds}$ and $Y = \frac{d}{dt}$ be constant vector fields on $\mathbb{R}^2$, so $[X,Y]=0$. Then $\operatorname{Pt}(c,s) = \operatorname{Fl}^{CX}_s|S$ and so on. We put

$$f_{t,s} = \operatorname{Fl}^{CX}_{-s}\circ\operatorname{Fl}^{CY}_{-t}\circ\operatorname{Fl}^{CX}_{s}\circ\operatorname{Fl}^{CY}_{t} : S\to S,$$

so $f_{t,1} = f_t$. Then we have in the vector space $\mathfrak{X}(S)$

$$\begin{aligned}
(\tfrac{d}{dt}f_{t,s})\circ f_{t,s}^{-1} &= -(\operatorname{Fl}^{CX}_s)^*CY + (\operatorname{Fl}^{CX}_s)^*(\operatorname{Fl}^{CY}_t)^*(\operatorname{Fl}^{CX}_{-s})^*CY,\\
(\tfrac{d}{dt}f_{t,1})\circ f_{t,1}^{-1} &= \int_0^1 \tfrac{d}{ds}\left((\tfrac{d}{dt}f_{t,s})\circ f_{t,s}^{-1}\right)ds\\
&= \int_0^1 \Big(-(\operatorname{Fl}^{CX}_s)^*[CX,CY] + (\operatorname{Fl}^{CX}_s)^*[CX,(\operatorname{Fl}^{CY}_t)^*(\operatorname{Fl}^{CX}_{-s})^*CY]\\
&\qquad -(\operatorname{Fl}^{CX}_s)^*(\operatorname{Fl}^{CY}_t)^*(\operatorname{Fl}^{CX}_{-s})^*[CX,CY]\Big)\,ds.
\end{aligned}$$

Since $[X,Y]=0$ we have $[CX,CY]=\Phi[CX,CY]=R(CX,CY)$ and $(\operatorname{Fl}^X_t)^*Y=Y$ thus

$$\begin{aligned}(\operatorname{Fl}^{CX}_t)^*CY &= C\Big((\operatorname{Fl}^X_t)^*Y\Big)+\Phi\Big((\operatorname{Fl}^{CX}_t)^*CY\Big)\\ &= CY+\int_0^t \tfrac{d}{dt}\Phi(\operatorname{Fl}^{CX}_t)^*CY\,dt = CY+\int_0^t \Phi(\operatorname{Fl}^{CX}_t)^*[CX,CY]\,dt\\ &= CY+\int_0^t \Phi(\operatorname{Fl}^{CX}_t)^*R(CX,CY)\,dt = CY+\int_0^t (\operatorname{Fl}^{CX}_t)^*R(CX,CY)\,dt.\end{aligned}$$

The flows $(\operatorname{Fl}^{CX}_s)^*$ and its derivatives $\mathcal{L}_{CX}=[CX,\quad]$ do not lead out of $\mathfrak{g}$, thus all parts of the integrand above are in $\mathfrak{g}$ and so $(\frac{d}{dt}f_{t,1})\circ f_{t,1}^{-1}$ is in $\mathfrak{g}$ for all t and claim 2 follows.

Now claim 1 can be shown as follows. There is a unique smooth curve $g(t)$ in G_0 satisfying $T_e(\mu^{g(t)})Z_t=Z_t.g(t)=\frac{d}{dt}g(t)$ and $g(0)=e$; via the action of G_0 on S the curve $g(t)$ is a curve of diffeomorphisms on S, generated by the time dependent vector field Z_t, so $g(t)=f_t$ and $f=f_1$ is in G_0. So we get $\operatorname{Hol}_0(\Phi,x_0)\subseteq G_0$.

Claim 3. $\operatorname{Hol}_0(\Phi,x_0)$ equals G_0.
In the proof of claim 1 we have seen that $\operatorname{Hol}_0(\Phi,x_0)$ is a smoothly arcwise connected subgroup of G_0, so it is a connected Lie subgroup by the theorem of Yamabe (5.6). It suffices thus to show that the Lie algebra $\mathfrak{g}$ of G_0 is contained in the Lie algebra of $\operatorname{Hol}_0(\Phi,x_0)$, and for that it is enough to show, that for each ξ in a linearly spanning subset of $\mathfrak{g}$ there is a smooth mapping $f:[-1,1]\times S\to S$ such that the associated curve $\check f$ lies in $\operatorname{Hol}_0(\Phi,x_0)$ with $\check f'(0)=0$ and $\check f''(0)=\xi$.

By definition we may assume $\xi=\operatorname{Pt}(c,1)^*R(CX_x,CY_x)$ for X_x, $Y_x\in T_xM$ and a smooth curve c in M from x_0 to x. We extend X_x and Y_x to vector fields X and $Y\in\mathfrak{X}(M)$ with $[X,Y]=0$ near x. We may also suppose that $Z\in\mathfrak{X}(M)$ is a vector field which extends $c'(t)$ along $c(t)$: if c is simple we approximate it by an embedding and can consequently extend $c'(t)$ to such a vector field. If c is not simple we do this for each simple piece of c and have then several vector fields Z instead of one below. So we have

$$\begin{aligned}\xi &= (\operatorname{Fl}^{CZ}_1)^*R(CX,CY)=(\operatorname{Fl}^{CZ}_1)^*[CX,CY]\quad\text{since } [X,Y](x)=0\\ &= (\operatorname{Fl}^{CZ}_1)^*\tfrac12\tfrac{d^2}{dt^2}|_{t=0}(\operatorname{Fl}^{CY}_{-t}\circ\operatorname{Fl}^{CX}_{-t}\circ\operatorname{Fl}^{CY}_t\circ\operatorname{Fl}^{CX}_t)\quad\text{by (3.16)}\\ &= \tfrac12\tfrac{d^2}{dt^2}|_{t=0}(\operatorname{Fl}^{CZ}_{-1}\circ\operatorname{Fl}^{CY}_{-t}\circ\operatorname{Fl}^{CX}_{-t}\circ\operatorname{Fl}^{CY}_t\circ\operatorname{Fl}^{CX}_t\circ\operatorname{Fl}^{CZ}_1),\end{aligned}$$

where the parallel transport in the last equation first follows c from x_0 to x, then follows a small closed parallelogram near x in M (since $[X,Y]=0$ near x) and then follows c back to x_0. This curve is clearly nullhomotopic.

Step 4. Now we make $\operatorname{Hol}(\Phi,x_0)$ into a Lie group which we call G, by taking $\operatorname{Hol}_0(\Phi,x_0)=G_0$ as its connected component of the identity. Then the quotient $\operatorname{Hol}(\Phi,x_0)/\operatorname{Hol}_0(\Phi,x_0)$ is a countable group, since the fundamental group $\pi_1(M)$ is countable (by Morse theory M is homotopy equivalent to a countable CW-complex).

Step 5. Construction of a cocycle of transition functions with values in G. Let $(U_\alpha, u_\alpha : U_\alpha \to \mathbb{R}^m)$ be a locally finite smooth atlas for M such that each $u_\alpha : U_\alpha \to \mathbb{R}^m$ is surjective. Put $x_\alpha := u_\alpha^{-1}(0)$ and choose smooth curves $c_\alpha : [0,1] \to M$ with $c_\alpha(0) = x_0$ and $c_\alpha(1) = x_\alpha$. For each $x \in U_\alpha$ let $c_\alpha^x : [0,1] \to M$ be the smooth curve $t \mapsto u_\alpha^{-1}(t.u_\alpha(x))$, then c_α^x connects x_α and x and the mapping $(x,t) \mapsto c_\alpha^x(t)$ is smooth $U_\alpha \times [0,1] \to M$. Now we define a fiber bundle atlas $(U_\alpha, \psi_\alpha : E|U_\alpha \to U_\alpha \times S)$ by $\psi_\alpha^{-1}(x,s) = \operatorname{Pt}(c_\alpha^x, 1)\operatorname{Pt}(c_\alpha, 1)\, s$. Then ψ_α is smooth since $\operatorname{Pt}(c_\alpha^x, 1) = \operatorname{Fl}_1^{CX_x}$ for a local vector field X_x depending smoothly on x. Let us investigate the transition functions.

$$\begin{aligned}
\psi_\alpha\psi_\beta^{-1}(x,s) &= \big(x, \operatorname{Pt}(c_\alpha,1)^{-1}\operatorname{Pt}(c_\alpha^x,1)^{-1}\operatorname{Pt}(c_\beta^x,1)\operatorname{Pt}(c_\beta,1)\, s\big)\\
&= \big(x, \operatorname{Pt}(c_\beta.c_\beta^x.(c_\alpha^x)^{-1}.(c_\alpha)^{-1}, 4)\, s\big)\\
&=: (x, \psi_{\alpha\beta}(x)\, s), \text{ where } \psi_{\alpha\beta} : U_{\alpha\beta} \to G.
\end{aligned}$$

Clearly $\psi_{\beta\alpha} : U_{\beta\alpha} \times S \to S$ is smooth which implies that $\psi_{\beta\alpha} : U_{\beta\alpha} \to G$ is also smooth. $(\psi_{\alpha\beta})$ is a cocycle of transition functions and we use it to glue a principal bundle with structure group G over M which we call (P, p, M, G). From its construction it is clear that the associated bundle $P[S] = P\times_G S$ equals (E, p, M, S).

Step 6. Lifting the connection Φ to P.
For this we have to compute the Christoffel symbols of Φ with respect to the atlas of step 5. To do this directly is quite difficult since we have to differentiate the parallel transport with respect to the curve. Fortunately there is another way. Let $c : [0,1] \to U_\alpha$ be a smooth curve. Then we have

$$\begin{aligned}
&\psi_\alpha(\operatorname{Pt}(c,t)\psi_\alpha^{-1}(c(0),s)) =\\
&\quad = \Big(c(t), \operatorname{Pt}((c_\alpha)^{-1},1)\operatorname{Pt}((c_\alpha^{c(0)})^{-1},1)\operatorname{Pt}(c,t)\operatorname{Pt}(c_\alpha^{c(0)},1)\operatorname{Pt}(c_\alpha,1)s\Big)\\
&\quad = (c(t), \gamma(t).s),
\end{aligned}$$

where $\gamma(t)$ is a smooth curve in the holonomy group G. Let $\Gamma^\alpha \in \Omega^1(U_\alpha, \mathfrak{X}(S))$ be the Christoffel symbol of the connection Φ with respect to the chart (U_α, ψ_α). From the third proof of theorem (20.8) we have

$$\psi_\alpha(\operatorname{Pt}(c,t)\psi_\alpha^{-1}(c(0),s)) = (c(t), \bar\gamma(t,s)),$$

where $\bar\gamma(t,s)$ is the integral curve through s of the time dependent vector field $\Gamma^\alpha(\frac{d}{dt}c(t))$ on S. But then we get

$$\begin{aligned}
\Gamma^\alpha(\tfrac{d}{dt}c(t))(\bar\gamma(t,s)) = \tfrac{d}{dt}\bar\gamma(t,s) &= \tfrac{d}{dt}(\gamma(t).s) = (\tfrac{d}{dt}\gamma(t)).s,\\
\Gamma^\alpha(\tfrac{d}{dt}c(t)) &= (\tfrac{d}{dt}\gamma(t)) \circ \gamma(t)^{-1} \in \mathfrak{g}.
\end{aligned}$$

So Γ^α takes values in the Lie sub algebra of fundamental vector fields for the action of G on S. By theorem (22.9) below the connection Φ is thus induced by a principal connection ω on P. Since by (22.8) the principal connection ω has the 'same' holonomy group as Φ and since this is also the structure group of P, the principal connection ω is irreducible, see (22.7). □

21. Principal Fiber Bundles and G-Bundles

21.1. Definition. Let G be a Lie group and let (E, p, M, S) be a fiber bundle as in (20.1). A *G-bundle structure* on the fiber bundle consists of the following data:

(1) A left action $\ell : G \times S \to S$ of the Lie group on the standard fiber.
(2) A fiber bundle atlas (U_α, ψ_α) whose transition functions $(\psi_{\alpha\beta})$ act on S via the G-action: There is a family of smooth mappings $(\varphi_{\alpha\beta} : U_{\alpha\beta} \to G)$ which satisfies the cocycle condition $\varphi_{\alpha\beta}(x)\varphi_{\beta\gamma}(x) = \varphi_{\alpha\gamma}(x)$ for $x \in U_{\alpha\beta\gamma}$ and $\varphi_{\alpha\alpha}(x) = e$, the unit in the group, such that $\psi_{\alpha\beta}(x, s) = \ell(\varphi_{\alpha\beta}(x), s) = \varphi_{\alpha\beta}(x).s$.

A fiber bundle with a G-bundle structure is called a *G-bundle*. A fiber bundle atlas as in (2) is called a *G-atlas* and the family $(\varphi_{\alpha\beta})$ is also called a cocycle of transition functions, but now for the G-bundle.

To be more precise, two G-atlases are said to be equivalent (to describe the same G-bundle), if their union is also a G-atlas. This translates as follows to the two cocycles of transition functions, where we assume that the two coverings of M are the same (by passing to the common refinement, if necessary): $(\varphi_{\alpha\beta})$ and $(\varphi'_{\alpha\beta})$ are called *cohomologous* if there is a family $(\tau_\alpha : U_\alpha \to G)$ such that $\varphi_{\alpha\beta}(x) = \tau_\alpha(x)^{-1}.\varphi'_{\alpha\beta}(x).\tau_\beta(x)$ holds for all $x \in U_{\alpha\beta}$, compare with (6.3).

In (2) one should specify only an equivalence class of G-bundle structures or only a cohomology class of cocycles of G-valued transition functions. The proof of (6.3) now shows that from any open cover (U_α) of M, some cocycle of transition functions $(\varphi_{\alpha\beta} : U_{\alpha\beta} \to G)$ for it, and a left G-action on a manifold S, we may construct a G-bundle, which depends only on the cohomology class of the cocycle. By some abuse of notation we write (E, p, M, S, G) for a fiber bundle with specified G-bundle structure.

Examples. The tangent bundle of a manifold M is a fiber bundle with structure group $GL(m)$. More general a vector bundle (E, p, M, V) as in (6.1) is a fiber bundle with standard fiber the vector space V and with $GL(V)$-structure.

21.2. Definition. A *principal (fiber) bundle* (P, p, M, G) is a G-bundle with typical fiber a Lie group G, where the left action of G on G is just the left translation.

So by (21.1) we are given a bundle atlas $(U_\alpha, \varphi_\alpha : P|U_\alpha \to U_\alpha \times G)$ such that we have $\varphi_\alpha\varphi_\beta^{-1}(x, a) = (x, \varphi_{\alpha\beta}(x).a)$ for the cocycle of transition functions $(\varphi_{\alpha\beta} : U_{\alpha\beta} \to G)$. This is now called a *principal bundle atlas*. Clearly the principal bundle is uniquely specified by the cohomology class of its cocycle of transition functions.

Each principal bundle admits a unique right action $r : P \times G \to P$, called the *principal right action*, given by $\varphi_\alpha(r(\varphi_\alpha^{-1}(x, a), g)) = (x, ag)$. Since left and right translation on G commute, this is well defined. As in (5.10) we write $r(u, g) = u.g$ when the meaning is clear. The principal right action is visibly free and for any $u_x \in P_x$ the partial mapping $r_{u_x} = r(u_x, \quad) : G \to P_x$ is a diffeomorphism onto the fiber through u_x, whose inverse is denoted by $\tau_{u_x} : P_x \to G$. These inverses together give a smooth mapping $\tau : P \times_M P \to G$, whose local expression is $\tau(\varphi_\alpha^{-1}(x,a), \varphi_\alpha^{-1}(x,b)) = a^{-1}.b$. This mapping is also uniquely determined by the implicit equation $r(u_x, \tau(u_x, v_x)) = v_x$, thus we also have $\tau(u_x.g, u'_x.g') = g^{-1}.\tau(u_x, u'_x).g'$ and $\tau(u_x, u_x) = e$.

When considering principal bundles the reader should think of frame bundles as the foremost examples for this book. They will be treated in (21.11) below.

21.3. Lemma. *Let $p : P \to M$ be a surjective submersion (a fibered manifold), and let G be a Lie group which acts freely on P such that the orbits of the action are exactly the fibers $p^{-1}(x)$ of p. Then (P, p, M, G) is a principal fiber bundle.*

Proof. Let the action be a right one by using the group inversion if necessary. Let $s_\alpha : U_\alpha \to P$ be local sections (right inverses) for $p : P \to M$ such that (U_α) is an open cover of M. Let $\varphi_\alpha^{-1} : U_\alpha \times G \to P|U_\alpha$ be given by $\varphi_\alpha^{-1}(x,a) = s_\alpha(x).a$, which is obviously injective with invertible tangent mapping, so its inverse $\varphi_\alpha : P|U_\alpha \to U_\alpha \times G$ is a fiber respecting diffeomorphism. So $(U_\alpha, \varphi_\alpha)$ is already a fiber bundle atlas. Let $\tau : P \times_M P \to G$ be given by the implicit equation $r(u_x, \tau(u_x, u'_x)) = u'_x$, where r is the right G-action. τ is smooth by the implicit function theorem and clearly we have $\tau(u_x, u'_x.g) = \tau(u_x, u'_x).g$ and $\varphi_\alpha(u_x) = (x, \tau(s_\alpha(x), u_x))$. Thus we have $\varphi_\alpha\varphi_\beta^{-1}(x,g) = \varphi_\alpha(s_\beta(x).g) = (x, \tau(s_\alpha(x), s_\beta(x).g)) = (x, \tau(s_\alpha(x), s_\beta(x)).g)$ and $(U_\alpha, \varphi_\alpha)$ is a principal bundle atlas. □

21.4. Remarks. In the proof of Lemma (21.3) we have seen, that a principal bundle atlas of a principal fiber bundle (P, p, M, G) is already determined if we specify a family of smooth sections of P, whose domains of definition cover the base M.

Lemma (21.3) can serve as an equivalent definition for a principal bundle. But this is true only if an implicit function theorem is available, so in topology or in infinite dimensional differential geometry one should stick to our original definition.

From the Lemma itself it follows, that the pullback f^*P over a smooth mapping $f : M' \to M$ is again a principal fiber bundle.

21.5. Homogeneous spaces. Let G be a Lie group with Lie algebra $\mathfrak{g}$. Let K be a closed subgroup of G, then by theorem (5.5) K is a closed Lie subgroup whose Lie algebra will be denoted by $\mathfrak{k}$. By theorem (5.11) there is a unique structure of a smooth manifold on the quotient space G/K such that the projection $p : G \to G/K$ is a submersion, so by the implicit function theorem p admits local sections.

Theorem. *$(G, p, G/K, K)$ is a principal fiber bundle.*

Proof. The group multiplication of G restricts to a free right action $\mu : G \times K \to G$, whose orbits are exactly the fibers of p. By lemma (21.3) the result follows. □

For the convenience of the reader we discuss now the best known homogeneous spaces.

The group $SO(n)$ acts transitively on $S^{n-1} \subset \mathbb{R}^n$. The isotropy group of the 'north pole' $(1, 0, \dots, 0)$ is the subgroup

$$\begin{pmatrix} 1 & 0 \\ 0 & SO(n-1) \end{pmatrix}$$

which we identify with $SO(n-1)$. So $S^{n-1} = SO(n)/SO(n-1)$ and we get a principal fiber bundle $(SO(n), p, S^{n-1}, SO(n-1))$. Likewise
$(O(n), p, S^{n-1}, O(n-1))$,
$(SU(n), p, S^{2n-1}, SU(n-1))$,
$(U(n), p, S^{2n-1}, U(n-1))$, and
$(Sp(n), p, S^{4n-1}, Sp(n-1))$ are principal fiber bundles.

The *Grassmann manifold* $G(k, n; \mathbb{R})$ is the space of all k-planes containing 0 in $\mathbb{R}^n$. The group $O(n)$ acts transitively on it and the isotropy group of the k-plane $\mathbb{R}^k \times \{0\}$ is the subgroup

$$\begin{pmatrix} O(k) & 0 \\ 0 & O(n-k) \end{pmatrix},$$

therefore $G(k, n; \mathbb{R}) = O(n)/O(k) \times O(n-k)$ is a compact manifold and we get the principal fiber bundle $(O(n), p, G(k, n; \mathbb{R}), O(k) \times O(n-k))$. Likewise
$(SO(n), p, G(k, n; \mathbb{R}), S(O(k) \times O(n-k)))$,
$(SO(n), p, \tilde{G}(k, n; \mathbb{R}), SO(k) \times SO(n-k))$,
$(U(n), p, G(k, n; \mathbb{C}), U(k) \times U(n-k))$, and
$(Sp(n), p, G(k, n; \mathbb{H}), Sp(k) \times Sp(n-k))$ are principal fiber bundles.

The *Stiefel manifold* $V(k, n; \mathbb{R})$ is the space of all orthonormal k-frames in $\mathbb{R}^n$. Clearly the group $O(n)$ acts transitively on $V(k, n; \mathbb{R})$ and the isotropy subgroup of $(e_1, \dots, e_k)$ is $\mathbb{I}_k \times O(n-k)$, so $V(k, n; \mathbb{R}) = O(n)/O(n-k)$ is a compact manifold, and $(O(n), p, V(k, n; \mathbb{R}), O(n-k))$ is a principal fiber bundle. But $O(k)$ also acts from the right on $V(k, n; \mathbb{R})$, its orbits are exactly the fibers of the projection $p : V(k, n; \mathbb{R}) \to G(k, n; \mathbb{R})$. So by lemma (21.3) we get a principal fiber bundle $(V(k, n, \mathbb{R}), p, G(k, n; \mathbb{R}), O(k))$. Indeed we have the following diagram where all arrows are projections of principal fiber bundles, and where the respective structure groups are written on the arrows:

(1)
$$\begin{array}{ccc} O(n) & \xrightarrow{\quad O(n-k) \quad} & V(k, n; \mathbb{R}) \\ {\scriptstyle O(k)}\big\downarrow & & \big\downarrow{\scriptstyle O(k)} \\ V(n-k, n; \mathbb{R}) & \xrightarrow[\quad O(n-k) \quad]{} & G(k, n; \mathbb{R}), \end{array}$$

$V(k, n)$ is also diffeomorphic to the space $\{ A \in L(\mathbb{R}^k, \mathbb{R}^n) : A^t.A = \mathbb{I}_k \}$, i.e. the space of all linear isometries $\mathbb{R}^k \to \mathbb{R}^n$. There are furthermore complex and quaternionic versions of the Stiefel manifolds, and flag manifolds.

21.6. Homomorphisms. Let $\chi : (P, p, M, G) \to (P', p', M', G)$ be a *principal fiber bundle homomorphism*, i.e. a smooth G-equivariant mapping $\chi : P \to P'$.

Then obviously the diagram

$$(1)\qquad \begin{CD} P @>\chi>> P' \\ @VpVV @VV{p'}V \\ M @>\underline{\chi}>> M' \end{CD}$$

commutes for a uniquely determined smooth mapping $\underline{\chi} : M \to M'$. For each $x \in M$ the mapping $\chi_x := \chi|P_x : P_x \to P'_{\underline{\chi}(x)}$ is G-equivariant and therefore a diffeomorphism, so diagram (1) is a pullback diagram.

But the most general notion of a homomorphism of principal bundles is the following. Let $\Phi : G \to G'$ be a homomorphism of Lie groups. $\chi : (P, p, M, G) \to (P', p', M', G')$ is called a *homomorphism over* Φ *of principal bundles*, if $\chi : P \to P'$ is smooth and $\chi(u.g) = \chi(u).\Phi(g)$ holds in general. Then χ is fiber respecting, so diagram (1) makes again sense, but it is no longer a pullback diagram in general.

If χ covers the identity on the base, it is called a *reduction of the structure group* G' *to* G for the principal bundle (P', p', M', G') — the name comes from the case, when Φ is the embedding of a subgroup.

By the universal property of the pullback any general homomorphism χ of principal fiber bundles over a group homomorphism can be written as the composition of a reduction of structure groups and a pullback homomorphism as follows, where we also indicate the structure groups:

$$(2)\qquad \begin{array}{ccccc} (P, G) & \longrightarrow & (\bar{\chi}^* P', G') & \longrightarrow & (P', G') \\ & \searrow^{p} & \Big\downarrow & & \Big\downarrow{\scriptstyle p'} \\ & & M & \xrightarrow{\ \bar{\chi}\ } & M'. \end{array}$$

21.7. Associated bundles. Let (P, p, M, G) be a principal bundle and let $\ell : G \times S \to S$ be a left action of the structure group G on a manifold S. We consider the right action $R : (P \times S) \times G \to P \times S$, given by $R((u, s), g) = (u.g, g^{-1}.s)$.

Theorem. *In this situation we have:*

(1) *The space $P \times_G S$ of orbits of the action R carries a unique smooth manifold structure such that the quotient map $q : P \times S \to P \times_G S$ is a submersion.*

(2) *$(P \times_G S, \bar{p}, M, S, G)$ is a G-bundle in a canonical way, where $\bar{p} : P \times_G S \to M$ is given by*

$$(a)\qquad \begin{CD} P \times S @>q>> P \times_G S \\ @V{pr_1}VV @VV{\bar{p}}V \\ P @>p>> M. \end{CD}$$

In this diagram $q_u : \{u\} \times S \to (P \times_G S)_{p(u)}$ is a diffeomorphism for each $u \in P$.

(3) $(P \times S, q, P \times_G S, G)$ *is a principal fiber bundle with principal action* R.

(4) *If* $(U_\alpha, \varphi_\alpha : P|U_\alpha \to U_\alpha \times G)$ *is a principal bundle atlas with cocycle of transition functions* $(\varphi_{\alpha\beta} : U_{\alpha\beta} \to G)$*, then together with the left action* $\ell : G \times S \to S$ *this cocycle is also one for the* G*-bundle* $(P \times_G S, \bar{p}, M, S, G)$.

Notation. $(P \times_G S, \bar{p}, M, S, G)$ is called the *associated bundle* for the action $\ell : G \times S \to S$. We will also denote it by $P[S, \ell]$ or simply $P[S]$ and we will write p for $\bar{p}$ if no confusion is possible. We also define the smooth mapping $\tau = \tau^S : P \times_M P[S, \ell] \to S$ by $\tau(u_x, v_x) := q_{u_x}^{-1}(v_x)$. It satisfies $\tau(u, q(u, s)) = s$, $q(u_x, \tau(u_x, v_x)) = v_x$, and $\tau(u_x.g, v_x) = g^{-1}.\tau(u_x, v_x)$. In the special situation, where $S = G$ and the action is left translation, so that $P[G] = P$, this mapping coincides with τ considered in (21.2).

Proof. In the setting of diagram (a) in (2) the mapping $p \circ pr_1$ is constant on the R-orbits, so $\bar{p}$ exists as a mapping. Let $(U_\alpha, \varphi_\alpha : P|U_\alpha \to U_\alpha \times G)$ be a principal bundle atlas with transition functions $(\varphi_{\alpha\beta} : U_{\alpha\beta} \to G)$. We define $\psi_\alpha^{-1} : U_\alpha \times S \to \bar{p}^{-1}(U_\alpha) \subset P \times_G S$ by $\psi_\alpha^{-1}(x, s) = q(\varphi_\alpha^{-1}(x, e), s)$, which is fiber respecting. For each point in $\bar{p}^{-1}(x) \subset P \times_G S$ there is exactly one $s \in S$ such that the orbit corresponding to this point passes through $(\varphi_\alpha^{-1}(x, e), s)$, namely $s = \tau^G(u_x, \varphi_\alpha^{-1}(x, e))^{-1}.s'$ if (u_x, s') is the orbit, since the principal right action is free. Thus $\psi_\alpha^{-1}(x, \quad) : S \to \bar{p}^{-1}(x)$ is bijective. Furthermore

$$\begin{aligned}
\psi_\beta^{-1}(x, s) &= q(\varphi_\beta^{-1}(x, e), s) \\
&= q(\varphi_\alpha^{-1}(x, \varphi_{\alpha\beta}(x).e), s) = q(\varphi_\alpha^{-1}(x, e).\varphi_{\alpha\beta}(x), s) \\
&= q(\varphi_\alpha^{-1}(x, e), \varphi_{\alpha\beta}(x).s) = \psi_\alpha^{-1}(x, \varphi_{\alpha\beta}(x).s),
\end{aligned}$$

so $\psi_\alpha \psi_\beta^{-1}(x, s) = (x, \varphi_{\alpha\beta}(x).s)$ So (U_α, ψ_α) is a G-atlas for $P \times_G S$ and makes it into a smooth manifold and a G-bundle. The defining equation for ψ_α shows that q is smooth and a submersion and consequently the smooth structure on $P \times_G S$ is uniquely defined, and $\bar{p}$ is smooth by the universal properties of a submersion.

By the definition of ψ_α the diagram

$$\text{(5)} \qquad \begin{array}{ccc}
p^{-1}(U_\alpha) \times S & \xrightarrow{\varphi_\alpha \times Id} & U_\alpha \times G \times S \\
{\scriptstyle q}\downarrow & & \downarrow{\scriptstyle Id \times \ell} \\
\bar{p}^{-1}(U_\alpha) & \xrightarrow{\psi_\alpha} & U_\alpha \times S
\end{array}$$

commutes; since its lines are diffeomorphisms we conclude that $q_u : \{u\} \times S \to \bar{p}^{-1}(p(u))$ is a diffeomorphism. So (1), (2), and (4) are checked.

(3) follows directly from lemma (21.3). We give below an explicit chart construction. We rewrite the last diagram in the following form:

$$\text{(6)} \qquad \begin{array}{ccccc}
p^{-1}(U_\alpha) \times S & \xrightarrow{=} & q^{-1}(V_\alpha) & \xrightarrow{\lambda_\alpha} & V_\alpha \times G \\
& & {\scriptstyle q}\downarrow & & \downarrow{\scriptstyle pr_1} \\
& & \bar{p}^{-1}(U_\alpha) & \xrightarrow{=} & V_\alpha
\end{array}$$

Here $V_\alpha := \bar{p}^{-1}(U_\alpha) \subset P\times_G S$, and the diffeomorphism λ_α is given by the expression $\lambda_\alpha^{-1}(\psi_\alpha^{-1}(x,s),g) := (\varphi_\alpha^{-1}(x,g), g^{-1}.s)$. Then we have

$$\begin{aligned}\lambda_\beta^{-1}(\psi_\alpha^{-1}(x,s),g) &= \lambda_\beta^{-1}(\psi_\beta^{-1}(x,\varphi_{\beta\alpha}(x).s),g)\\ &= (\varphi_\beta^{-1}(x,g), g^{-1}.\varphi_{\beta\alpha}(x).s)\\ &= (\varphi_\alpha^{-1}(x,\varphi_{\alpha\beta}(x).g), g^{-1}.\varphi_{\alpha\beta}(x)^{-1}.s)\\ &= \lambda_\alpha^{-1}(\psi_\alpha^{-1}(x,s),\varphi_{\alpha\beta}(x).g),\end{aligned}$$

so $\lambda_\alpha\lambda_\beta^{-1}(\psi_\alpha^{-1}(x,s),g) = (\psi_\alpha^{-1}(x,s),\varphi_{\alpha\beta}(x).g)$ and $(P\times S, q, P\times_G S, G)$ is a principal bundle with structure group G and the same cocycle $(\varphi_{\alpha\beta})$ we started with. $\square$

21.8. Corollary. *Let (E,p,M,S,G) be a G-bundle, specified by a cocycle of transition functions $(\varphi_{\alpha\beta})$ with values in G and a left action ℓ of G on S. Then from the cocycle of transition functions we may glue a unique principal bundle (P,p,M,G) such that $E = P[S,\ell]$.* $\square$

This is the usual way a differential geometer thinks of an associated bundle. He is given a bundle E, a principal bundle P, and the G-bundle structure then is described with the help of the mappings τ and q.

21.9. Equivariant mappings and associated bundles.

(1) Let (P,p,M,G) be a principal fiber bundle and consider two left actions of G, $\ell : G\times S\to S$ and $\ell' : G\times S'\to S'$. Let furthermore $f : S\to S'$ be a G-equivariant smooth mapping, so $f(g.s) = g.f(s)$ or $f\circ\ell_g = \ell'_g\circ f$. Then $Id_P\times f : P\times S\to P\times S'$ is equivariant for the actions $R : (P\times S)\times G\to P\times S$ and $R' : (P\times S')\times G\to P\times S'$ and is thus a homomorphism of principal bundles, so there is an induced mapping

$$(2)\qquad \begin{array}{ccc} P\times S & \xrightarrow{Id\times f} & P\times S' \\ {\scriptstyle q}\downarrow & & \downarrow{\scriptstyle q'} \\ P\times_G S & \xrightarrow{Id\times_G f} & P\times_G S', \end{array}$$

which is fiber respecting over M, and a homomorphism of G-bundles in the sense of the definition (21.10) below.

(3) Let $\chi : (P,p,M,G)\to(P',p',M',G)$ be a principal fiber bundle homomorphism as in (21.6). Furthermore we consider a smooth left action $\ell : G\times S\to S$. Then $\chi\times Id_S : P\times S\to P'\times S$ is G-equivariant and induces a mapping $\chi\times_G Id_S : P\times_G S\to P'\times_G S$, which is fiber respecting over M, fiber wise a diffeomorphism, and again a homomorphism of G-bundles in the sense of definition (21.10) below.

(4) Now we consider the situation of 1 and 2 at the same time. We have two associated bundles $P[S,\ell]$ and $P'[S',\ell']$. Let $\chi : (P,p,M,G)\to(P',p',M',G)$ be a principal fiber bundle homomorphism and let $f : S\to S'$ be an G-equivariant mapping. Then $\chi\times f : P\times S\to P'\times S'$ is clearly G-equivariant and therefore induces a mapping $\chi\times_G f : P[S,\ell]\to P'[S',\ell']$ which again is a homomorphism of G-bundles.

(5) Let S be a point. Then $P[S] = P \times_G S = M$. Furthermore let $y \in S'$ be a fixed point of the action $\ell' : G \times S' \to S'$, then the inclusion $i : \{y\} \hookrightarrow S'$ is G-equivariant, thus $Id_P \times i$ induces $Id_P \times_G i : M = P[\{y\}] \to P[S']$, which is a global section of the associated bundle $P[S']$.

If the action of G on S is trivial, so $g.s = s$ for all $s \in S$, then the associated bundle is trivial: $P[S] = M \times S$. For a trivial principal fiber bundle any associated bundle is trivial.

21.10. Definition. In the situation of (21.9), a smooth fiber respecting mapping $\gamma : P[S, \ell] \to P'[S', \ell']$ covering a smooth mapping $\bar\gamma : M \to M'$ of the bases is called a *homomorphism of G-bundles*, if the following conditions are satisfied: P is isomorphic to the pullback $\bar\gamma^* P'$, and the local representations of γ in pullback-related fiber bundle atlases belonging to the two G-bundles are fiber wise G-equivariant.

Let us describe this in more detail now. Let $(U'_\alpha, \psi'_\alpha)$ be a G-atlas for $P'[S', \ell']$ with cocycle of transition functions $(\varphi'_{\alpha\beta})$, belonging to the principal fiber bundle atlas $(U'_\alpha, \varphi'_\alpha)$ of (P', p', M', G). Then the pullback-related principal fiber bundle atlas $(U_\alpha = \bar\gamma^{-1}(U'_\alpha), \varphi_\alpha)$ for $P = \bar\gamma^* P'$ as described in the proof of (20.5) has the cocycle of transition functions $(\varphi_{\alpha\beta} = \varphi'_{\alpha\beta} \circ \bar\gamma)$; it induces the G-atlas (U_α, ψ_α) for $P[S, \ell]$. Then $(\psi'_\alpha \circ \gamma \circ \psi_\alpha^{-1})(x, s) = (\bar\gamma(x), \gamma_\alpha(x, s))$ and $\gamma_\alpha(x, \quad) : S \to S'$ is required to be G-equivariant for all α and all $x \in U_\alpha$.

Lemma. *Let $\gamma : P[S, \ell] \to P'[S', \ell']$ be a homomorphism of G-bundles as defined above. Then there is a homomorphism $\chi : (P, p, M, G) \to (P', p', M', G)$ of principal bundles and a G-equivariant mapping $f : S \to S'$ such that $\gamma = \chi \times_G f : P[S, \ell] \to P'[S', \ell']$.*

Proof. The homomorphism $\chi : (P, p, M, G) \to (P', p', M', G)$ of principal fiber bundles is already determined by the requirement that $P = \bar\gamma^* P'$, and we have $\bar\gamma = \bar\chi$. The G-equivariant mapping $f : S \to S'$ can be read off the following diagram

$$\begin{array}{ccc} P \times_M P[S] & \xrightarrow{\tau^S} & S \\ {\scriptstyle \chi \times_M \gamma}\downarrow & & \downarrow{\scriptstyle f} \\ P' \times_{M'} P'[S'] & \xrightarrow{\tau^{S'}} & S', \end{array} \tag{1}$$

which by the assumptions is seen to be well defined in the right column. $\square$

So a homomorphism of G-bundles is described by the whole triple $(\chi : P \to P', f : S \to S'$ (G-equivariant)$, \gamma : P[S] \to P'[S'])$, such that diagram (1) commutes.

21.11. Associated vector bundles. Let (P, p, M, G) be a principal fiber bundle, and consider a representation $\rho : G \to GL(V)$ of G on a finite dimensional vector space V. Then $P[V, \rho]$ is an associated fiber bundle with structure group G, but also with structure group $GL(V)$, for in the canonically associated fiber bundle atlas the transition functions have also values in $GL(V)$. So by section (6) $P[V,\rho]$ is a vector bundle.

Now let $\mathcal{F}$ be a covariant smooth functor from the category of finite dimensional vector spaces and linear mappings into itself, as considered in section (6.8). Then clearly $\mathcal{F}\circ\rho : G \to GL(V) \to GL(\mathcal{F}(V))$ is another representation of G and the associated bundle $P[\mathcal{F}(V),\mathcal{F}\circ\rho]$ coincides with the vector bundle $\mathcal{F}(P[V,\rho])$ constructed with the method of (6.8), but now it has an extra G-bundle structure. For contravariant functors $\mathcal{F}$ we have to consider the representation $\mathcal{F}\circ\rho\circ\nu$, where $\nu(g) = g^{-1}$. A similar choice works for bifunctors. In particular the bifunctor $L(V,W)$ may be applied to two different representations of two structure groups of two principal bundles over the same base M to construct a vector bundle $L(P[V,\rho],P'[V',\rho']) = (P\times_M P')[L(V,V'),L\circ((\rho\circ\nu)\times\rho')]$.

If (E,p,M) is a vector bundle with n-dimensional fibers we may consider the open subset $GL(\mathbb{R}^n,E) \subset L(M\times\mathbb{R}^n,E)$, a fiber bundle over the base M, whose fiber over $x\in M$ is the space $GL(\mathbb{R}^n,E_x)$ of all invertible linear mappings. Composition from the right by elements of $GL(n)$ gives a free right action on $GL(\mathbb{R}^n,E)$ whose orbits are exactly the fibers, so by lemma (21.3) we have a principal fiber bundle $(GL(\mathbb{R}^n,E),p,M,GL(n))$. The associated bundle $GL(\mathbb{R}^n,E)[\mathbb{R}^n]$ for the banal representation of $GL(n)$ on $\mathbb{R}^n$ is isomorphic to the vector bundle (E,p,M) we started with, for the evaluation mapping $ev : GL(\mathbb{R}^n,E)\times\mathbb{R}^n \to E$ is invariant under the right action R of $GL(n)$, and locally in the image there are smooth sections to it, so it factors to a fiber linear diffeomorphism $GL(\mathbb{R}^n,E)[\mathbb{R}^n] = GL(\mathbb{R}^n,E)\times_{GL(n)}\mathbb{R}^n \to E$. The principal bundle $GL(\mathbb{R}^n,E)$ is called the *linear frame bundle of* E. Note that local sections of $GL(\mathbb{R}^n,E)$ are exactly the local frame fields of the vector bundle E as discussed in (6.5).

To illustrate the notion of reduction of structure group, we consider now a vector bundle $(E,p,M,\mathbb{R}^n)$ equipped with a *Riemannian metric* g, that is a section $g\in C^\infty(S^2E^*)$ such that g_x is a positive definite inner product on E_x for each $x\in M$. Any vector bundle admits Riemannian metrics: local existence is clear and we may glue with the help of a partition of unity on M, since the positive definite sections form an open convex subset. Now let $s' = (s'_1,\dots,s'_n)\in C^\infty(GL(\mathbb{R}^n,E)|U)$ be a local frame field of the bundle E over $U\subset M$. Now we may apply the Gram-Schmidt orthonormalization procedure to the basis $(s_1(x),\dots,s_n(x))$ of E_x for each $x\in U$. Since this procedure is smooth (even real analytic), we obtain a frame field $s = (s_1,\dots,s_n)$ of E over U which is orthonormal with respect to g. We call it an *orthonormal frame field*. Now let (U_α) be an open cover of M with orthonormal frame fields $s^\alpha = (s^\alpha_1,\dots,s^\alpha_n)$, where s^α is defined on U_α. We consider the vector bundle charts $(U_\alpha,\psi_\alpha : E|U_\alpha \to U_\alpha\times\mathbb{R}^n)$ given by the orthonormal frame fields: $\psi_\alpha^{-1}(x,v^1,\dots,v^n) = \sum s^\alpha_i(x).v^i =: s^\alpha(x).v$. For $x\in U_{\alpha\beta}$ we have $s^\alpha_i(x) = \sum s^\beta_j(x).g_{\beta\alpha}{}^j_i(x)$ for C^∞-functions $g_{\alpha\beta}{}^j_i : U_{\alpha\beta}\to\mathbb{R}$. Since $s^\alpha(x)$ and $s^\beta(x)$ are both orthonormal bases of E_x, the matrix $g_{\alpha\beta}(x) = (g_{\alpha\beta}{}^j_i(x))$ is an element of $O(n,\mathbb{R})$. We write $s^\alpha = s^\beta.g_{\beta\alpha}$ for short. Then we have $\psi_\beta^{-1}(x,v) = s^\beta(x).v = s^\alpha(x).g_{\alpha\beta}(x).v = \psi_\alpha^{-1}(x,g_{\alpha\beta}(x).v)$ and consequently $\psi_\alpha\psi_\beta^{-1}(x,v) = (x,g_{\alpha\beta}(x).v)$. So the $(g_{\alpha\beta} : U_{\alpha\beta}\to O(n,\mathbb{R}))$ are the cocycle of transition functions for the vector bundle atlas (U_α, ψ_α). So we have constructed an $O(n,\mathbb{R})$-structure on E. The corresponding principal fiber bundle will be denoted by $O(\mathbb{R}^n,(E,g))$; it is usually called the *orthonormal frame bundle* of E. It is derived from the linear frame bundle $GL(\mathbb{R}^n, E)$ by reduction of the structure group from $GL(n)$ to $O(n)$. The phenomenon discussed here plays a prominent role in the theory of *classifying spaces.*

21.12. Sections of associated bundles. Let (P,p,M,G) be a principal fiber bundle and $\ell : G \times S \to S$ a left action. Let $C^\infty(P,S)^G$ denote the space of all smooth mappings $f : P \to S$ which are G-equivariant in the sense that $f(u.g) = g^{-1}.f(u)$ holds for $g \in G$ and $u \in P$.

Theorem. *The sections of the associated bundle $P[S,\ell]$ correspond exactly to the G-equivariant mappings $P \to S$; we have a bijection $C^\infty(P,S)^G \cong \Gamma(P[S])$.*

This result follows from (21.9) and (21.10). Since it is very important we include a direct proof.

Proof. If $f \in C^\infty(P,S)^G$ we construct $s_f \in \Gamma(P[S])$ in the following way: The mapping graph$(f) = (Id,f) : P \to P \times S$ is G-equivariant, since $(Id,f)(u.g) = (u.g, f(u.g)) = (u.g, g^{-1}.f(u)) = ((Id,f)(u)).g$. So it induces a smooth section $s_f \in \Gamma(P[S])$ as seen from (21.9) and the diagram:

(1)
$$\begin{array}{ccc} P \times \{Pt\} \cong P & \xrightarrow{(Id,f)} & P \times S \\ {\scriptstyle p}\downarrow & & \downarrow{\scriptstyle q} \\ M & \xrightarrow{s_f} & P[S] \end{array}$$

If conversely $s \in \Gamma(P[S])$ we define $f_s \in C^\infty(P,S)^G$ by $f_s := \tau^S \circ (Id_P \times_M s) : P = P \times_M M \to P \times_M P[S] \to S$. This is G-equivariant since $f_s(u_x.g) = \tau^S(u_x.g, s(x)) = g^{-1}.\tau^S(u_x, s(x)) = g^{-1}.f_s(u_x)$ by (21.7). These constructions are inverse to each other since we have $f_{s(f)}(u) = \tau^S(u, s_f(p(u))) = \tau^S(u, q(u,f(u))) = f(u)$ and $s_{f(s)}(p(u)) = q(u, f_s(u)) = q(u, \tau^S(u, s(p(u))) = s(p(u))$. $\square$

21.13. Induced representations. Let K be a closed subgroup of a Lie group G. Let $\rho : K \to GL(V)$ be a representation in a vector space V, which we assume to be finite dimensional for the beginning. Then we consider the principal fiber bundle $(G,p,G/K,K)$ and the associated vector bundle $(G[V],p,G/K)$. The smooth (or even continuous) sections of $G[V]$ correspond exactly to the K-equivariant mappings $f : G \to V$, those satisfying $f(gk) = \rho(k^{-1})f(g)$, by lemma (21.12). Each $g \in G$ acts as a principal bundle homomorphism by left translation

$$\begin{array}{ccc} G & \xrightarrow{\mu_g} & G \\ {\scriptstyle p}\downarrow & & \downarrow{\scriptstyle p} \\ G/K & \xrightarrow{\bar\mu_g} & G/K. \end{array}$$

So by (21.9) we have an induced isomorphism of vector bundles

$$\begin{array}{ccc} G\times V & \xrightarrow{\mu_g\times \mathrm{Id}_V} & G\times V \\ q\downarrow & & \downarrow q \\ G[V] & \xrightarrow{\mu_g\times_K V} & G[V] \\ p\downarrow & & \downarrow p \\ G/K & \xrightarrow{\bar\mu_g} & G/K \end{array}$$

which gives rise to the representation $\widetilde{\mathrm{ind}}_K^G\rho$ of G in the space $\Gamma(G[V])$, defined by

$$(\widetilde{\mathrm{ind}}_K^G\rho)(g)(s) := (\mu_g\times_K V)\circ s\circ \bar\mu_{g^{-1}} = (\mu_g\times_K V)_*(s).$$

Now let us assume that the original representation ρ is unitary, $\rho : K\to U(V)$ for a complex vector space V with inner product $\langle\quad,\quad\rangle_V$. Then $v\mapsto \|v\|^2 = \langle v,v\rangle$ is an invariant symmetric homogeneuous polynomial $V\to\mathbb{R}$ of degree 2, so it is equivariant where K acts trivial on $\mathbb{R}$. By (21.9) again we get an induced mapping $G[V]\to G[\mathbb{R}] = G/K\times\mathbb{R}$, which we can polarize to a smooth fiberwise hermitian form $\langle\quad,\quad\rangle_{G[V]}$ on the vector bundle $G[V]$. We may also express this by

$$\begin{aligned}\langle v_x,w_x\rangle_{G[V]} &= \langle\tau^V(u_x,v_x),\tau^V(u_x,w_x)\rangle_V = \langle k^{-1}\tau^V(u_x,v_x),k^{-1}\tau^V(u_x,w_x)\rangle_V = \\ &= \langle\tau^V(u_x.k,v_x),\tau^V(u_x.k,w_x)\rangle_V\end{aligned}$$

for some $u_x\in G_x$, using the mapping $\tau^V : G\times_{G/M} G[V]\to V$ from (21.7); it does not depend on the choice of u_x. Still another way to describe the fiberwise hermitian form is

$$\begin{array}{ccc} (G\times V)\times_{G/K}(G\times V) & \xrightarrow{\quad f\quad} & \mathbb{C} \\ \downarrow & & \\ G[V]\times_{G/K} G[V] & \xrightarrow[\langle\ ,\ \rangle_{G[V]}]{} & \mathbb{C} \\ \downarrow & & \\ G/K; & & \end{array}$$

here $f((g_1,v_1),(g_2,v_2)) := \langle v_1,\rho(\tau^K(g_1,g_2))v_2\rangle_V$ where we use the mapping $\tau^K : G\times_{G/K}G\to K$ given by $\tau^K(g_1,g_2) = g_1^{-1}g_2$ from (21.2). From this last description it is also clear that each $g\in G$ acts as an isometric vector bundle homomorphism.

Now we consider the natural line bundle $\mathrm{Vol}^{1/2}(G/K)$ of all $\frac12$-densities on the manifold G/K from (8.4). Then for $\frac12$-densities $\mu_i\in\Gamma(\mathrm{Vol}^{1/2}(G/M))$ and any diffeomorphism $f : G/K\to G/K$ the push forward $f_*\mu_i$ is defined and for those with compact support we have $\int_{G/K}(f_*\mu_1.f_*\mu_2) = \int_{G/K} f_*(\mu_1.\mu_2) = \int_{G/K}\mu_1.\mu_2$. The hermitian inner product on $G[V]$ now defines a fiberwise hermitian mapping

$$(G[V]\otimes\mathrm{Vol}^{1/2}(G/K))\times_{G/K}(G[V]\otimes\mathrm{Vol}^{1/2}(G/K))\xrightarrow{\langle\ ,\ \rangle_{G[V]}}\mathrm{Vol}^1(G/L)$$

and on the space $C_c^\infty(G[V] \otimes \mathrm{Vol}^{1/2}(G/K))$ of all smooth sections with compact support we have the following hermitian inner product

$$\langle \sigma_1, \sigma_2 \rangle := \int_{G/K} \langle \sigma_1, \sigma_2 \rangle_{G[V]}.$$

For a decomposable section $\sigma_i = s_i \otimes \alpha_i$ (where $s_i \in \Gamma(G[V])$ and where $\alpha_i \in C_c^\infty(\mathrm{Vol}^{1/2}(G/K))$) we may consider (using (21.12)) the equivariants lifts $f_{s_i} : G \to V$, their invariant inner product $\langle f_{s_1}, f_{s_2} \rangle_V : G \to \mathbb{C}$, and its factorisation to $\langle f_{s_1}, f_{s_2} \rangle_V^- : G/K \to \mathbb{C}$. Then

$$\langle \sigma_1, \sigma_2 \rangle := \int_{G/K} \langle f_{s_1}, f_{s_2} \rangle_V^- \; \alpha_1 \alpha_2.$$

Obviously the resulting action of the group G on $\Gamma(G[V] \otimes \mathrm{Vol}^{1/2}(G/K))$ is unitary with respect to the hermitian inner product, and it can be extended to the Hilbert space completion of this space of sections. The resulting unitary representation is called the *induced representation* and is denoted by $\mathrm{ind}_K^G \rho$.

If the original unitary representation $\rho : K \to U(V)$ is in an infinite dimensional Hilbert space V, one can first restrict the representation ρ to the subspace of smooth vectors, on which it is differentiable, and repeat the above construction with some modifications. See [Michor, 1990] for more details on this infinite dimensional construction.

21.14. Theorem. *Consider a principal fiber bundle (P, p, M, G) and a closed subgroup K of G. Then the reductions of structure group from G to K correspond bijectively to the global sections of the associated bundle $P[G/K, \bar\lambda]$ in a canonical way, where $\bar\lambda : G \times G/K \to G/K$ is the left action on the homogeneous space from* (5.11).

Proof. By (21.12) the section $s \in \Gamma(P[G/K])$ corresponds to $f_s \in C^\infty(P, G/K)^G$, which is a surjective submersion since the action $\bar\lambda : G \times G/K \to G/K$ is transitive. Thus $P_s := f_s^{-1}(\bar e)$ is a submanifold of P which is stable under the right action of K on P. Furthermore the K-orbits are exactly the fibers of the mapping $p : P_s \to M$, so by lemma (21.3) we get a principal fiber bundle (P_s, p, M, K). The embedding $P_s \hookrightarrow P$ is then a reduction of structure groups as required.

If conversely we have a principal fiber bundle (P', p', M, K) and a reduction of structure groups $\chi : P' \to P$, then χ is an embedding covering the identity of M and is K-equivariant, so we may view P' as a sub fiber bundle of P which is stable under the right action of K. Now we consider the mapping $\tau : P \times_M P \to G$ from (21.2) and restrict it to $P \times_M P'$. Since we have $\tau(u_x, v_x.k) = \tau(u_x, v_x).k$ for $k \in K$ this restriction induces $f : P \to G/K$ by

$$\begin{array}{ccc} P \times_M P' & \xrightarrow{\quad \tau \quad} & G \\ \downarrow & & \downarrow p \\ P = P \times_M P'/K & \xrightarrow{\quad f \quad} & G/K, \end{array}$$

since $P'/K = M$; and from $\tau(u_x.g, v_x) = g^{-1}.\tau(u_x, v_x)$ it follows that f is G-equivariant as required. Finally $f^{-1}(\bar{e}) = \{u \in P : \tau(u, P'_{p(u)}) \subseteq K\} = P'$, so the two constructions are inverse to each other. $\square$

21.15. The bundle of gauges. If (P, p, M, G) is a principal fiber bundle we denote by $\operatorname{Aut}(P)$ the group of all G-equivariant diffeomorphisms $\chi : P \to P$. Then $p \circ \chi = \bar{\chi} \circ p$ for a unique diffeomorphism $\bar{\chi}$ of M, so there is a group homomorphism from $\operatorname{Aut}(P)$ into the group $\operatorname{Diff}(M)$ of all diffeomorphisms of M. The kernel of this homomorphism is called $\operatorname{Gau}(P)$, the group of *gauge transformations*. So $\operatorname{Gau}(P)$ is the space of all $\chi : P \to P$ which satisfy $p \circ \chi = p$ and $\chi(u.g) = \chi(u).g$. A vector field $\xi \in \mathfrak{X}(P)$ is an *infinitesimal gauge transformation* if its flow Fl^ξ_t consists of gauge transformations, i.e., if ξ is vertical and G-invariant, $(r^g)^*\xi = \xi$.

Theorem. *The group $Gau(P)$ of gauge transformations is equal to the space*

$$Gau(P) \cong C^\infty(P, (G, \operatorname{conj}))^G \cong \Gamma(P[G, \operatorname{conj}]).$$

The Lie algebra $\mathfrak{X}_{\text{vert}}(P)^G$ of infinitesimal gauge transformations is equal to the space

$$\mathfrak{X}_{\text{vert}}(P)^G \cong C^\infty(P, (\mathfrak{g}, \operatorname{Ad}))^G \cong \Gamma(P[\mathfrak{g}, \operatorname{Ad}]).$$

Proof. We use again the mapping $\tau : P \times_M P \to G$ from (21.2). For $\chi \in \operatorname{Gau}(P)$ we define $f_\chi \in C^\infty(P, (G, \operatorname{conj}))^G$ by $f_\chi := \tau \circ (Id, \chi)$. Then $f_\chi(u.g) = \tau(u.g, \chi(u.g)) = g^{-1}.\tau(u, \chi(u)).g = \operatorname{conj}_{g^{-1}} f_\chi(u)$, so f_χ is indeed G-equivariant.

If conversely $f \in C^\infty(P, (G, \operatorname{conj}))^G$ is given, we define $\chi_f : P \to P$ by $\chi_f(u) := u.f(u)$. It is easy to check that χ_f is indeed in $\operatorname{Gau}(P)$ and that the two constructions are inverse to each other, namely

$$\begin{aligned}
&\chi_f(ug) = ugf(ug) = ugg^{-1}f(u)g = \chi_f(u)g,\\
&f_{\chi_f}(u) = \tau^G(u, \chi_f(u)) = \tau^G(u, u.f(u)) = \tau^G(u, u)f(u) = f(u),\\
&\chi_{f_\chi}(u) = uf_\chi(u) = u\tau^G(u, \chi(u)) = \chi(u).
\end{aligned}$$

The isomorphism $C^\infty(P, (G, \operatorname{conj}))^G \cong \Gamma(P[G, \operatorname{conj}])$ is a special case of theorem (21.12).

A vertical vector field $\xi \in \mathfrak{X}_{\text{vert}}(P) = \Gamma(VP)$ is given uniquely by a mapping $f_\xi : P \to \mathfrak{g}$ via $\xi(u) = T_e(r_u).f_\xi(u)$, and it is G-equivariant if and only if

$$\begin{aligned}
T_e(r_u).f_\xi(u) = \xi(u) &= ((r^g)^*\xi)(u) = T(r^{g^{-1}}).\xi(u.g)\\
&= T(r^{g^{-1}}).T_e(r_{u.g}).f_\xi(u.g) = T_e(r^{g^{-1}} \circ r_{u.g}).f_\xi(u.g)\\
&= T_e(r_u \circ \operatorname{conj}_g).f_\xi(u.g) = T_e(r_u).\operatorname{Ad}_g .f_\xi(u.g)
\end{aligned}$$

The isomorphism $C^\infty(P, (\mathfrak{g}, \operatorname{Ad}))^G \cong \Gamma(P[\mathfrak{g}, \operatorname{Ad}])$ is again a special case of theorem (21.12). $\square$

21.16. The tangent bundles of homogeneous spaces. Let G be a Lie group and K a closed subgroup, with Lie algebras $\mathfrak{g}$ and $\mathfrak{k}$, respectively. We recall the mapping $\mathrm{Ad}_G : G \to \mathrm{Aut}_{\mathrm{Lie}}(\mathfrak{g})$ from (4.24) and put $\mathrm{Ad}_{G,K} := \mathrm{Ad}_G |K : K \to \mathrm{Aut}_{\mathrm{Lie}}(\mathfrak{g})$. For $X \in \mathfrak{k}$ and $k \in K$ we have $\mathrm{Ad}_{G,K}(k)X = \mathrm{Ad}_G(k)X = \mathrm{Ad}_K(k)X \in \mathfrak{k}$, so $\mathfrak{k}$ is an invariant subspace for the representation $\mathrm{Ad}_{G,K}$ of K in $\mathfrak{g}$, and we have the factor representation $\mathrm{Ad}^\perp : K \to GL(\mathfrak{g}/\mathfrak{k})$. Then

$$0 \to \mathfrak{k} \to \mathfrak{g} \to \mathfrak{g}/\mathfrak{k} \to 0 \tag{1}$$

is short exact and K-equivariant.

Now we consider the principal fiber bundle $(G, p, G/K, K)$ and the associated vector bundles $G[\mathfrak{g}/\mathfrak{k}, \mathrm{Ad}^\perp]$ and $G[\mathfrak{k}, \mathrm{Ad}_K]$.

Theorem. *In these circumstances we have*

$$T(G/K) = G[\mathfrak{g}/\mathfrak{k}, \mathrm{Ad}^\perp] = (G \times_K \mathfrak{g}/\mathfrak{k}, p, G/K, \mathfrak{g}/\mathfrak{k}).$$

The left action $g \mapsto T(\bar\mu_g)$ of G on $T(G/K)$ corresponds to the canonical left action of G on $G \times_K \mathfrak{g}/\mathfrak{k}$. Furthermore $G[\mathfrak{g}/\mathfrak{k}, \mathrm{Ad}^\perp] \oplus G[\mathfrak{k}, \mathrm{Ad}_K]$ is a trivial vector bundle.

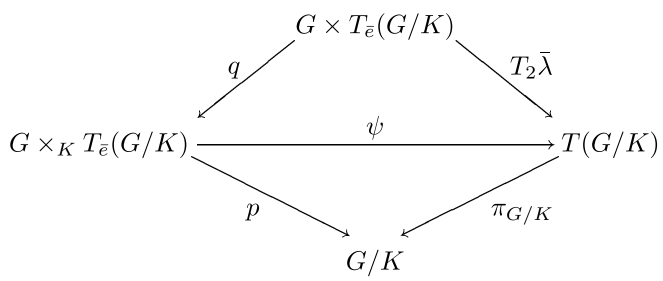
Proof. For $p : G \to G/K$ we consider the tangent mapping $T_e p : \mathfrak{g} \to T_{\bar e}(G/K)$ which is linear and surjective and induces a linear isomorphism $\overline{T_e p} : \mathfrak{g}/\mathfrak{k} \to T_{\bar e}(G/K)$. For $k \in K$ we have $p \circ \mathrm{conj}_k = p \circ \mu_k \circ \mu^{k^{-1}} = \bar\mu_k \circ p$ and consequently $T_e p \circ \mathrm{Ad}_{G,K}(k) = T_e p \circ T_e(\mathrm{conj}_k) = T_{\bar e}\bar\mu_k \circ T_e p$. Thus the isomorphism $\overline{T_e p} : \mathfrak{g}/\mathfrak{k} \to T_{\bar e}(G/K)$ is K-equivariant for the representations $\mathrm{Ad}^\perp$ and $T_{\bar e}\bar\lambda : k \mapsto T_{\bar e}\bar\mu_k$, where, for the moment, we use the notation $\bar\lambda : G \times G/K \to G/K$ for the left action.

Let us now consider the associated vector bundle

$$G[T_{\bar e}(G/K), T_{\bar e}\bar\lambda] = (G \times_K T_{\bar e}(G/K), p, G/K, T_{\bar e}(G/K)),$$

which is isomorphic to the vector bundle $G[\mathfrak{g}/\mathfrak{k}, \mathrm{Ad}^\perp]$, since the representation spaces are isomorphic. The mapping $T_2\bar\lambda : G \times T_{\bar e}(G/K) \to T(G/K)$ (where T_2 is the second partial tangent functor) is K-invariant, since $T_2\bar\lambda((g, X)k) = T_2\bar\lambda(gk, T_{\bar e}\bar\mu_{k^{-1}}.X) = T\bar\mu_{gk}.T\bar\mu_{k^{-1}}.X = T\bar\mu_g.X$. Therefore it induces a mapping ψ as in the following diagram:

(2)



This mapping ψ is an isomorphism of vector bundles.

It remains to show the last assertion. The short exact sequence (1) induces a sequence of vector bundles over G/K:

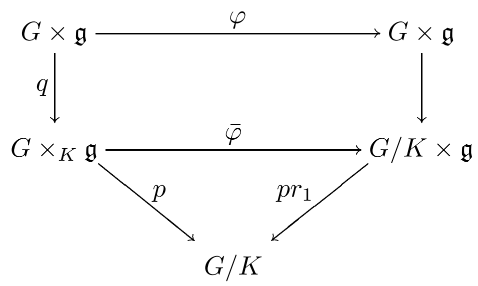
$$G/K \times 0 \to G[\mathfrak{k}, \mathrm{Ad}_K] \to G[\mathfrak{g}, \mathrm{Ad}_{G,K}] \to G[\mathfrak{g}/\mathfrak{k}, \mathrm{Ad}^\perp] \to G/K \times 0$$

This sequence splits fiber wise thus also locally over G/K, so we get $G[\mathfrak{g}/\mathfrak{k}, \mathrm{Ad}^\perp] \oplus G[\mathfrak{k}, \mathrm{Ad}_K] \cong G[\mathfrak{g}, \mathrm{Ad}_{G,K}]$. We have to show that $G[\mathfrak{g}, \mathrm{Ad}_{G,K}]$ is a trivial vector bundle. Let $\varphi : G \times \mathfrak{g} \to G \times \mathfrak{g}$ be given by $\varphi(g, X) = (g, \mathrm{Ad}_G(g)X)$. Then for $k \in K$ we have

$$\begin{aligned} \varphi((g, X).k) &= \varphi(gk, \mathrm{Ad}_{G,K}(k^{-1})X) \\ &= (gk, \mathrm{Ad}_G(g.k.k^{-1})X) = (gk, \mathrm{Ad}_G(g)X). \end{aligned}$$

So φ is K-equivariant for the 'joint' K-action to the 'on the left' K-action and therefore induces a mapping $\bar\varphi$ as in the diagram:

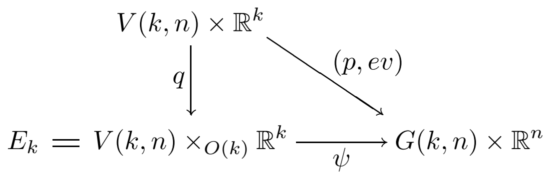
(3)



The map $\bar\varphi$ is a vector bundle isomorphism. □

21.17. Tangent bundles of Grassmann manifolds. From (21.5) we know that $(V(k, n) = O(n)/O(n-k), p, G(k, n), O(k))$ is a principal fiber bundle. Using the standard representation of $O(k)$ we consider the associated vector bundle $(E_k := V(k, n)[\mathbb{R}^k], p, G(k, n))$. Recall from (21.5) the description of $V(k, n)$ as the space of all linear isometries $\mathbb{R}^k \to \mathbb{R}^n$; we get from it the evaluation mapping $ev : V(k, n) \times \mathbb{R}^k \to \mathbb{R}^n$. The mapping (p, ev) in the diagram

(1)



is $O(k)$-invariant for the action R and factors therefore to an embedding of vector bundles $\psi : E_k \to G(k, n) \times \mathbb{R}^n$. So the fiber $(E_k)_W$ over the k-plane W in $\mathbb{R}^n$ is just the linear subspace W. Note finally that the fiber wise orthogonal complement ${E_k}^\perp$ of E_k in the trivial vector bundle $G(k, n) \times \mathbb{R}^n$ with its standard Riemannian metric is isomorphic to the universal vector bundle E_{n-k} over $G(n-k, n)$, where the isomorphism covers the diffeomorphism $G(k, n) \to G(n-k, n)$ given also by the orthogonal complement mapping.

Corollary. *The tangent bundle of the Grassmann manifold is*

$$TG(k, n) \cong L(E_k, {E_k}^\perp).$$

Proof. We have $G(k,n)=O(n)/(O(k)\times O(n-k))$, so by theorem (21.16) we get

$$TG(k,n)=O(n)\underset{O(k)\times O(n-k)}{\times}(\mathfrak{so}(n)/(\mathfrak{so}(k)\times\mathfrak{so}(n-k))).$$

On the other hand we have $V(k,n)=O(n)/O(n-k)$ and the right action of $O(k)$ commutes with the right action of $O(n-k)$ on $O(n)$, therefore

$$V(k,n)[\mathbb{R}^k]=(O(n)/O(n-k))\underset{O(k)}{\times}\mathbb{R}^k=O(n)\underset{O(k)\times O(n-k)}{\times}\mathbb{R}^k,$$

where $O(n-k)$ acts trivially on $\mathbb{R}^k$. We have

$$\begin{aligned} L(E_k,{E_k}^\perp)&=L\left(O(n)\underset{O(k)\times O(n-k)}{\times}\mathbb{R}^k, O(n)\underset{O(k)\times O(n-k)}{\times}\mathbb{R}^{n-k}\right)\\ &=O(n)\underset{O(k)\times O(n-k)}{\times}L(\mathbb{R}^k,\mathbb{R}^{n-k}),\end{aligned}$$

where $O(k)\times O(n-k)$ acts on $L(\mathbb{R}^k,\mathbb{R}^{n-k})$ by $(A,B)(C)=B.C.A^{-1}$. Finally, we have an $O(k)\times O(n-k)$ - equivariant linear isomorphism $L(\mathbb{R}^k,\mathbb{R}^{n-k})\to\mathfrak{so}(n)/(\mathfrak{so}(k)\times\mathfrak{so}(n-k))$, as follows:

$$\mathfrak{so}(n)/(\mathfrak{so}(k)\times\mathfrak{so}(n-k))=\\ \frac{(\text{skew})}{\begin{pmatrix}\text{skew}&0\\0&\text{skew}\end{pmatrix}}=\left\{\begin{pmatrix}0&-A^\top\\A&0\end{pmatrix}:\quad A\in L(\mathbb{R}^k,\mathbb{R}^{n-k})\right\}\quad\square$$

21.18. Tangent bundles and vertical bundles. Let (E,p,M,S) be a fiber bundle. The sub vector bundle $VE=\{\,\xi\in TE:\quad Tp.\xi=0\,\}$ of TE is called the *vertical bundle* and is denoted by (VE,π_E,E).

Theorem. *Let (P,p,M,G) be a principal fiber bundle with principal right action $r:P\times G\to P$. Let $\ell:G\times S\to S$ be a left action. Then the following assertions hold:*

(1) *(TP,Tp,TM,TG) is again a principal fiber bundle with principal right action $Tr:TP\times TG\to TP$, where the structure group TG is the tangent group of G, see* (5.17)*.*
(2) *The vertical bundle $(VP,\pi,P,\mathfrak{g})$ of the principal bundle is trivial as a vector bundle over P: $VP\cong P\times\mathfrak{g}$.*
(3) *The vertical bundle of the principal bundle as bundle over M is again a principal bundle: $(VP,p\circ\pi,M,TG)$.*
(4) *The tangent bundle of the associated bundle $P[S,\ell]$ is given by $T(P[S,\ell])=TP[TS,T\ell]$.*
(5) *The vertical bundle of the associated bundle $P[S,\ell]$ is given by $V(P[S,\ell])=P[TS,T_2\ell]=P\times_G TS$.*

Proof. Let $(U_\alpha, \varphi_\alpha : P|U_\alpha \to U_\alpha \times G)$ be a principal fiber bundle atlas with cocycle of transition functions $(\varphi_{\alpha\beta} : U_{\alpha\beta} \to G)$. Since T is a functor which respects products, $(TU_\alpha, T\varphi_\alpha : TP|TU_\alpha \to TU_\alpha \times TG)$ is again a principal fiber bundle atlas with cocycle of transition functions $(T\varphi_{\alpha\beta} : TU_{\alpha\beta} \to TG)$, describing the principal fiber bundle (TP, Tp, TM, TG). The assertion about the principal action is obvious. So (1) follows. For completeness sake we include here the transition formula for this atlas in the right trivialization of TG:

$$T(\varphi_\alpha \circ \varphi_\beta^{-1})(\xi_x, T_e(\mu^g).X) = (\xi_x, T_e(\mu^{\varphi_{\alpha\beta}(x).g}).(\delta^r\varphi_{\alpha\beta}(\xi_x) + \operatorname{Ad}(\varphi_{\alpha\beta}(x))X)),$$

where $\delta\varphi_{\alpha\beta} \in \Omega^1(U_{\alpha\beta}; \mathfrak{g})$ is the right logarithmic derivative of $\varphi_{\alpha\beta}$, see (4.26).

(2) The mapping $(u, X) \mapsto T_e(r_u).X = T_{(u,e)}r.(0_u, X)$ is a vector bundle isomorphism $P \times \mathfrak{g} \to VP$ over P.

(3) Obviously $Tr : TP \times TG \to TP$ is a free right action which acts transitively on the fibers of $Tp : TP \to TM$. Since $VP = (Tp)^{-1}(0_M)$, the bundle $VP \to M$ is isomorphic to $TP|0_M$ and Tr restricts to a free right action, which is transitive on the fibers, so by lemma (21.3) the result follows.

(4) The transition functions of the fiber bundle $P[S, \ell]$ are given by the expression $\ell \circ (\varphi_{\alpha\beta} \times Id_S) : U_{\alpha\beta} \times S \to G \times S \to S$. Then the transition functions of $T(P[S, \ell])$ are $T(\ell \circ (\varphi_{\alpha\beta} \times Id_S)) = T\ell \circ (T\varphi_{\alpha\beta} \times Id_{TS}) : TU_{\alpha\beta} \times TS \to TG \times TS \to TS$, from which the result follows.

(5) Vertical vectors in $T(P[S, \ell])$ have local representations $(0_x, \eta_s) \in TU_{\alpha\beta} \times TS$. Under the transition functions of $T(P[S, \ell])$ they transform as $T(\ell \circ (\varphi_{\alpha\beta} \times Id_S)).(0_x, \eta_s) = T\ell.(0_{\varphi_{\alpha\beta}(x)}, \eta_s) = T(\ell_{\varphi_{\alpha\beta}(x)}).\eta_s = T_2\ell.(\varphi_{\alpha\beta}(x), \eta_s)$ and this implies the result $\square$

22. Principal and Induced Connections

22.1. Principal connections. Let (P, p, M, G) be a principal fiber bundle. Recall from (20.3) that a (general) connection on P is a fiber projection $\Phi : TP \to VP$, viewed as a 1-form in $\Omega^1(P, TP)$. Such a connection Φ is called a *principal connection* if it is G-equivariant for the principal right action $r : P \times G \to P$, so that $T(r^g).\Phi = \Phi.T(r^g)$ and Φ is r^g-related to itself, or $(r^g)^*\Phi = \Phi$ in the sense of (19.16), for all $g \in G$. By theorem (19.15.6) the curvature $R = \frac{1}{2}.[\Phi, \Phi]$ is then also r^g-related to itself for all $g \in G$.

Recall from (21.18.2) that the vertical bundle of P is trivialized as a vector bundle over P by the principal action. So

(1) $$\omega(X_u) := T_e(r_u)^{-1}.\Phi(X_u) \in \mathfrak{g}$$

and in this way we get a $\mathfrak{g}$-valued 1-form $\omega \in \Omega^1(P, \mathfrak{g})$, which is called the *(Lie algebra valued) connection form* of the connection Φ. Recall from (5.13). the fundamental vector field mapping $\zeta : \mathfrak{g} \to \mathfrak{X}(P)$ for the principal right action given by $\zeta_X(u) = T_e(r_u)X$ which satisfies $T_u(r^g)\zeta_X(u) = \zeta_{\operatorname{Ad}(g^{-1})X}(u.g)$. The defining equation for ω can be written also as $\Phi(X_u) = \zeta_{\omega(X_u)}(u)$.

Lemma. *If $\Phi \in \Omega^1(P, VP)$ is a principal connection on the principal fiber bundle (P, p, M, G) then the connection form has the following two properties:*

(2) *ω reproduces the generators of fundamental vector fields: $\omega(\zeta_X(u)) = X$ for all $X \in \mathfrak{g}$.*

(3) *ω is G-equivariant, $((r^g)^*\omega)(X_u) = \omega(T_u(r^g).X_u) = \operatorname{Ad}(g^{-1}).\omega(X_u)$ for all $g \in G$ and $X_u \in T_uP$. Consequently we have for the Lie derivative $\mathcal{L}_{\zeta_X}\omega = -\operatorname{ad}(X).\omega$.*

Conversely a 1-form $\omega \in \Omega^1(P, \mathfrak{g})$ satisfying (2) defines a connection Φ on P by $\Phi(X_u) = T_e(r_u).\omega(X_u)$, which is a principal connection if and only if (3) is satisfied.

Proof. (2) $T_e(r_u).\omega(\zeta_X(u)) = \Phi(\zeta_X(u)) = \zeta_X(u) = T_e(r_u).X$. Since $T_e(r_u) : \mathfrak{g} \to V_uP$ is an isomorphism, the result follows.

(3) Both directions follow from

$$\begin{aligned} T_e(r_{ug}).\omega(T_u(r^g).X_u) &= \zeta_{\omega(T_u(r^g).X_u)}(ug) = \Phi(T_u(r^g).X_u) \\ T_e(r_{ug}).\operatorname{Ad}(g^{-1}).\omega(X_u) &= \zeta_{\operatorname{Ad}(g^{-1}).\omega(X_u)}(ug) = T_u(r^g).\zeta_{\omega(X_u)}(u) \\ &= T_u(r^g).\Phi(X_u) \quad \square \end{aligned}$$

22.2. Curvature. Let Φ be a principal connection on the principal fiber bundle (P, p, M, G) with connection form $\omega \in \Omega^1(P, \mathfrak{g})$. We already noted in (22.1) that the curvature $R = \frac{1}{2}[\Phi, \Phi]$ is then also G-equivariant, $(r^g)^*R = R$ for all $g \in G$. Since R has vertical values we may again define a $\mathfrak{g}$-valued 2-form $\Omega \in \Omega^2(P, \mathfrak{g})$ by $\Omega(X_u, Y_u) := -T_e(r_u)^{-1}.R(X_u, Y_u)$, which is called the *(Lie algebra-valued) curvature form* of the connection. We also have $R(X_u, Y_u) = -\zeta_{\Omega(X_u, Y_u)}(u)$. We take the negative sign here to get the usual curvature form as in [Kobayashi-Nomizu I, 1963].

We equip the space $\Omega(P, \mathfrak{g})$ of all $\mathfrak{g}$-valued forms on P in a canonical way with the structure of a graded Lie algebra by

$$\begin{aligned} &[\Psi, \Theta]_\wedge(X_1, \dots, X_{p+q}) = \\ &\qquad = \frac{1}{p!\,q!} \sum_\sigma \operatorname{sign}\sigma\, [\Psi(X_{\sigma 1}, \dots, X_{\sigma p}), \Theta(X_{\sigma(p+1)}, \dots, X_{\sigma(p+q)})]_\mathfrak{g} \end{aligned}$$

or equivalently by $[\psi \otimes X, \theta \otimes Y]_\wedge := \psi \wedge \theta \otimes [X, Y]_\mathfrak{g}$. From the latter description it is clear that $d[\Psi, \Theta]_\wedge = [d\Psi, \Theta]_\wedge + (-1)^{\deg \Psi}[\Psi, d\Theta]_\wedge$. In particular for $\omega \in \Omega^1(P, \mathfrak{g})$ we have $[\omega, \omega]_\wedge(X, Y) = 2[\omega(X), \omega(Y)]_\mathfrak{g}$.

Theorem. *The curvature form Ω of a principal connection with connection form ω has the following properties:*

(1) *Ω is horizontal, i.e. it kills vertical vectors.*

(2) *Ω is G-equivariant in the following sense: $(r^g)^*\Omega = \operatorname{Ad}(g^{-1}).\Omega$. Consequently $\mathcal{L}_{\zeta_X}\Omega = -\operatorname{ad}(X).\Omega$.*

(3) *The Maurer-Cartan formula holds: $\Omega = d\omega + \frac{1}{2}[\omega, \omega]_\wedge$.*

Proof. (1) is true for R by (20.4). For (2) we compute as follows:

$$\begin{aligned}T_e(r_{ug}).((r^g)^*\Omega)(X_u,Y_u) &= T_e(r_{ug}).\Omega(T_u(r^g).X_u,T_u(r^g).Y_u) = \\ &= -R_{ug}(T_u(r^g).X_u,T_u(r^g).Y_u) = -T_u(r^g).((r^g)^*R)(X_u,Y_u) = \\ &= -T_u(r^g).R(X_u,Y_u) = T_u(r^g).\zeta_{\Omega(X_u,Y_u)}(u) = \\ &= \zeta_{\operatorname{Ad}(g^{-1}).\Omega(X_u,Y_u)}(ug) = T_e(r_{ug}).\operatorname{Ad}(g^{-1}).\Omega(X_u,Y_u), \quad \text{by (5.13).}\end{aligned}$$

(3) For $X\in\mathfrak g$ we have $i_{\zeta_X}R=0$ by (1), and using (22.1.2) we get

$$\begin{aligned}i_{\zeta_X}(d\omega+\tfrac12[\omega,\omega]_\wedge) &= i_{\zeta_X}d\omega+\tfrac12[i_{\zeta_X}\omega,\omega]_\wedge-\tfrac12[\omega,i_{\zeta_X}\omega]_\wedge = \\ &= \mathcal L_{\zeta_X}\omega+[X,\omega]_\wedge = -\operatorname{ad}(X)\omega+\operatorname{ad}(X)\omega = 0\end{aligned}$$

So the formula holds for vertical vectors, and for horizontal vector fields $\xi,\eta\in\Gamma(H(P))$ we have

$$R(\xi,\eta)=\Phi[\xi-\Phi\xi,\eta-\Phi\eta]=\Phi[\xi,\eta]=\zeta_{\omega([\xi,\eta])}$$
$$(d\omega+\tfrac12[\omega,\omega])(\xi,\eta)=\xi\omega(\eta)-\eta\omega(\xi)-\omega([\xi,\eta])+0=-\omega([\xi,\eta]) \quad \square$$

22.3. Lemma. *Any principal fiber bundle (P,p,M,G) (with paracompact basis) admits principal connections.*

Proof. Let $(U_\alpha,\varphi_\alpha: P|U_\alpha\to U_\alpha\times G)_\alpha$ be a principal fiber bundle atlas. Let us define $\gamma_\alpha(T\varphi_\alpha^{-1}(\xi_x,T_e\mu_g.X)):=X$ for $\xi_x\in T_xU_\alpha$ and $X\in\mathfrak g$. Using lemma (5.13) we get

$$\begin{aligned}((r^h)^*\gamma_\alpha)(T\varphi_\alpha^{-1}(\xi_x,T_e\mu_g.X)) &= \gamma_\alpha(Tr^h.T\varphi_\alpha^{-1}(\xi_x,T_e\mu_g.X)) = \\ &= \gamma_\alpha(T\varphi_\alpha^{-1}(\xi_x,T\mu^h.T_e\mu_g.X)) = \\ &= \gamma_\alpha(T\varphi_\alpha^{-1}(\xi_x,T_e\mu_{gh}.\operatorname{Ad}(h^{-1}).X)) = \operatorname{Ad}(h^{-1}).X,\end{aligned}$$

so that $\gamma_\alpha\in\Omega^1(P|U_\alpha,\mathfrak g)$ satisfies the requirements of lemma (22.1) and thus is a principal connection on $P|U_\alpha$. Now let (f_α) be a smooth partition of unity on M which is subordinated to the open cover (U_α), and let $\omega:=\sum_\alpha(f_\alpha\circ p)\gamma_\alpha$. Since both requirements of lemma (22.1) are invariant under convex linear combinations, ω is a principal connection on P. $\square$

22.4. Local descriptions of principal connections. We consider a principal fiber bundle (P,p,M,G) with some principal fiber bundle atlas $(U_\alpha,\varphi_\alpha: P|U_\alpha\to U_\alpha\times G)$ and corresponding cocycle $(\varphi_{\alpha\beta}:U_{\alpha\beta}\to G)$ of transition functions. We consider the sections $s_\alpha\in\Gamma(P|U_\alpha)$ which are given by $\varphi_\alpha(s_\alpha(x))=(x,e)$ and satisfy $s_\alpha.\varphi_{\alpha\beta}=s_\beta$, since we have in turn:

$$\begin{aligned}\varphi_\alpha(s_\beta(x)) &= \varphi_\alpha\varphi_\beta^{-1}(x,e)=(x,\varphi_{\alpha\beta}(x))\\ s_\beta(x) &= \varphi_\alpha^{-1}(x,e\varphi_{\alpha\beta}(e)),=\varphi_\alpha^{-1}(x,e)\varphi_{\alpha\beta}(x)=s_\alpha(x)\varphi_{\alpha\beta}(x).\end{aligned}$$

(1) Let $\Theta\in\Omega^1(G,\mathfrak g)$ be the left logarithmic derivative of the identity, i.e. $\Theta(\eta_g):=T_g(\mu_{g^{-1}}).\eta_g$. We will use the forms $\Theta_{\alpha\beta}:={\varphi_{\alpha\beta}}^*\Theta\in\Omega^1(U_{\alpha\beta},\mathfrak g)$.

Let $\Phi = \zeta \circ \omega \in \Omega^1(P, VP)$ be a principal connection with connection form $\omega \in \Omega^1(P, \mathfrak{g})$. We may associate the following local data to the connection:

(2) $\omega_\alpha := s_\alpha{}^*\omega \in \Omega^1(U_\alpha, \mathfrak{g})$, the *physicists version* or *Cartan moving frame version* of the connection.

(3) The Christoffel forms $\Gamma^\alpha \in \Omega^1(U_\alpha, \mathfrak{X}(G))$ from (20.7), which are given by $(0_x, \Gamma^\alpha(\xi_x, g)) = -T(\varphi_\alpha).\Phi.T(\varphi_\alpha)^{-1}(\xi_x, 0_g)$.

(4) $\gamma_\alpha := (\varphi_\alpha^{-1})^*\omega \in \Omega^1(U_\alpha \times G, \mathfrak{g})$, the local expressions of ω.

Lemma. *These local data have the following properties and are related by the following formulas.*

(5) *The forms $\omega_\alpha \in \Omega^1(U_\alpha, \mathfrak{g})$ satisfy the transition formulas*

$$\omega_\alpha = \operatorname{Ad}(\varphi_{\beta\alpha}^{-1})\omega_\beta + \Theta_{\beta\alpha},$$

and any set of forms like that with this transition behavior determines a unique principal connection.

(6) *We have $\gamma_\alpha(\xi_x, T\mu_g.X) = \gamma_\alpha(\xi_x, 0_g) + X = \operatorname{Ad}(g^{-1})\omega_\alpha(\xi_x) + X$.*

(7) *We have $\Gamma^\alpha(\xi_x) = -R_{\omega_\alpha(\xi_x)}$, a right invariant vector field, since*

$$\begin{aligned}\Gamma^\alpha(\xi_x, g) &= -T_e(\mu_g).\gamma_\alpha(\xi_x, 0_g) = \\ &= -T_e(\mu_g).\operatorname{Ad}(g^{-1})\omega_\alpha(\xi_x) = -T(\mu^g)\omega_\alpha(\xi_x).\end{aligned}$$

Proof. From the definition of the Christoffel forms we have

$$\begin{aligned}(0_x, \Gamma^\alpha(\xi_x, g)) &= -T(\varphi_\alpha).\Phi.T(\varphi_\alpha)^{-1}(\xi_x, 0_g) \\ &= -T(\varphi_\alpha).T_e(r_{\varphi_\alpha^{-1}(x,g)}).\omega.T(\varphi_\alpha)^{-1}(\xi_x, 0_g) \quad \text{by (22.1.1)} \\ &= -T_e(\varphi_\alpha \circ r_{\varphi_\alpha^{-1}(x,g)})\omega.T(\varphi_\alpha)^{-1}(\xi_x, 0_g) \\ &= -(0_x, T_e(\mu_g)\omega.T(\varphi_\alpha)^{-1}(\xi_x, 0_g)) \\ &= -(0_x, T_e(\mu_g)\gamma_\alpha(\xi_x, 0_g)), \quad \text{by (4)},\end{aligned}$$

where we also used $\varphi_\alpha(r_{\varphi_\alpha^{-1}(x,g)}h) = \varphi_\alpha(\varphi_\alpha^{-1}(x,g)h) = \varphi_\alpha(\varphi_\alpha^{-1}(x,gh)) = (x,gh)$. This is the first part of (7). The second part follows from (6).

$$\begin{aligned}\gamma_\alpha(\xi_x, T\mu_g.X) &= \gamma_\alpha(\xi_x, 0_g) + \gamma_\alpha(0_x, T\mu_g.X) \\ &= \gamma_\alpha(\xi_x, 0_g) + \omega(T(\varphi_\alpha)^{-1}(0_x, T\mu_g.X)) \\ &= \gamma_\alpha(\xi_x, 0_g) + \omega(\zeta_X(\varphi_\alpha^{-1}(x,g))) \\ &= \gamma_\alpha(\xi_x, 0_g) + X.\end{aligned}$$

So the first part of (6) holds. The second part is seen from

$$\begin{aligned}\gamma_\alpha(\xi_x, 0_g) &= \gamma_\alpha(\xi_x, T_e(\mu^g)0_e) = (\omega \circ T(\varphi_\alpha)^{-1} \circ T(Id_X \times \mu^g))(\xi_x, 0_e) = \\ &= (\omega \circ T(r^g \circ \varphi_\alpha^{-1}))(\xi_x, 0_e) = \operatorname{Ad}(g^{-1})\omega(T(\varphi_\alpha^{-1})(\xi_x, 0_e)) \\ &= \operatorname{Ad}(g^{-1})(s_\alpha{}^*\omega)(\xi_x) = \operatorname{Ad}(g^{-1})\omega_\alpha(\xi_x).\end{aligned}$$

Via (7) the transition formulas for the ω_α are easily seen to be equivalent to the transition formulas for the Christoffel forms in lemma (20.7). A direct proof goes as follows: We have $s_\alpha(x) = s_\beta(x)\varphi_{\beta\alpha}(x) = r(s_\beta(x), \varphi_{\beta\alpha}(x))$ and thus

$$\begin{aligned}
\omega_\alpha(\xi_x) &= \omega(T_x(s_\alpha).\xi_x)\\
&= (\omega \circ T_{(s_\beta(x),\varphi_{\beta\alpha}(x))}r)((T_x s_\beta.\xi_x, 0_{\varphi_{\beta\alpha}(x)}) + (0_{s_\beta}(x), T_x\varphi_{\beta\alpha}.\xi_x))\\
&= \omega(T(r^{\varphi_{\beta\alpha}(x)}).T_x(s_\beta).\xi_x) + \omega(T_{\varphi_{\beta\alpha}(x)}(r_{s_\beta(x)}).T_x(\varphi_{\beta\alpha}).\xi_x)\\
&= \operatorname{Ad}(\varphi_{\beta\alpha}(x)^{-1})\omega(T_x(s_\beta).\xi_x)\\
&\qquad + \omega(T_{\varphi_{\beta\alpha}(x)}(r_{s_\beta(x)}).T(\mu_{\varphi_{\beta\alpha}(x)} \circ \mu_{\varphi_{\beta\alpha}(x)^{-1}})T_x(\varphi_{\beta\alpha}).\xi_x)\\
&= \operatorname{Ad}(\varphi_{\beta\alpha}(x)^{-1})\omega_\beta(\xi_x)\\
&\qquad + \omega(T_e(r_{s_\beta(x)\varphi_{\beta\alpha}(x)}).\Theta_{\beta\alpha}.\xi_x)\\
&= \operatorname{Ad}(\varphi_{\beta\alpha}(x)^{-1})\omega_\beta(\xi_x) + \Theta_{\beta\alpha}(\xi_x). \quad \square
\end{aligned}$$

22.5. The covariant derivative. Let (P, p, M, G) be a principal fiber bundle with principal connection $\Phi = \zeta \circ \omega$. We consider the horizontal projection $\chi = Id_{TP} - \Phi : TP \to HP$, cf. (20.3), which satisfies $\chi \circ \chi = \chi$, $\operatorname{im} \chi = HP$, $\ker \chi = VP$, and $\chi \circ T(r^g) = T(r^g) \circ \chi$ for all $g \in G$.

If W is a finite dimensional vector space, we consider the mapping $\chi^* : \Omega(P, W) \to \Omega(P, W)$ which is given by

$$(\chi^*\varphi)_u(X_1, \dots, X_k) = \varphi_u(\chi(X_1), \dots, \chi(X_k)).$$

The mapping χ^* is a projection onto the subspace of *horizontal differential forms*, i.e. the space $\Omega_{hor}(P, W) := \{\psi \in \Omega(P, W) : i_X\psi = 0 \text{ for } X \in VP\}$. The notion of horizontal form is independent of the choice of a connection.

The projection χ^* has the following properties: $\chi^*(\varphi \wedge \psi) = \chi^*\varphi \wedge \chi^*\psi$ if one of the two forms has values in $\mathbb{R}$; $\chi^* \circ \chi^* = \chi^*$; $\chi^* \circ (r^g)^* = (r^g)^* \circ \chi^*$ for all $g \in G$; $\chi^*\omega = 0$; and $\chi^* \circ \mathcal{L}(\zeta_X) = \mathcal{L}(\zeta_X) \circ \chi^*$. They follow easily from the corresponding properties of χ, the last property uses that $\mathrm{Fl}_t^{\zeta(X)} = r^{\exp tX}$.

We define the *covariant exterior derivative* $d_\omega : \Omega^k(P, W) \to \Omega^{k+1}(P, W)$ by the prescription $d_\omega := \chi^* \circ d$.

Theorem. *The covariant exterior derivative d_ω has the following properties.*

(1) $d_\omega(\varphi \wedge \psi) = d_\omega(\varphi) \wedge \chi^*\psi + (-1)^{\deg \varphi}\chi^*\varphi \wedge d_\omega(\psi)$ *if φ or ψ is real valued.*
(2) $\mathcal{L}(\zeta_X) \circ d_\omega = d_\omega \circ \mathcal{L}(\zeta_X)$ *for each $X \in \mathfrak{g}$.*
(3) $(r^g)^* \circ d_\omega = d_\omega \circ (r^g)^*$ *for each $g \in G$.*
(4) $d_\omega \circ p^* = d \circ p^* = p^* \circ d : \Omega(M, W) \to \Omega_{hor}(P, W)$.
(5) $d_\omega\omega = \Omega$, *the curvature form.*
(6) $d_\omega\Omega = 0$, *the Bianchi identity.*
(7) $d_\omega \circ \chi^* - d_\omega = \chi^* \circ i(R)$, *where R is the curvature.*
(8) $d_\omega \circ d_\omega = \chi^* \circ i(R) \circ d$.

(9) *Let* $\Omega_{\text{hor}}(P,\mathfrak{g})^G$ *be the algebra of all horizontal* G*-equivariant* $\mathfrak{g}$*-valued forms, i.e.* $(r^g)^*\psi = Ad(g^{-1})\psi$. *Then for any* $\psi \in \Omega_{\text{hor}}(P,\mathfrak{g})^G$ *we have* $d_\omega\psi = d\psi + [\omega,\psi]_\wedge$.

(10) *The mapping* $\psi \mapsto \zeta_\psi$, *where* $\zeta_\psi(X_1,\dots,X_k)(u) = \zeta_{\psi(X_1,\dots,X_k)(u)}(u)$, *is an isomorphism between* $\Omega_{\text{hor}}(P,\mathfrak{g})^G$ *and the algebra* $\Omega_{\text{hor}}(P,VP)^G$ *of all horizontal* G*-equivariant forms with values in the vertical bundle* VP. *Then we have* $\zeta_{d_\omega\psi} = -[\Phi,\zeta_\psi]$.

Proof. (1) through (4) follow from the properties of χ^*.

(5) We have

$$\begin{aligned}(d_\omega\omega)(\xi,\eta) &= (\chi^* d\omega)(\xi,\eta) = d\omega(\chi\xi,\chi\eta)\\ &= (\chi\xi)\omega(\chi\eta) - (\chi\eta)\omega(\chi\xi) - \omega([\chi\xi,\chi\eta])\\ &= -\omega([\chi\xi,\chi\eta]) \text{ and}\\ -\zeta(\Omega(\xi,\eta)) &= R(\xi,\eta) = \Phi[\chi\xi,\chi\eta] = \zeta_{\omega([\chi\xi,\chi\eta])}.\end{aligned}$$

(6) Using (22.2) we have

$$\begin{aligned}d_\omega\Omega &= d_\omega(d\omega + \tfrac{1}{2}[\omega,\omega]_\wedge)\\ &= \chi^* dd\omega + \tfrac{1}{2}\chi^* d[\omega,\omega]_\wedge\\ &= \tfrac{1}{2}\chi^*([d\omega,\omega]_\wedge - [\omega,d\omega]_\wedge) = \chi^*[d\omega,\omega]_\wedge\\ &= [\chi^* d\omega,\chi^*\omega]_\wedge = 0, \text{ since } \chi^*\omega = 0.\end{aligned}$$

(7) For $\varphi \in \Omega(P,W)$ we have

$$\begin{aligned}(d_\omega\chi^*\varphi)(X_0,\dots,X_k) &= (d\chi^*\varphi)(\chi(X_0),\dots,\chi(X_k))\\ &= \sum_{0\le i\le k}(-1)^i\chi(X_i)((\chi^*\varphi)(\chi(X_0),\dots,\widehat{\chi(X_i)},\dots,\chi(X_k)))\\ &\quad+\sum_{i<j}(-1)^{i+j}(\chi^*\varphi)([\chi(X_i),\chi(X_j)],\chi(X_0),\dots\\ &\qquad\qquad\dots,\widehat{\chi(X_i)},\dots,\widehat{\chi(X_j)},\dots)\\ &= \sum_{0\le i\le k}(-1)^i\chi(X_i)(\varphi(\chi(X_0),\dots,\widehat{\chi(X_i)},\dots,\chi(X_k)))\\ &\quad+\sum_{i<j}(-1)^{i+j}\varphi([\chi(X_i),\chi(X_j)]-\Phi[\chi(X_i),\chi(X_j)],\chi(X_0),\dots\\ &\qquad\qquad\dots,\widehat{\chi(X_i)},\dots,\widehat{\chi(X_j)},\dots)\\ &= (d\varphi)(\chi(X_0),\dots,\chi(X_k)) + (i_R\varphi)(\chi(X_0),\dots,\chi(X_k))\\ &= (d_\omega + \chi^* i_R)(\varphi)(X_0,\dots,X_k).\end{aligned}$$

(8) $d_\omega d_\omega = \chi^* d\chi^* d = (\chi^* i_R + \chi^* d)d = \chi^* i_R d$ holds by (7).

(9) If we insert one vertical vector field, say ζ_X for $X \in \mathfrak{g}$, into $d_\omega\psi$, we get 0 by definition. For the right hand side we use $i_{\zeta_X}\psi = 0$ and $\mathcal{L}_{\zeta_X}\psi = \frac{\partial}{\partial t}\big|_0 (\mathrm{Fl}^{\zeta_X}_t)^*\psi = \frac{\partial}{\partial t}\big|_0 (r^{\exp tX}) * \psi = \frac{\partial}{\partial t}\big|_0 \mathrm{Ad}(\exp(-tX))\psi = -ad(X)\psi$ to get

$$\begin{aligned} i_{\zeta_X}(d\psi + [\omega,\psi]_\wedge) &= i_{\zeta_X}d\psi + di_{\zeta_X}\psi + [i_{\zeta_X}\omega,\psi] - [\omega, i_{\zeta_X}\psi] \\ &= \mathcal{L}_{\zeta_X}\psi + [X,\psi] = -ad(X)\psi + [X,\psi] = 0. \end{aligned}$$

Let now all vector fields ξ_i be horizontal, then we get

$$\begin{aligned} (d_\omega\psi)(\xi_0,\dots,\xi_k) = (\chi^* d\psi)(\xi_0,\dots,\xi_k) = d\psi(\xi_0,\dots,\xi_k), \\ (d\psi + [\omega,\psi]_\wedge)(\xi_0,\dots,\xi_k) = d\psi(\xi_0,\dots,\xi_k). \end{aligned}$$

So the first formula holds.

(10) We proceed in a similar manner. Let Ψ be in the space $\Omega^\ell_{\mathrm{hor}}(P,VP)^G$ of all horizontal G-equivariant forms with vertical values. Then for each $X \in \mathfrak{g}$ we have $i_{\zeta_X}\Psi = 0$; furthermore the G-equivariance $(r^g)^*\Psi = \Psi$ implies that $\mathcal{L}_{\zeta_X}\Psi = [\zeta_X,\Psi] = 0$ by (19.16.5). Using formula (19.11.2) we have

$$\begin{aligned} i_{\zeta_X}[\Phi,\Psi] &= [i_{\zeta_X}\Phi,\Psi] - [\Phi, i_{\zeta_X}\Psi] + i([\Phi,\zeta_X])\Psi + i([\Psi,\zeta_X])\Phi \\ &= [\zeta_X,\Psi] - 0 + 0 + 0 = 0. \end{aligned}$$

Let now all vector fields ξ_i again be horizontal, then from the huge formula (19.9) for the Frölicher-Nijenhuis bracket only the following terms in the third and fifth line survive:

$$\begin{aligned} &[\Phi,\Psi](\xi_1,\dots,\xi_{\ell+1}) = \\ &\quad = \tfrac{(-1)^\ell}{\ell!}\sum_\sigma \operatorname{sign}\sigma\ \Phi([\Psi(\xi_{\sigma 1},\dots,\xi_{\sigma\ell}),\xi_{\sigma(\ell+1)}]) \\ &\quad\quad + \tfrac{1}{(\ell-1)!\,2!}\sum_\sigma \operatorname{sign}\sigma\ \Phi(\Psi([\xi_{\sigma1},\xi_{\sigma2}],\xi_{\sigma3},\dots,\xi_{\sigma(\ell+1)}). \end{aligned}$$

For $f : P \to \mathfrak{g}$ and horizontal ξ we have $\Phi[\xi,\zeta_f] = \zeta_{\xi(f)} = \zeta_{df(\xi)}$: It is $C^\infty(P)$-linear in ξ; or imagine it in local coordinates. So the last expression becomes

$$-\zeta(d_\omega\psi(\xi_0,\dots,\xi_k)) = -\zeta(d\psi(\xi_0,\dots,\xi_k)) = -\zeta((d\psi + [\omega,\psi]_\wedge)(\xi_0,\dots,\xi_k))$$

as required. $\square$

22.6. Theorem. *Let (P,p,M,G) be a principal fiber bundle with principal connection ω. Then the parallel transport for the principal connection is globally defined and G-equivariant.*

In detail: For each smooth curve $c : \mathbb{R} \to M$ there is a smooth mapping $\mathrm{Pt}_c : \mathbb{R} \times P_{c(0)} \to P$ such that the following holds:

1. $\mathrm{Pt}(c,t,u) \in P_{c(t)}$, $\mathrm{Pt}(c,0) = Id_{P_{c(0)}}$, *and* $\omega(\frac{d}{dt}\mathrm{Pt}(c,t,u)) = 0$.
2. $\mathrm{Pt}(c,t) : P_{c(0)} \to P_{c(t)}$ *is G-equivariant, i.e.* $\mathrm{Pt}(c,t,u.g) = \mathrm{Pt}(c,t,u).g$ *holds for all $g \in G$ and $u \in P$. Moreover we have* $\mathrm{Pt}(c,t)^*(\zeta_X|P_{c(t)}) = \zeta_X|P_{c(0)}$ *for all $X \in \mathfrak{g}$.*
3. *For any smooth function $f : \mathbb{R} \to \mathbb{R}$ we have*
   $\mathrm{Pt}(c,f(t),u) = \mathrm{Pt}(c\circ f, t, \mathrm{Pt}(c,f(0),u))$.

Proof. By (22.4) the Christoffel forms $\Gamma^\alpha \in \Omega^1(U_\alpha, \mathfrak{X}(G))$ of the connection ω with respect to a principal fiber bundle atlas $(U_\alpha, \varphi_\alpha)$ are given by $\Gamma^\alpha(\xi_x) = R_{\omega_\alpha(\xi_x)}$, so they take values in the Lie subalgebra $\mathfrak{X}_R(G)$ of all right invariant vector fields on G, which are bounded with respect to any right invariant Riemannian metric on G. Each right invariant metric on a Lie group is complete. So the connection is complete by the remark in (14.9).

Properties (1) and (3) follow from theorem (20.8), and (2) is seen as follows: $\omega(\frac{d}{dt}\operatorname{Pt}(c,t,u).g) = \operatorname{Ad}(g^{-1})\omega(\frac{d}{dt}\operatorname{Pt}(c,t,u)) = 0$ implies $\operatorname{Pt}(c,t,u).g = \operatorname{Pt}(c,t,u.g)$. For the second assertion we compute for $u \in P_{c(0)}$:

$$\begin{aligned}\operatorname{Pt}(c,t)^*(\zeta_X|P_{c(t)})(u) &= T\operatorname{Pt}(c,t)^{-1}\zeta_X(\operatorname{Pt}(c,t,u))\\ &= T\operatorname{Pt}(c,t)^{-1}\tfrac{d}{ds}|_0\operatorname{Pt}(c,t,u).\exp(sX)\\ &= T\operatorname{Pt}(c,t)^{-1}\tfrac{d}{ds}|_0\operatorname{Pt}(c,t,u.\exp(sX))\\ &= \tfrac{d}{ds}|_0\operatorname{Pt}(c,t)^{-1}\operatorname{Pt}(c,t,u.\exp(sX))\\ &= \tfrac{d}{ds}|_0 u.\exp(sX) = \zeta_X(u). \quad \square\end{aligned}$$

22.7. Holonomy groups. Let (P,p,M,G) be a principal fiber bundle with principal connection $\Phi = \zeta \circ \omega$. We assume that M is connected and we fix $x_0 \in M$.

In (20.10) we defined the holonomy group $\operatorname{Hol}(\Phi, x_0) \subset \operatorname{Diff}(P_{x_0})$ as the group of all $\operatorname{Pt}(c,1) : P_{x_0} \to P_{x_0}$ for c any piecewise smooth closed loop through x_0. (Reparametrizing c by a function which is flat at each corner of c we may assume that any c is smooth.) If we consider only those curves c which are nullhomotopic, we obtain the restricted holonomy group $\operatorname{Hol}_0(\Phi, x_0)$, a normal subgroup.

Now let us fix $u_0 \in P_{x_0}$. The elements $\tau(u_0, \operatorname{Pt}(c,t,u_0)) \in G$ form a subgroup of the structure group G which is isomorphic to $\operatorname{Hol}(\Phi, x_0)$; we denote it by $\operatorname{Hol}(\omega, u_0)$ and we call it also the *holonomy group* of the connection. Considering only nullhomotopic curves we get the *restricted holonomy group* $\operatorname{Hol}_0(\omega, u_0)$ a normal subgroup of $\operatorname{Hol}(\omega, u_0)$.

Theorem.

(1) *We have an isomorphism* $\operatorname{Hol}(\omega, u_0) \to \operatorname{Hol}(\Phi, x_0)$ *given by* $g \mapsto (u \mapsto f_g(u) = u_0.g.\tau(u_0, u))$ *with inverse* $g_f := \tau(u_0, f(u_0)) \leftarrow f$.

(2) *We have* $\operatorname{Hol}(\omega, u_0.g) = \operatorname{conj}(g^{-1})\operatorname{Hol}(\omega, u_0)$ *and* $\operatorname{Hol}_0(\omega, u_0.g) = \operatorname{conj}(g^{-1})\operatorname{Hol}_0(\omega, u_0)$.

(3) *For each curve c with $c(0) = x_0$ we have* $\operatorname{Hol}(\omega, \operatorname{Pt}(c,t,u_0)) = \operatorname{Hol}(\omega, u_0)$ *and* $\operatorname{Hol}_0(\omega, \operatorname{Pt}(c,t,u_0)) = \operatorname{Hol}_0(\omega, u_0)$.

(4) *The restricted holonomy group* $\operatorname{Hol}_0(\omega, u_0)$ *is a connected Lie subgroup of G. The quotient group* $\operatorname{Hol}(\omega, u_0)/\operatorname{Hol}_0(\omega, u_0)$ *is at most countable, so* $\operatorname{Hol}(\omega, u_0)$ *is also a Lie subgroup of G.*

(5) *The Lie algebra* $\operatorname{hol}(\omega, u_0) \subset \mathfrak{g}$ *of* $\operatorname{Hol}(\omega, u_0)$ *is generated by* $\{\Omega(X_u, Y_u) : X_u, Y_u \in T_uP\}$ *as a vector space. It is isomorphic to the Lie algebra* $\operatorname{hol}(\Phi, x_0)$ *we considered in* (20.10).

(6) *For* $u_0 \in P_{x_0}$ *let* $P(\omega, u_0)$ *be the set of all* $\mathrm{Pt}(c, t, u_0)$ *for* c *any (piecewise) smooth curve in* M *with* $c(0) = x_0$ *and for* $t \in \mathbb{R}$*. Then* $P(\omega, u_0)$ *is a sub fiber bundle of* P *which is invariant under the right action of* $\mathrm{Hol}(\omega, u_0)$*; so it is itself a principal fiber bundle over* M *with structure group* $\mathrm{Hol}(\omega, u_0)$ *and we have a reduction of structure group, cf.* (21.6) *and* (21.14)*. The pullback of* ω *to* $P(\omega, u_0)$ *is then again a principal connection form* $i^*\omega \in \Omega^1(P(\omega, u_0); \mathrm{hol}(\omega, u_0))$*.*

(7) P *is foliated by the leaves* $P(\omega, u)$*,* $u \in P_{x_0}$*.*

(8) *If the curvature* $\Omega = 0$ *then* $\mathrm{Hol}_0(\omega, u_0) = \{e\}$ *and each* $P(\omega, u)$ *is a covering of* M*. They are all isomorphic and are associated to the universal covering of* M*, which is a principal fiber bundle with structure group the fundamental group* $\pi_1(M)$*.*

In view of assertion (6) a principal connection ω is called *irreducible *-principle connection* if $\mathrm{Hol}(\omega, u_0)$ equals the structure group G for some (equivalently any) $u_0 \in P_{x_0}$.

Proof. (1) follows from the definiton of $\mathrm{Hol}(\omega, u_0)$.

(2) This follows from the properties of the mapping τ from (21.2) and from the from the G-equivariance of the parallel transport:

$$\tau(u_0.g, \mathrm{Pt}(c, 1, u_0.g)) = \tau(u_0, \mathrm{Pt}(c, 1, u_0).g) = g^{-1}.\tau(u_0, \mathrm{Pt}(c, 1, u_0)).g.$$

So via the diffeomorphism $\tau(u_0, \quad) : P_{x_0} \to G$ the action of the holonomy group $\mathrm{Hol}(\Phi, u_0)$ on P_{x_0} is conjugate to the left translation of $\mathrm{Hol}(\omega, u_0)$ on G.

(3) By reparameterizing the curve c we may assume that $t = 1$, and we put $\mathrm{Pt}(c, 1, u_0) =: u_1$. Then by definition for an element $g \in G$ we have $g \in \mathrm{Hol}(\omega, u_1)$ if and only if $g = \tau(u_1, \mathrm{Pt}(e, 1, u_1))$ for some closed smooth loop e through $x_1 := c(1) = p(u_1)$, i. e.

$$\begin{aligned} \mathrm{Pt}(c, 1)(u_0.g) = \mathrm{Pt}(c, 1)(r^g(u_0)) = r^g(\mathrm{Pt}(c, 1)(u_0)) = u_1 g = \mathrm{Pt}(e, 1)(\mathrm{Pt}(c, 1)(u_0)) \\ u_0.g = \mathrm{Pt}(c, 1)^{-1}\,\mathrm{Pt}(e, 1)\,\mathrm{Pt}(c, 1)(u_0) = \mathrm{Pt}(c.e.c^{-1}, 3)(u_0), \end{aligned}$$

where $c.e.c^{-1}$ is the curve travelling along $c(t)$ for $0 \le t \le 1$, along $e(t-1)$ for $1 \le t \le 2$, and along $c(3-t)$ for $2 \le t \le 3$. This is equivalent to $g \in \mathrm{Hol}(\omega, u_0)$. Furthermore e is nullhomotopic if and only if $c.e.c^{-1}$ is nullhomotopic, so we also have $\mathrm{Hol}_0(\omega, u_1) = \mathrm{Hol}_0(\omega, u_0)$.

(4) Let $c : [0, 1] \to M$ be a nullhomotopic curve through x_0 and let $h : \mathbb{R}^2 \to M$ be a smooth homotopy with $h_1|[0, 1] = c$ and $h(0, s) = h(t, 0) = h(t, 1) = x_0$. We consider the pullback bundle

$$\begin{array}{ccc} h^*P & \xrightarrow{\;p^*h\;} & P \\ {\scriptstyle h^*p}\downarrow & & \downarrow{\scriptstyle p} \\ \mathbb{R}^2 & \xrightarrow{\;h\;} & M. \end{array}$$

Then for the parallel transport Pt^Φ on P and for the parallel transport $\operatorname{Pt}^{h^*\Phi}$ of the pulled back connection we have

$$\operatorname{Pt}^\Phi(h_t,1,u_0) = (p^*h)\operatorname{Pt}^{h^*\Phi}((t,\quad),1,u_0) = (p^*h)\operatorname{Fl}_1^{C^{h^*\Phi}\partial_s}(t,u_0).$$

So $t\mapsto\tau(u_0,\operatorname{Pt}^\Phi(h_t,1,u_0))$ is a smooth curve in the Lie group G starting from e, so $\operatorname{Hol}_0(\omega,u_0)$ is an arcwise connected subgroup of G. By the theorem of Yamabe (which we mentioned without proof in (5.6)) the subgroup $\operatorname{Hol}_0(\omega,u_0)$ is a Lie subgroup of G. The quotient group $\operatorname{Hol}(\omega,u_0)/\operatorname{Hol}_0(\omega,u_0)$ is a countable group, since by Morse theory M is homotopy equivalent to a countable CW-complex, so the fundamental group $\pi_1(M)$ is countably generated, thus countable.

(5) Note first that for $g\in G$ and $X\in\mathfrak{X}(M)$ we have for the horizontal lift $(r^g)^*CX = CX$, since $(r^g)^*\Phi=\Phi$ implies $T_u(r^g).H_uP = H_{u.g}P$ and thus

$$\begin{aligned}T_u(r^g).C(X,u) &= T_u(r^g).(T_up|H_uP)^{-1}(X(p(u)))\\ &= (T_{u.g}p|H_{u.g}P)^{-1}(X(p(u))) = C(X,u.g).\end{aligned}$$

Thus $\operatorname{hol}(\omega)$ is an ideal in the Lie algebra $\mathfrak{g}$, since

$$\begin{aligned}\operatorname{Ad}(g^{-1})\Omega(C(X,u),C(Y,u)) &= \Omega(T_u(r^g).C(X,u),T_u(r^g).C(Y,u))\\ &= \Omega(C(X,u.g),C(Y,u.g))\in\operatorname{hol}(\omega).\end{aligned}$$

We consider now the mapping

$$\begin{gathered}\xi^{u_0}:\operatorname{hol}(\omega)\to\mathfrak{X}(P_{x_0})\\ \xi^{u_0}_X(u) = \zeta_{\operatorname{Ad}(\tau(u_0,u)^{-1})X}(u).\end{gathered}$$

It turns out that $\xi^{u_0}_X$ is related to the right invariant vector field R_X on G under the diffeomorphism $\tau(u_0,\quad) = (r_{u_0})^{-1}:P_{x_0}\to G$, since we have

$$\begin{aligned}T_g(r_{u_0}).R_X(g) &= T_g(r_{u_0}).T_e(\mu^g).X = T_{u_0}(r^g).T_e(r_{u_0}).X\\ &= T_{u_0}(r^g)\zeta_X(u_0) = \zeta_{\operatorname{Ad}(g^{-1})X}(u_0.g) = \xi^{u_0}_X(u_0.g).\end{aligned}$$

Thus ξ^{u_0} is a Lie algebra anti homomorphism, and each vector field $\xi^{u_0}_X$ on P_{x_0} is complete. The dependence of ξ^{u_0} on u_0 is explained by

$$\begin{aligned}\xi^{u_0g}_X(u) &= \zeta_{\operatorname{Ad}(\tau(u_0g,u)^{-1})X}(u) = \zeta_{\operatorname{Ad}(\tau(u_0,u)^{-1})\operatorname{Ad}(g)X}(u)\\ &= \xi^{u_0}_{\operatorname{Ad}(g)X}(u).\end{aligned}$$

Recall now that the holonomy Lie algebra $\operatorname{hol}(\Phi,x_0)$ is the closed linear span of all vector fields of the form $\operatorname{Pt}(c,1)^*R(CX,CY)$, where $X,Y\in T_xM$ and c is a curve from x_0 to x. Then we have for $u=\operatorname{Pt}(c,1,u_0)$

$$\begin{aligned}R(C(X,u),C(Y,u)) &= \zeta_{\Omega(C(X,u),C(Y,u))}(u)\\ R(CX,CY)(ug) &= T(r^g)R(CX,CY)(u) = T(r^g)\zeta_{\Omega(C(X,u),C(Y,u))}(u)\\ &= \zeta_{\operatorname{Ad}(g^{-1})\Omega(C(X,u),C(Y,u))}(ug) = \xi^u_{\Omega(C(X,u),C(Y,u))}(ug)\\ (\operatorname{Pt}(c,1)^*R(CX,CY))(u_0.g) &=\\ &= T(\operatorname{Pt}(c,1)^{-1})\zeta_{\operatorname{Ad}(g^{-1})\Omega(C(X,u),C(Y,u))}(\operatorname{Pt}(c,1,u_0.g))\\ &= (\operatorname{Pt}(c,1)^*\zeta_{\operatorname{Ad}(g^{-1})\Omega(C(X,u),C(Y,u))})(u_0.g)\\ &= \zeta_{\operatorname{Ad}(g^{-1})\Omega(C(X,u),C(Y,u))}(u_0.g) \qquad \text{by (22.6.2)}\\ &= \xi^{u_0}_{\Omega(C(X,u),C(Y,u))}(u_0.g).\end{aligned}$$

So $\xi^{u_0} : \mathrm{hol}(\omega) \to \mathrm{hol}(\Phi, x_0)$ is a Lie algebra anti isomorphism. Moreover $\mathrm{hol}(\Phi, x_0)$ consists of complete vector fields and we may apply theorem (20.11) (only claim 3) which tells us that the Lie algebra of the Lie group $\mathrm{Hol}(\Phi, x_0)$ is $\mathrm{hol}(\Phi, x_0)$. The diffeomorphism $\tau(u_0, \quad) : P_{x_0} \to G$ intertwines the actions and the infinitesimal actions in the right way.

(6) We define the sub vector bundle $E \subset TP$ by $E_u := H_uP + T_e(r_u).\,\mathrm{hol}(\omega)$. From the proof of 4 it follows that $\xi^{u_0}_X$ are sections of E for each $X \in \mathrm{hol}(\omega)$, thus E is a vector bundle. Any vector field $\eta \in \mathfrak{X}(P)$ with values in E is a linear combination with coefficients in $C^\infty(P)$ of horizontal vector fields CX for $X \in \mathfrak{X}(M)$ and of ζ_Z for $Z \in \mathrm{hol}(\omega)$. Their Lie brackets are in turn

$$\begin{aligned}
[CX, CY](u) &= C[X, Y](u) + R(CX, CY)(u)\\
&= C[X, Y](u) + \zeta_{\Omega(C(X,u),C(Y,u))}(u) \in \Gamma(E)\\
[\zeta_Z, CX] &= \mathcal{L}_{\zeta_Z} CX = \tfrac{d}{dt}|_0 (\mathrm{Fl}^{\zeta_Z}_t)^* CX = 0,
\end{aligned}$$

since $(r^g)^* CX = CX$, see step (5) above. So E is an integrable subbundle and induces a foliation by (3.28.2). Let $L(u_0)$ be the leaf of the foliation through u_0. Since for a curve c in M the parallel transport $\mathrm{Pt}(c, t, u_0)$ is tangent to the leaf, we have $P(\omega, u_0) \subseteq L(u_0)$. By definition the holonomy group $\mathrm{Hol}(\Phi, x_0)$ acts transitively and freely on $P(\omega, u_0) \cap P_{x_0}$, and by (5) the restricted holonomy group $\mathrm{Hol}_0(\Phi, x_0)$ acts transitively on each connected component of $L(u_0) \cap P_{x_0}$, since the vertical part of E is spanned by the generating vector fields of this action. This is true for any fiber since we may conjugate the holonomy groups by a suitable parallel transport to each fiber. Thus $P(\omega, u_0) = L(u_0)$ and by lemma (21.2) the sub fiber bundle $P(\omega, x_0)$ is a principal fiber bundle with structure group $\mathrm{Hol}(\omega, u_0)$. Since all horizontal spaces H_uP with $u \in P(\omega, x_0)$ are tangential to $P(\omega, x_0)$, the connection Φ restricts to a principal connection on $P(\omega, x_0)$ and we obtain the looked for reduction of the structure group.

(7) This is obvious from the proof of (6).

(8) If the curvature Ω is everywhere 0, the holonomy Lie algebra is zero, so $P(\omega, u)$ is a principal fiber bundle with discrete structure group, $p|P(\omega, u) : P(\omega, u) \to M$ is a local diffeomorphism, since $T_uP(\omega, u) = H_uP$ and Tp is invertible on it. By the right action of the structure group we may translate each local section of p to any point of the fiber, so p is a covering map. Parallel transport defines a group homomorphism $\varphi : \pi_1(M, x_0) \to \mathrm{Hol}(\Phi, u_0) \cong \mathrm{Hol}(\omega, u_0)$ (see the proof of (4)). Let $\tilde M$ be the universal covering space of M, then from topology one knows that $\tilde M \to M$ is a principal fiber bundle with discrete structure group $\pi_1(M, x_0)$. Let $\pi_1(M)$ act on $\mathrm{Hol}(\omega, u_0)$ by left translation via φ, then the mapping $f : \tilde M \times \mathrm{Hol}(\omega, u_0) \to P(\omega, u_0)$ which is given by $f([c], g) = \mathrm{Pt}(c, 1, u_0).g$ is $\pi_1(M)$-invariant and thus factors to a mapping

$$\tilde M \times_{\pi_1(M)} \mathrm{Hol}(\omega, u_0) = \tilde M[\mathrm{Hol}(\omega, u_0)] \to P(\omega, u_0)$$

which is an isomorphism of $\mathrm{Hol}(\omega, u_0)$-bundles since the upper mapping admits local sections by the curve lifting property of the universal cover. □

22.8. Inducing principal connections on associated bundles. Let (P, p, M, G) be a principal bundle with principal right action $r : P \times G \to P$ and let $\ell : G \times S \to S$ be a left action of the structure group G on some manifold S. Then we consider the associated bundle $P[S] = P[S, \ell] = P \times_G S$, constructed in (21.7). Recall from (21.18) that its tangent and vertical bundle are given by $T(P[S, \ell]) = TP[TS, T\ell] = TP \times_{TG} TS$ and $V(P[S, \ell]) = P[TS, T_2\ell] = P \times_G TS$.

Let $\Phi = \zeta \circ \omega \in \Omega^1(P, TP)$ be a principal connection on the principal bundle P. We construct the *induced connection* $\bar\Phi \in \Omega^1(P[S], T(P[S]))$ by factorizing as in the following diagram:

$$\begin{array}{ccccc}
TP \times TS & \xrightarrow{\Phi \times Id} & TP \times TS & \xrightarrow{=} & T(P \times S) \\
{\scriptstyle Tq = q'}\big\downarrow & & {\scriptstyle q'}\big\downarrow & & {\scriptstyle Tq}\big\downarrow \\
TP \times_{TG} TS & \xrightarrow{\bar\Phi} & TP \times_{TG} TS & \xrightarrow{=} & T(P \times_G S).
\end{array}$$

Let us first check that the top mapping $\Phi \times Id$ is TG-equivariant. For $g \in G$ and $X \in \mathfrak{g}$ the inverse of $T_e(\mu_g)X$ in the Lie group TG is denoted by $(T_e(\mu_g)X)^{-1}$, see lemma (5.17). Furthermore by (5.13) we have

$$\begin{aligned}
Tr(\xi_u, T_e(\mu_g)X) &= T_u(r^g)\xi_u + Tr((0_P \times L_X)(u, g)) \\
&= T_u(r^g)\xi_u + T_g(r_u)(T_e(\mu_g)X) \\
&= T_u(r^g)\xi_u + \zeta_X(ug).
\end{aligned}$$

We may compute

$$\begin{aligned}
&(\Phi \times Id)(Tr(\xi_u, T_e(\mu_g)X), T\ell((T_e(\mu_g)X)^{-1}, \eta_s)) \\
&\quad = (\Phi(T_u(r^g)\xi_u + \zeta_X(ug)), T\ell((T_e(\mu_g)X)^{-1}, \eta_s)) \\
&\quad = (\Phi(T_u(r^g)\xi_u) + \Phi(\zeta_X(ug)), T\ell((T_e(\mu_g)X)^{-1}, \eta_s)) \\
&\quad = ((T_u(r^g)\Phi\xi_u) + \zeta_X(ug), T\ell((T_e(\mu_g)X)^{-1}, \eta_s)) \\
&\quad = (Tr(\Phi(\xi_u), T_e(\mu_g)X), T\ell((T_e(\mu_g)X)^{-1}, \eta_s)).
\end{aligned}$$

So the mapping $\Phi \times Id$ factors to $\bar\Phi$ as indicated in the diagram, and we have $\bar\Phi \circ \bar\Phi = \bar\Phi$ from $(\Phi \times Id) \circ (\Phi \times Id) = \Phi \times Id$. The mapping $\bar\Phi$ is fiberwise linear, since $\Phi \times Id$ and $q' = Tq$ are. The image of $\bar\Phi$ is

$$\begin{aligned}
q'(VP \times TS) &= q'(\ker(Tp : TP \times TS \to TM)) \\
&= \ker(Tp : TP \times_{TG} TS \to TM) = V(P[S, \ell]).
\end{aligned}$$

Thus $\bar\Phi$ is a connection on the associated bundle $P[S]$. We call it the *induced connection.*

From the diagram it also follows, that the vector valued forms $\Phi \times Id \in \Omega^1(P \times S, TP \times TS)$ and $\bar\Phi \in \Omega^1(P[S], T(P[S]))$ are $(q : P \times S \to P[S])$-related. So by (19.15) we have for the curvatures

$$\begin{aligned}
R_{\Phi \times Id} &= \tfrac{1}{2}[\Phi \times Id, \Phi \times Id] = \tfrac{1}{2}[\Phi, \Phi] \times 0 = R_\Phi \times 0, \\
R_{\bar\Phi} &= \tfrac{1}{2}[\bar\Phi, \bar\Phi],
\end{aligned}$$

that they are also q-related, i.e. $Tq \circ (R_\Phi \times 0) = R_{\bar\Phi} \circ (Tq \times_M Tq)$.

By uniqueness of the solutions of the defining differential equation we also get that

$$\mathrm{Pt}_{\bar\Phi}(c,t,q(u,s)) = q(\mathrm{Pt}_\Phi(c,t,u),s).$$

22.9. Recognizing induced connections. We consider again a principal fiber bundle (P,p,M,G) and a left action $\ell : G \times S \to S$. Suppose that we have a conection $\Psi \in \Omega^1(P[S], T(P[S]))$ on the associated bundle $P[S] = P[S,\ell]$. Then the following question arises: When is the connection Ψ induced from a principal connection on P? If this is the case, we say that Ψ is compatible with the G-structure on $P[S]$. The answer is given in the following

Theorem. *Let Ψ be a (general) connection on the associated bundle $P[S]$. Let us suppose that the action ℓ is infinitesimally effective, i.e. the fundamental vector field mapping $\zeta : \mathfrak{g} \to \mathfrak{X}(S)$ is injective.*

Then the connection Ψ is induced from a principal connection ω on P if and only if the following condition is satisfied:

> *In some (equivalently any) fiber bundle atlas (U_α, ψ_α) of $P[S]$ belonging to the G-structure of the associated bundle the Christoffel forms $\Gamma^\alpha \in \Omega^1(U_\alpha, \mathfrak{X}(S))$ have values in the sub Lie algebra $\mathfrak{X}_{fund}(S)$ of fundamental vector fields for the action ℓ.*

Proof. Let $(U_\alpha, \varphi_\alpha : P|U_\alpha \to U_\alpha \times G)$ be a principal fiber bundle atlas for P. Then by the proof of theorem (21.7) the induced fiber bundle atlas $(U_\alpha, \psi_\alpha : P[S]|U_\alpha \to U_\alpha \times S)$ is given by

$$\psi_\alpha^{-1}(x,s) = q(\varphi_\alpha^{-1}(x,e),s), \tag{1}$$

$$(\psi_\alpha \circ q)(\varphi_\alpha^{-1}(x,g),s) = (x, g.s). \tag{2}$$

Let $\Phi = \zeta \circ \omega$ be a principal connection on P and let $\bar\Phi$ be the induced connection on the associated bundle $P[S]$. By (20.7) its Christoffel symbols are given by

$$\begin{aligned}
(0_x, \Gamma^\alpha_{\bar\Phi}(\xi_x, s)) &= -(T(\psi_\alpha) \circ \bar\Phi \circ T(\psi_\alpha^{-1}))(\xi_x, 0_s)\\
&= -(T(\psi_\alpha) \circ \bar\Phi \circ Tq \circ (T(\varphi_\alpha^{-1}) \times Id))(\xi_x, 0_e, 0_s) &&\text{by (1)}\\
&= -(T(\psi_\alpha) \circ Tq \circ (\Phi \times Id))(T(\varphi_\alpha^{-1})(\xi_x, 0_e), 0_s) &&\text{by (22.8)}\\
&= -(T(\psi_\alpha) \circ Tq)(\Phi(T(\varphi_\alpha^{-1})(\xi_x, 0_e)), 0_s)\\
&= (T(\psi_\alpha) \circ Tq)(T(\varphi_\alpha^{-1})(0_x, \Gamma^\alpha_\Phi(\xi_x, e)), 0_s) &&\text{by (22.4.3)}\\
&= -T(\psi_\alpha \circ q \circ (\varphi_\alpha^{-1} \times Id))(0_x, \omega_\alpha(\xi_x), 0_s) &&\text{by (22.4.7)}\\
&= -T_e(\ell^s)\omega_\alpha(\xi_x) &&\text{by (2)}\\
&= -\zeta_{\omega_\alpha(\xi_x)}(s).
\end{aligned}$$

So the condition is necessary. Now let us conversely suppose that a connection Ψ on $P[S]$ is given such that the Christoffel forms Γ^α_Ψ with respect to a fiber bundle atlas of the G-structure have values in $\mathfrak{X}_{fund}(S)$. Then unique $\mathfrak{g}$-valued forms $\omega_\alpha \in \Omega^1(U_\alpha, \mathfrak{g})$ are given by the equation

$$\Gamma^\alpha_\Psi(\xi_x) = -\zeta(\omega_\alpha(\xi_x)),$$

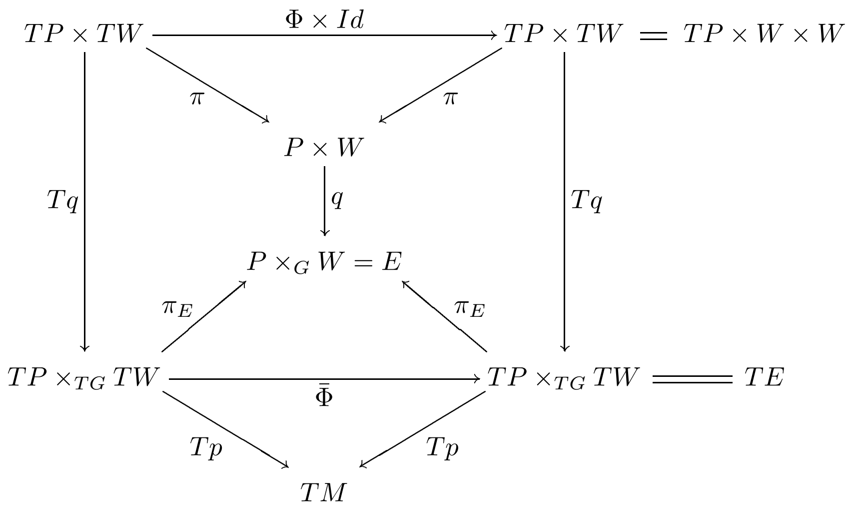
since the action is infinitesimally effective. From the transition formulas (20.7) for the Γ^α_Ψ follow the transition formulas (22.4.5) for the ω^α, so that they give a unique principal connection on P, which by the first part of the proof induces the given connection Ψ on $P[S]$. □

22.10. Inducing principal connections on associated vector bundles. Let (P, p, M, G) be a principal fiber bundle and let $\rho : G \to GL(W)$ be a representation of the structure group G on a finite dimensional vector space W. We consider the associated vector bundle $(E := P[W, \rho], p, M, W)$, which was treated in some detail in (21.11).

Recall from (6.12) that $T(E) = TP \times_{TG} TW$ has two vector bundle structures with the projections

$$\begin{aligned} \pi_E &: T(E) = TP \times_{TG} TW \to P \times_G W = E, \\ Tp \circ pr_1 &: T(E) = TP \times_{TG} TW \to TM. \end{aligned}$$

Now let $\Phi = \zeta \circ \omega \in \Omega^1(P, TP)$ be a principal connection on P. We consider the induced connection $\bar\Phi \in \Omega^1(E, T(E))$ from (22.8). A look at the diagram below shows that the induced connection is linear in both vector bundle structures. We say that it is a *linear connection* on the associated bundle.



Recall now from (6.12) the vertical lift $vl_E : E \times_M E \to VE$, which is an isomorphism, pr_1–π_E–fiberwise linear and also pr_2–Tp–fiberwise linear.

Now we define the *connector* K of the linear connection $\bar\Phi$ by

$$K := pr_2 \circ (vl_E)^{-1} \circ \bar\Phi : TE \to VE \to E \times_M E \to E.$$

Lemma. *The connector $K : TE \to E$ is a vector bundle homomorphism for both vector bundle structures on TE and satisfies $K \circ vl_E = pr_2 : E \times_M E \to TE \to E$.*

So K is π_E–p–fiberwise linear and Tp–p–fiberwise linear.

Proof. This follows from the fiberwise linearity of the composants of K and from its definition. □

22.11. Linear connections. If (E, p, M) is a vector bundle, a connection $\Psi \in \Omega^1(E, TE)$ such that $\Psi : TE \to VE \to TE$ is also Tp–Tp–fiberwise linear is called a *linear connection*. An easy check with (22.9) or a direct construction shows that Ψ is then induced from a unique principal connection on the linear frame bundle $GL(\mathbb{R}^n, E)$ of E (where n is the fiber dimension of E).

Equivalently a linear connection may be specified by a connector $K : TE \to E$ with the three properties of lemma (22.10). For then $HE := \{\xi_u : K(\xi_u) = 0_{p(u)}\}$ is a complement to VE in TE which is Tp–fiberwise linearly chosen.

22.12. Covariant derivative on vector bundles. Let (E, p, M) be a vector bundle with a linear connection, given by a connector $K : TE \to E$ with the properties in lemma (22.10).

For any manifold N, smooth mapping $s : N \to E$, and vector field $X \in \mathfrak{X}(N)$ we define the *covariant derivative* of s along X by

$$\nabla_X s := K \circ Ts \circ X : N \to TN \to TE \to E. \tag{1}$$

If $f : N \to M$ is a fixed smooth mapping, let us denote by $C^\infty_f(N, E)$ the vector space of all smooth mappings $s : N \to E$ with $p \circ s = f$ – they are called sections of E along f. From the universal property of the pullback it follows that the vector space $C^\infty_f(N, E)$ is canonically linearly isomorphic to the space $\Gamma(f^*E)$ of sections of the pullback bundle. Then the covariant derivative may be viewed as a bilinear mapping

$$\nabla : \mathfrak{X}(N) \times C^\infty_f(N, E) \to C^\infty_f(N, E). \tag{2}$$

In particular for $f = Id_M$ we have

$$\nabla : \mathfrak{X}(M) \times \Gamma(E) \to \Gamma(E).$$

Lemma. *This covariant derivative has the following properties:*

(3) *$\nabla_X s$ is $C^\infty(N)$-linear in $X \in \mathfrak{X}(N)$. So for a tangent vector $X_x \in T_xN$ the mapping $\nabla_{X_x} : C^\infty_f(N, E) \to E_{f(x)}$ makes sense and we have $(\nabla_X s)(x) = \nabla_{X(x)} s$.*

(4) *$\nabla_X s$ is $\mathbb{R}$-linear in $s \in C^\infty_f(N, E)$.*

(5) *$\nabla_X(h.s) = dh(X).s + h.\nabla_X s$ for $h \in C^\infty(N)$, the derivation property of ∇_X.*

(6) *For any manifold Q and smooth mapping $g : Q \to N$ and $Y_y \in T_yQ$ we have $\nabla_{Tg.Y_y} s = \nabla_{Y_y}(s \circ g)$. If $Y \in \mathfrak{X}(Q)$ and $X \in \mathfrak{X}(N)$ are g-related, then we have $\nabla_Y(s \circ g) = (\nabla_X s) \circ g$.*

Proof. All these properties follow easily from the definition (1). □

Remark. Property (6) is not well understood in some differential geometric literature. See e.g. the clumsy and unclear treatment of it in [Eells-Lemaire, 1983].

For vector fields X, $Y \in \mathfrak{X}(M)$ and a section $s \in \Gamma(E)$ an easy computation shows that

$$\begin{aligned} R^E(X,Y)s :&= \nabla_X \nabla_Y s - \nabla_Y \nabla_X s - \nabla_{[X,Y]} s \\ &= ([\nabla_X, \nabla_Y] - \nabla_{[X,Y]})s \end{aligned}$$

is $C^\infty(M)$-linear in X, Y, and s. By the method of (7.3) it follows that R^E is a 2-form on M with values in the vector bundle $L(E,E)$, i.e. $R^E \in \Omega^2(M, L(E,E))$. It is called the *curvature* of the covariant derivative. See (22.16) below for the relation to the principal curvature if E is an associated bundle.

For $f : N \to M$, vector fields X, $Y \in \mathfrak{X}(N)$ and a section $s \in C^\infty_f(N,E)$ along f one may prove that

$$\nabla_X \nabla_Y s - \nabla_Y \nabla_X s - \nabla_{[X,Y]} s = (f^* R^E)(X,Y)s := R^E(Tf.X, Tf.Y)s.$$

22.13. Covariant exterior derivative. Let (E,p,M) be a vector bundle with a linear connection, given by a connector $K : TE \to E$.

For a smooth mapping $f : N \to M$ let $\Omega(N, f^*E)$ be the vector space of all forms on N with values in the vector bundle f^*E. We can also view them as forms on N with values along f in E, but we do not introduce an extra notation for this.

The graded space $\Omega(N, f^*E)$ is a graded $\Omega(N)$-module via

$$\begin{aligned} &(\varphi \wedge \Phi)(X_1, \dots, X_{p+q}) = \\ &\qquad = \tfrac{1}{p!\,q!} \sum_\sigma \operatorname{sign}(\sigma)\ \varphi(X_{\sigma 1}, \dots, X_{\sigma p}) \Phi(X_{\sigma(p+1)}, \dots, X_{\sigma(p+q)}). \end{aligned}$$

The graded module homomorphisms $H : \Omega(N, f^*E) \to \Omega(N, f^*E)$ (so that $H(\varphi \wedge \Phi) = (-1)^{\deg H . \deg \varphi} \varphi \wedge H(\Phi)$) are easily seen to coincide with the mappings $\mu(A)$ for $A \in \Omega^p(N, f^*L(E,E))$, which are given by

$$\begin{aligned} &(\mu(A)\Phi)(X_1, \dots, X_{p+q}) = \\ &\qquad = \tfrac{1}{p!\,q!} \sum_\sigma \operatorname{sign}(\sigma)\ A(X_{\sigma 1}, \dots, X_{\sigma p})(\Phi(X_{\sigma(p+1)}, \dots, X_{\sigma(p+q)})). \end{aligned}$$

The *covariant exterior derivative* $d_\nabla : \Omega^p(N, f^*E) \to \Omega^{p+1}(N, f^*E)$ is defined by (where the X_i are vector fields on N)

$$\begin{aligned} (d_\nabla \Phi)(X_0, \dots, X_p) &= \sum_{i=0}^p (-1)^i \nabla_{X_i} \Phi(X_0, \dots, \widehat{X_i}, \dots, X_p) \\ &\quad + \sum_{0 \le i < j \le p} (-1)^{i+j} \Phi([X_i, X_j], X_0, \dots, \widehat{X_i}, \dots, \widehat{X_j}, \dots, X_p). \end{aligned}$$

Lemma. *The covariant exterior derivative is well defined and has the following properties.*

(1) *For* $s \in \Gamma(f^*E) = \Omega^0(N, f^*E)$ *we have* $(d_\nabla s)(X) = \nabla_X s$.
(2) $d_\nabla(\varphi \wedge \Phi) = d\varphi \wedge \Phi + (-1)^{\deg \varphi}\varphi \wedge d_\nabla \Phi$.
(3) *For smooth* $g : Q \to N$ *and* $\Phi \in \Omega(N, f^*E)$ *we have* $d_\nabla(g^*\Phi) = g^*(d_\nabla \Phi)$.
(4) $d_\nabla d_\nabla \Phi = \mu(f^*R^E)\Phi$.

Proof. It suffices to investigate decomposable forms $\Phi = \varphi \otimes s$ for $\varphi \in \Omega^p(N)$ and $s \in \Gamma(f^*E)$. Then from the definition we have $d_\nabla(\varphi \otimes s) = d\varphi \otimes s + (-1)^p \varphi \wedge d_\nabla s$. Since by (22.12.3) $d_\nabla s \in \Omega^1(N, f^*E)$, the mapping d_∇ is well defined. This formula also implies (2) immediately. (3) follows from (22.12.6). (4) is checked as follows:

$$\begin{aligned}
d_\nabla d_\nabla(\varphi \otimes s) &= d_\nabla(d\varphi \otimes s + (-1)^p \varphi \wedge d_\nabla s) \text{ by (2)}\\
&= 0 + (-1)^{2p} \varphi \wedge d_\nabla d_\nabla s\\
&= \varphi \wedge \mu(f^*R^E)s \text{ by the definition of } R^E\\
&= \mu(f^*R^E)(\varphi \otimes s). \quad \square
\end{aligned}$$

22.14. Let (P, p, M, G) be a principal fiber bundle and let $\rho : G \to GL(W)$ be a representation of the structure group G on a finite dimensional vector space W.

Theorem. *There is a canonical isomorphism from the space of* $P[W, \rho]$*-valued differential forms on* M *onto the space of horizontal* G*-equivariant* W*-valued differential forms on* P*:*

$$\begin{aligned}
q^\sharp : \Omega(M, P[W, \rho]) \to \Omega_{hor}(P, W)^G = \{\varphi \in \Omega(P, W) : i_X \varphi = 0\\
\text{for all } X \in VP, (r^g)^*\varphi = \rho(g^{-1}) \circ \varphi \text{ for all } g \in G\}.
\end{aligned}$$

In particular for $W = \mathbb{R}$ *with trivial representation we see that*

$$p^* : \Omega(M) \to \Omega_{hor}(P)^G = \{\varphi \in \Omega_{hor}(P) : (r^g)^*\varphi = \varphi\}$$

is also an isomorphism. The isomorphism

$$q^\sharp : \Omega^0(M, P[W]) = \Gamma(P[W]) \to \Omega^0_{hor}(P, W)^G = C^\infty(P, W)^G$$

is a special case of the one from (21.12).

Proof. Recall the smooth mapping $\tau^G : P \times_M P \to G$ from (21.2), which satisfies $r(u_x, \tau^G(u_x, v_x)) = v_x$, $\tau^G(u_x.g, u'_x.g') = g^{-1}.\tau^G(u_x, u'_x).g'$, and $\tau^G(u_x, u_x) = e$. Let $\varphi \in \Omega^k_{hor}(P, W)^G$, $X_1, \dots, X_k \in T_uP$, and $X'_1, \dots, X'_k \in T_{u'}P$ such that $T_up.X_i = T_{u'}p.X'_i$ for each i. Then we have for $g = \tau^G(u, u')$, so that $ug = u'$:

$$\begin{aligned}
q(u, \varphi_u(X_1, \dots, X_k)) &= q(ug, \rho(g^{-1})\varphi_u(X_1, \dots, X_k))\\
&= q(u', ((r^g)^*\varphi)_u(X_1, \dots, X_k))\\
&= q(u', \varphi_{ug}(T_u(r^g).X_1, \dots, T_u(r^g).X_k))\\
&= q(u', \varphi_{u'}(X'_1, \dots, X'_k)), \text{ since } T_u(r^g)X_i - X'_i \in V_{u'}P.
\end{aligned}$$

By this a vector bundle valued form $\Phi \in \Omega^k(M, P[W])$ is uniquely determined.

For the converse recall the smooth mapping $\tau^W : P \times_M P[W,\rho] \to W$ from (21.7), which satisfies $\tau^W(u, q(u,w)) = w$, $q(u_x, \tau^W(u_x, v_x)) = v_x$, and $\tau^W(u_x g, v_x) = \rho(g^{-1})\tau^W(u_x, v_x)$.

For $\Phi \in \Omega^k(M, P[W])$ we define $q^\sharp\Phi \in \Omega^k(P, W)$ as follows. For $X_i \in T_uP$ we put

$$(q^\sharp\Phi)_u(X_1, \dots, X_k) := \tau^W(u, \Phi_{p(u)}(T_up.X_1, \dots, T_up.X_k)).$$

Then $q^\sharp\Phi$ is smooth and horizontal. For $g \in G$ we have

$$\begin{aligned}
((r^g)^*(q^\sharp\Phi))_u(X_1, \dots, X_k) &= (q^\sharp\Phi)_{ug}(T_u(r^g).X_1, \dots, T_u(r^g).X_k) \\
&= \tau^W(ug, \Phi_{p(ug)}(T_{ug}p.T_u(r^g).X_1, \dots, T_{ug}p.T_u(r^g).X_k)) \\
&= \rho(g^{-1})\tau^W(u, \Phi_{p(u)}(T_up.X_1, \dots, T_up.X_k)) \\
&= \rho(g^{-1})(q^\sharp\Phi)_u(X_1, \dots, X_k).
\end{aligned}$$

Clearly the two constructions are inverse to each other. □

22.15. Let (P, p, M, G) be a principal fiber bundle with a principal connection $\Phi = \zeta \circ \omega$, and let $\rho : G \to GL(W)$ be a representation of the structure group G on a finite dimensional vector space W. We consider the associated vector bundle $(E := P[W, \rho], p, M, W)$, the induced connection $\bar\Phi$ on it and the corresponding covariant derivative.

Theorem. *The covariant exterior derivative d_ω from* (22.5) *on P and the covariant exterior derivative for $P[W]$-valued forms on M are connected by the mapping $q^\sharp$ from* (22.14)*, as follows:*

$$q^\sharp \circ d_\nabla = d_\omega \circ q^\sharp : \Omega(M, P[W]) \to \Omega_{hor}(P, W)^G.$$

Proof. Let us consider first $f \in \Omega^0_{hor}(P, W)^G = C^\infty(P, W)^G$, then $f = q^\sharp s$ for $s \in \Gamma(P[W])$ and we have $f(u) = \tau^W(u, s(p(u)))$ and $s(p(u)) = q(u, f(u))$ by (22.14) and (21.12). Therefore we have $Ts.Tp.X_u = Tq(X_u, Tf.X_u)$, where $Tf.X_u = (f(u), df(X_u)) \in TW = W \times W$. If $\chi : TP \to HP$ is the horizontal projection as in (22.5), we have $Ts.Tp.X_u = Ts.Tp.\chi.X_u = Tq(\chi.X_u, Tf.\chi.X_u)$. So we get

$$\begin{aligned}
(q^\sharp d_\nabla s)(X_u) &= \tau^W(u, (d_\nabla s)(Tp.X_u)) \\
&= \tau^W(u, \nabla_{Tp.X_u} s) && \text{by (22.13.1)} \\
&= \tau^W(u, K.Ts.Tp.X_u) && \text{by (22.12.1)} \\
&= \tau^W(u, K.Tq(\chi.X_u, Tf.\chi.X_u)) && \text{from above} \\
&= \tau^W(u, pr_2.vl^{-1}_{P[W]}.\bar\Phi.Tq(\chi.X_u, Tf.\chi.X_u)) && \text{by (22.10)} \\
&= \tau^W(u, pr_2.vl^{-1}_{P[W]}.Tq.(\Phi \times Id)(\chi.X_u, Tf.\chi.X_u))) && \text{by (22.8)} \\
&= \tau^W(u, pr_2.vl^{-1}_{P[W]}.Tq(0_u, Tf.\chi.X_u))) && \text{since } \Phi.\chi = 0
\end{aligned}$$

$$
\begin{aligned}
&= \tau^W(u, q.pr_2.vl_{P\times W}^{-1}.(0_u, Tf.\chi.X_u))) && \text{since } q \text{ is fiber linear}\\
&= \tau^W(u, q(u, df.\chi.X_u)) = (\chi^* df)(X_u)\\
&= (d_\omega q^\sharp s)(X_u).
\end{aligned}
$$

Now we turn to the general case. It suffices to check the formula for a decomposable $P[W]$-valued form $\Psi = \psi \otimes s \in \Omega^k(M, P[W])$, where $\psi \in \Omega^k(M)$ and $s \in \Gamma(P[W])$. Then we have

$$
\begin{aligned}
d_\omega q^\sharp(\psi\otimes s) &= d_\omega(p^*\psi \cdot q^\sharp s)\\
&= d_\omega(p^*\psi)\cdot q^\sharp s + (-1)^k \chi^* p^*\psi \wedge d_\omega q^\sharp s && \text{by (22.5.1)}\\
&= \chi^* p^* d\psi \cdot q^\sharp s + (-1)^k p^*\psi \wedge q^\sharp d_\nabla s && \text{from above and (22.5.4)}\\
&= p^* d\psi \cdot q^\sharp s + (-1)^k p^*\psi \wedge q^\sharp d_\nabla s\\
&= q^\sharp(d\psi\otimes s + (-1)^k \psi\wedge d_\nabla s)\\
&= q^\sharp d_\nabla(\psi\otimes s). \quad \square
\end{aligned}
$$

22.16. Corollary. *In the situation of theorem* (22.15)*, the Lie algebra valued curvature form* $\Omega \in \Omega^2_{hor}(P, \mathfrak{g})$ *and the curvature* $R^{P[W]} \in \Omega^2(M, L(P[W], P[W]))$ *are related by*

$$q^\sharp_{L(P[W],P[W])} R^{P[W]} = \rho' \circ \Omega,$$

where $\rho' = T_e\rho : \mathfrak{g} \to L(W, W)$ *is the derivative of the representation* ρ.

Proof. We use the notation of the proof of theorem (22.15). By this theorem we have for X, $Y \in T_uP$

$$
\begin{aligned}
(d_\omega d_\omega q^\sharp_{P[W]} s)_u(X,Y) &= (q^\sharp d_\nabla d_\nabla s)_u(X,Y)\\
&= (q^\sharp R^{P[W]} s)_u(X,Y)\\
&= \tau^W(u, R^{P[W]}(T_up.X, T_up.Y)s(p(u)))\\
&= (q^\sharp_{L(P[W],P[W])} R^{P[W]})_u(X,Y)(q^\sharp_{P[W]} s)(u).
\end{aligned}
$$

On the other hand we have by theorem (22.5.8)

$$
\begin{aligned}
(d_\omega d_\omega q^\sharp s)_u(X,Y) &= (\chi^* i_R d q^\sharp s)_u(X,Y)\\
&= (dq^\sharp s)_u(R(X,Y)) && \text{since } R \text{ is horizontal}\\
&= (dq^\sharp s)(-\zeta_{\Omega(X,Y)}(u)) && \text{by (22.2)}\\
&= \tfrac{\partial}{\partial t}\big|_0 (q^\sharp s)(\mathrm{Fl}^{\zeta_{\Omega(X,Y)}}_{-t}(u))\\
&= \tfrac{\partial}{\partial t}\big|_0 \tau^W(u.\exp(-t\Omega(X,Y)), s(p(u.\exp(-t\Omega(X,Y)))))\\
&= \tfrac{\partial}{\partial t}\big|_0 \tau^W(u.\exp(-t\Omega(X,Y)), s(p(u)))\\
&= \tfrac{\partial}{\partial t}\big|_0 \rho(\exp t\Omega(X,Y))\tau^W(u, s(p(u))) && \text{by (21.7)}\\
&= \rho'(\Omega(X,Y))(q^\sharp s)(u). \quad \square
\end{aligned}
$$

23. Characteristic classes

23.1. Invariants of Lie algebras. Let G be a Lie group with Lie algebra $\mathfrak{g}$, let $\bigotimes \mathfrak{g}^*$ be the tensor algebra over the dual space $\mathfrak{g}^*$, the graded space of all multilinear real (or complex) functionals on $\mathfrak{g}$. Let $S(\mathfrak{g}^*)$ be the symmetric algebra over $\mathfrak{g}^*$ which corresponds to the algebra of polynomial functions on $\mathfrak{g}$. The adjoint representation $\operatorname{Ad} : G \to L(\mathfrak{g}, \mathfrak{g})$ induces representations $\operatorname{Ad}^* : G \to L(\bigotimes \mathfrak{g}^*, \bigotimes \mathfrak{g}^*)$ and also $\operatorname{Ad}^* : G \to L(S(\mathfrak{g}^*), S(\mathfrak{g}^*))$, which are both given by $\operatorname{Ad}^*(g)f = f \circ (\operatorname{Ad}(g^{-1}) \otimes \cdots \otimes \operatorname{Ad}(g^{-1}))$. A tensor $f \in \bigotimes \mathfrak{g}^*$ (or a polynomial $f \in S(\mathfrak{g}^*)$) is called an *invariant of the Lie algebra* if $\operatorname{Ad}^*(g)f = f$ for all $g \in G$. If the Lie group G is connected, f is an invariant if and only if $\mathcal{L}_X f = 0$ for all $X \in \mathfrak{g}$, where $\mathcal{L}_X$ is the restriction of the Lie derivative to left invariant tensor fields on G, which coincides with the unique extension of $\operatorname{ad}(X)^* : \mathfrak{g}^* \to \mathfrak{g}^*$ to a derivation on $\bigotimes \mathfrak{g}^*$ or $S(\mathfrak{g}^*)$, respectively. Compare this with the proof of (12.16.2). Obviously the space of all invariants is a graded subalgebra of $\bigotimes \mathfrak{g}^*$ or $S(\mathfrak{g}^*)$, respectively. The usual notation for the algebra of invariant polynomials is

$$I(G) := \bigoplus_{k\geq 0} I^k(G) = S(\mathfrak{g}^*)^G = \bigoplus_{k\geq 0} S^k(\mathfrak{g}^*)^G.$$

23.2. The Chern-Weil forms. Let (P, p, M, G) be a principal fiber bundle with principal connection $\Phi = \zeta \circ \omega$ and curvature $R = \zeta \circ \Omega$. For $\psi_i \in \Omega^{p_i}(P, \mathfrak{g})$ and $f \in S^k(\mathfrak{g}^*) \subset \bigotimes^k \mathfrak{g}^*$ we have the differential forms

$$\begin{aligned} \psi_1 \otimes_\wedge \cdots \otimes_\wedge \psi_k &\in \Omega^{p_1+\cdots+p_k}(P, \mathfrak{g} \otimes \cdots \otimes \mathfrak{g}), \\ f \circ (\psi_1 \otimes_\wedge \cdots \otimes_\wedge \psi_k) &\in \Omega^{p_1+\cdots+p_k}(P). \end{aligned}$$

The exterior derivative of the latter one is clearly given by

$$\begin{aligned} d(f \circ (\psi_1 \otimes_\wedge \cdots \otimes_\wedge \psi_k)) &= f \circ d(\psi_1 \otimes_\wedge \cdots \otimes_\wedge \psi_k) \\ &= f \circ \Big(\textstyle\sum_{i=1}^k (-1)^{p_1+\cdots+p_{i-1}} \psi_1 \otimes_\wedge \cdots \otimes_\wedge d\psi_i \otimes_\wedge \cdots \otimes_\wedge \psi_k\Big) \end{aligned}$$

Let us now consider an invariant polynomial $f \in I^k(G)$ and the curvature form $\Omega \in \Omega^2_{\text{hor}}(P, \mathfrak{g})^G$. Then the $2k$-form $f \circ (\Omega \otimes_\wedge \cdots \otimes_\wedge \Omega)$ is horizontal since by (22.2.2) Ω is horizontal. It is also G-invariant since by (22.2.2) we have

$$\begin{aligned} (r^g)^*(f \circ (\Omega \otimes_\wedge \cdots \otimes_\wedge \Omega)) &= f \circ ((r^g)^*\Omega \otimes_\wedge \cdots \otimes_\wedge (r^g)^*\Omega) \\ &= f \circ (\operatorname{Ad}(g^{-1})\Omega \otimes_\wedge \cdots \otimes_\wedge \operatorname{Ad}(g^{-1})\Omega) \\ &= f \circ (\Omega \otimes_\wedge \cdots \otimes_\wedge \Omega). \end{aligned}$$

So by theorem (22.14) there is a uniquely defined $2k$-form $\operatorname{cw}(f, P, \omega) \in \Omega^{2k}(M)$ with $p^* \operatorname{cw}(f, P, \omega) = f \circ (\Omega \otimes_\wedge \cdots \otimes_\wedge \Omega)$, which we will call the *Chern-Weil form* of f.

If $h : N \to M$ is a smooth mapping, then for the pullback bundle h^*P the Chern-Weil form is given by $\operatorname{cw}(f, h^*P, h^*\omega) = h^* \operatorname{cw}(f, P, \omega)$, which is easily seen by applying p^*.

23.3. Theorem. The Chern-Weil homomorphism. *In the setting of* (23.2) *we have:*

(1) *For* $f \in I^k(G)$ *the Chern Weil form* $\operatorname{cw}(f,P,\omega)$ *is closed:* $d\operatorname{cw}(f,P,\omega) = 0$*. So there is a well defined cohomology class* $\operatorname{Cw}(f,P) = [\operatorname{cw}(f,P,\omega)] \in H^{2k}(M)$*, called the characteristic class of the invariant polynomial* f*.*

(2) *The characteristic class* $\operatorname{Cw}(f,P)$ *does not depend on the choice of the principal connection* ω*.*

(3) *The mapping* $\operatorname{Cw}_P : I^*(G) \to H^{2*}(M)$ *is a homomorphism of commutative algebras, and it is called the Chern-Weil homomorphism.*

(4) *If* $h : N \to M$ *is a smooth mapping, then the Chern-Weil homomorphism for the pullback bundle* h^*P *is given by*

$$\operatorname{Cw}_{h^*P} = h^* \circ \operatorname{Cw}_P : I^*(G) \to H^{2*}(N).$$

Proof. (1) Since $f \in I^k(G)$ is invariant we have for any $X \in \mathfrak{g}$

$$\begin{aligned} 0 &= \tfrac{d}{dt}|_0 \operatorname{Ad}(\exp(tX_0))^* f(X_1,\dots,X_k) = \\ &= \tfrac{d}{dt}|_0 f(\operatorname{Ad}(\exp(tX_0))X_1,\dots,\operatorname{Ad}(\exp(tX_0)X_k) = \\ &= \textstyle\sum_{i=1}^k f(X_1,\dots,[X_0,X_i],\dots,X_k) = \\ &= \textstyle\sum_{i=1}^k f([X_0,X_i],X_1,\dots,\widehat{X_i}\dots,X_k). \end{aligned}$$

This implies that

$$\begin{aligned} d(f\circ(\Omega\otimes_\wedge\cdots\otimes_\wedge\Omega)) &= f\circ\Big(\textstyle\sum_{i=1}^k \Omega\otimes_\wedge\cdots\otimes_\wedge d\Omega\otimes_\wedge\cdots\otimes_\wedge\Omega\Big) \\ &= k\,f\circ(d\Omega\otimes_\wedge\cdots\otimes_\wedge\Omega) + k\,f\circ([\omega,\Omega]_\wedge\otimes_\wedge\cdots\otimes_\wedge\Omega) \\ &= k\,f\circ(d_\omega\Omega\otimes_\wedge\Omega\otimes_\wedge\cdots\otimes_\wedge\Omega) = 0, \qquad \text{by (22.5.6).} \\ p^*d\operatorname{cw}(f,P,\omega) &= d\,p^*\operatorname{cw}(f,P,\omega) \\ &= d\,(f\circ(\Omega\otimes_\wedge\cdots\otimes_\wedge\Omega)) = 0, \end{aligned}$$

and thus $d\operatorname{cw}(f,P,\omega) = 0$ since p^* is injective.

(2) Let $\omega_0,\ \omega_1 \in \Omega^1(P,\mathfrak{g})^G$ be two principal connections. Then we consider the principal bundle $(P\times\mathbb{R}, p\times Id, M\times\mathbb{R}, G)$ and the principal connection $\tilde\omega = (1-t)\omega_0 + t\omega_1 = (1-t)(pr_1)^*\omega_0 + t(pr_1)^*\omega_1$ on it, where t is the coordinate function on $\mathbb{R}$. Let $\tilde\Omega$ be the curvature form of $\tilde\omega$. Let $\operatorname{ins}_s : P \to P\times\mathbb{R}$ be the embedding at level s, $\operatorname{ins}_s(u) = (u,s)$. Then we have in turn by (22.2.3) for $s = 0,1$

$$\begin{aligned} \omega_s &= (\operatorname{ins}_s)^*\tilde\omega \\ \Omega_s &= d\omega_s + \tfrac12[\omega_s,\omega_s]_\wedge \\ &= d(\operatorname{ins}_s)^*\tilde\omega + \tfrac12[(\operatorname{ins}_s)^*\tilde\omega,(\operatorname{ins}_s)^*\tilde\omega]_\wedge \\ &= (\operatorname{ins}_s)^*(d\tilde\omega + \tfrac12[\tilde\omega,\tilde\omega]_\wedge) \\ &= (\operatorname{ins}_s)^*\tilde\Omega. \end{aligned}$$

So we get for $s = 0, 1$

$$\begin{aligned} p^*(\text{ins}_s)^* \operatorname{cw}(f, P \times \mathbb{R}, \tilde\omega) &= (\text{ins}_s)^*(p \times Id_{\mathbb{R}})^* \operatorname{cw}(f, P \times \mathbb{R}, \tilde\omega) \\ &= (\text{ins}_s)^*(f \circ (\tilde\Omega \otimes_\wedge \dots \otimes_\wedge \tilde\Omega)) \\ &= f \circ ((\text{ins}_s)^* \tilde\Omega \otimes_\wedge \dots \otimes_\wedge (\text{ins}_s)^* \tilde\Omega) \\ &= f \circ (\Omega_s \otimes_\wedge \dots \otimes_\wedge \Omega_s) \\ &= p^* \operatorname{cw}(f, P, \omega_s). \end{aligned}$$

Since p^* is injective we get $(ins_s)^* \operatorname{cw}(f, P \times \mathbb{R}, \tilde\omega) = \operatorname{cw}(f, P, \omega_s)$ for $s = 0, 1$, and since ins_0 and ins_1 are smoothly homotopic, the cohomology classes coincide.

(3) and (4) are obvious. $\square$

23.4. Local description of characteristic classes. Let (P, p, M, G) be a principal fiber bundle with a principal connection $\omega \in \Omega^1(P, \mathfrak{g})^G$. Let $s_\alpha \in \Gamma(P|U_\alpha)$ be a collection of local smooth sections of the bundle such that (U_α) is an open cover of M. Recall (from the proof of (21.3) for example) that then $\varphi_\alpha = (p, \tau^G(s_\alpha \circ p, \quad)) : P|U_\alpha \to U_\alpha \times G$ is a principal fiber bundle atlas with transition functions $\varphi_{\alpha\beta}(x) = \tau^G(s_\alpha(x), s_\beta(x))$.

Then we consider the physicists version from (22.4) of the connection ω which is descibed by the forms $\omega_\alpha := s_\alpha^* \omega \in \Omega^1(U_\alpha, \mathfrak{g})$. They transform according to $\omega_\alpha = \operatorname{Ad}(\varphi_{\beta\alpha}^{-1})\omega_\beta + \Theta_{\beta\alpha}$, where $\Theta_{\beta\alpha} = \varphi_{\beta\alpha}^{-1} d\varphi_{\alpha\beta}$ if G is a matrix group, see lemma (22.4). This affine transformation law is due to the fact that ω is not horizontal.

Let $\Omega = d\omega + \frac{1}{2}[\omega, \omega]_\wedge \in \Omega^2_{\text{hor}}(P, \mathfrak{g})^G$ be the curvature of ω, then we consider again the local forms of the curvature:

$$\begin{aligned} \Omega_\alpha : &= s_\alpha^* \Omega = s_\alpha^*(d\omega + \tfrac{1}{2}[\omega, \omega]_\wedge) \\ &= d(s_\alpha^* \omega) + \tfrac{1}{2}[s_\alpha^* \omega, s_\alpha^* \omega]_\wedge \\ &= d\omega_\alpha + \tfrac{1}{2}[\omega_\alpha, \omega_\alpha]_\wedge \end{aligned}$$

Recall from theorem (22.14) that we have an isomorphism $q^\sharp : \Omega(M, P[\mathfrak{g}, \operatorname{Ad}]) \to \Omega_{\text{hor}}(P, \mathfrak{g})^G$. Then $\Omega_\alpha = s_\alpha^* \Omega$ is the local frame expression of $(q^\sharp)^{-1}(\Omega)$ for the induced chart $P[\mathfrak{g}]|U_\alpha \to U_\alpha \times \mathfrak{g}$, thus we have the the simple transformation formula $\Omega_\alpha = \operatorname{Ad}(\varphi_{\alpha\beta})\Omega_\beta$.

If now $f \in I^k(G)$ is an invariant of G, for the Chern-Weil form $\operatorname{cw}(f, P, \omega)$ we have

$$\begin{aligned} \operatorname{cw}(f, P, \omega)|U_\alpha : &= s_\alpha^*(p^* \operatorname{cw}(f, P, \omega)) = s_\alpha^*(f \circ (\Omega \otimes_\wedge \dots \otimes_\wedge \Omega)) \\ &= f \circ (s_\alpha^* \Omega \otimes_\wedge \dots \otimes_\wedge s_\alpha^* \Omega) \\ &= f \circ (\Omega_\alpha \otimes_\wedge \dots \otimes_\wedge \Omega_\alpha), \end{aligned}$$

where $\Omega_\alpha \otimes_\wedge \dots \otimes_\wedge \Omega_\alpha \in \Omega^{2k}(U_\alpha, \mathfrak{g} \otimes \dots \otimes \mathfrak{g})$.

23.5. Characteristic classes for vector bundles. For a real vector bundle $(E, p, M, \mathbb{R}^n)$ the characteristic classes are by definition the characteristic classes of the linear frame bundle $(GL(\mathbb{R}^n, E), p, M, GL(n, \mathbb{R}))$. We write $\mathrm{Cw}(f, E) := \mathrm{Cw}(f, GL(\mathbb{R}^n, E))$ for short. Likewise for complex vector bundles.

Let (P, p, M, G) be a principal bundle and let $\rho : G \to GL(V)$ be a representation in a finite dimensional vector space. If ω is a principal connection form on P with curvature form Ω, then for the induced covariant derivative ∇ on the associated vector bundle $P[V]$ and its curvature $R^{P[V]}$ we have $q^\sharp R^{P[V]} = \rho' \circ \Omega$ by corollary (22.16). So if the representation ρ is infinitesimally effective, i. e. if $\rho' : \mathfrak{g} \to L(V, V)$ is injective, then we see that actually $R^{P[V]} \in \Omega^2(M, P[\mathfrak{g}])$. If $f \in I^k(G)$ is an invariant, then we have the induced mapping

$$\begin{array}{ccc} P \times (\bigotimes^k \mathfrak{g}) & \xrightarrow{Id_P \times f} & P \times \mathbb{R} \\ {\scriptstyle q}\big\downarrow & & \big\downarrow{\scriptstyle q} \\ P[\bigotimes^k \mathfrak{g}] & \xrightarrow{P[f]} & M \times \mathbb{R}. \end{array}$$

So the Chern-Weil form can also be written as (omitting $P[(\rho')^{-1}]$)

$$\mathrm{cw}(f, P, \omega) = P[f] \circ (R^{P[V]} \otimes_\wedge \cdots \otimes_\wedge R^{P[V]}).$$

Sometimes we will make use of this expression.

All characteristic classes for a trivial vector bundle are zero, since the frame bundle is then trivial and admits a principal connection with curvature 0.

We will determine the classical bases for the algebra of invariants for the matrix groups $GL(n, \mathbb{R})$, $GL(n, \mathbb{C})$, $O(n, \mathbb{R})$, $SO(n, \mathbb{R})$, $U(n)$, and discuss the resulting characteristic classes for vector bundles.

23.6. The characteristic coefficients. . For a matrix $A \in \mathfrak{gl}(n, \mathbb{R}) = L(\mathbb{R}^n, \mathbb{R}^n)$ we consider the characteristic coefficients $c_k^n(A)$ which are given by the implicit equation

$$\det(A + t\mathbb{I}) = \sum_{k=0}^{n} c_k^n(A).t^{n-k}. \tag{1}$$

From lemma (12.19) we have $c_k^n(A) = \mathrm{Trace}(\Lambda^k A : \Lambda^k \mathbb{R}^n \to \Lambda^k \mathbb{R}^n)$. The characteristic coefficient c_k^n is a homogeneous invariant polynomial of degree k, since we have $\det(\mathrm{Ad}(g)A + t\mathbb{I}) = \det(gAg^{-1} + t\mathbb{I}) = \det(g(A + t\mathbb{I})g^{-1}) = \det(A + t\mathbb{I})$.

Lemma. *We have*

$$c_k^{n+m}\left(\begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}\right) = \sum_{j=0}^{k} c_j^n(A) c_{k-j}^m(B).$$

Proof. We have

$$\begin{aligned}\det\left(\begin{pmatrix} A & 0 \\ 0 & B\end{pmatrix} + t\mathbb{I}_{n+m}\right) &= \det(A+t\mathbb{I}_n)\det(B+t\mathbb{I}_m) \\ &= \left(\sum_{k=0}^{n} c^n_k(A)t^{n-k}\right)\left(\sum_{j=0}^{m} c^m_j(A)t^{m-l}\right) \\ &= \sum_{k=0}^{n+m}\left(\sum_{j=0}^{k} c^n_j(A)c^m_{k-j}(B)\right) t^{n+m-k}. \quad \square\end{aligned}$$

23.7. Pontryagin classes. Let (E,p,M) be a real vector bundle. Then the *Pontryagin classes* are given by

$$p_k(E) := \left(\frac{-1}{2\pi\sqrt{-1}}\right)^{2k} \operatorname{Cw}(c^{\dim E}_{2k}, E) \in H^{4k}(M;\mathbb{R}), \quad p_0(E) = 1 \in H^0(M;\mathbb{R}).$$

The factor $\frac{-1}{2\pi\sqrt{-1}}$ makes this class to be an integer class (in $H^{4k}(M,\mathbb{Z})$) and makes several integral formulas (like the Gauss-Bonnet-Chern formula) more beautiful. In principle one should always replace the curvature Ω by $\frac{-1}{2\pi\sqrt{-1}}\Omega$. The inhomogeneous cohomology class

$$p(E) := \sum_{k\geq 0} p_k(E) \in H^{4*}(M,\mathbb{R})$$

is called the *total Pontryagin class.*

Theorem. *For the Pontryagin classes we have:*

(1) *If E_1 and E_2 are two real vector bundles over a manifold M, then for the fiberwise direct sum we have*

$$p(E_1\oplus E_2) = p(E_1)\wedge p(E_2) \in H^{4*}(M,\mathbb{R}).$$

(2) *For the pullback of a vector bundle along $f : N \to M$ we have*

$$p(f^*E) = f^*p(E).$$

(3) *For a real vector bundle and an invariant $f \in I^k(GL(n,\mathbb{R}))$ for odd k we have* $\operatorname{Cw}(f,E) = 0$. *Thus the Pontryagin classes exist only in dimension* $0, 4, 8, 12, \dots$.

Proof. (1) If $\omega^i \in \Omega^1(GL(\mathbb{R}^{n_i}, E_i), \mathfrak{gl}(n_i))^{GL(n_i)}$ are principal connection forms for the frame bundles of the two vector bundles, then for local frames of the two bundles $s^i_\alpha \in \Gamma(GL(\mathbb{R}^{n_i}, E_i|U_\alpha)$ the forms

$$\omega_\alpha := \begin{pmatrix}\omega^1_\alpha & 0 \\ 0 & \omega^2_\alpha\end{pmatrix} \in \Omega^1(U_\alpha, \mathfrak{gl}(n_1+n_2))$$

are exactly the local expressions of the direct sum connection, and from lemma (23.6) we see that $p_k(E_1 \oplus E_2) = \sum_{j=0}^{k} p_j(E_1)p_{k-j}(E_2)$ holds which implies the desired result.

(2) This follows from (23.3.4).

(3) Choose a fiber Riemannian metric g on E, consider the corresponding orthonormal frame bundle $(O(\mathbb{R}^n, E), p, M, O(n, \mathbb{R}))$, and choose a principal connection ω for it. Then the local expression with respect to local orthonormal frame fields s_α are skew symmetric matrices of 1-forms. So the local curvature forms are also skew symmetric. As we will show shortly, there exists a matrix $C \in O(n, \mathbb{R})$ such that $CAC^{-1} = A^\top = -A$ for any real skew symmetrix matrix; thus $C\Omega_\alpha C^{-1} = -\Omega_\alpha$. But then

$$\begin{aligned} f \circ (\Omega_\alpha \otimes_\wedge \cdots \otimes_\wedge \Omega_\alpha) &= f \circ (g_\alpha \Omega_\alpha g_\alpha^{-1} \otimes_\wedge \cdots \otimes_\wedge g_\alpha \Omega_\alpha g_\alpha^{-1}) \\ &= f \circ ((-\Omega_\alpha) \otimes_\wedge \cdots \otimes_\wedge (-\Omega_\alpha)) \\ &= (-1)^k f \circ (\Omega_\alpha \otimes_\wedge \cdots \otimes_\wedge \Omega_\alpha). \end{aligned}$$

This implies that $\mathrm{Cw}(f, E) = 0$ if k is odd.

Claim. There exists a matrix $C \in O(n, \mathbb{R})$ such that $CAC^{-1} = A^\top$ for each real matrix with 0's on the main diagonal.

Note first that

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} d & b \\ c & a \end{pmatrix}.$$

Let E_{ij} be the matrix which has 1 in the position (i, j) in the i-th row and j-th column. Then the (ij)-transposition matrix $P_{ij} = \mathbb{I}_n - E_{ii} - E_{jj} + E_{ij} + E_{ji}$ acts by conjugation on an arbitrary matrix A by exchanging the pair A_{ij} and A_{ji}, and also the pair A_{ii} and A_{jj} on the main diagonal. So the product $C = \prod_{i<j} P_{ij}$ has the required effect on a matrix with zeros on the main diagonal.

By the way, $Ad(C)$ acts on the main diagonal via the longest element in the permutation group, with respect to canoniccal system of positive roots in $\mathfrak{sl}(n)$:

$$\begin{pmatrix} 1 & 2 & \dots & n-1 & n \\ n & n-1 & \dots & 2 & 1 \end{pmatrix}. \quad \square$$

23.8. Remarks. (1) If two vector bundles E and F are *stably equivalent*, i. e. $E \oplus (M \times \mathbb{R}^p) \cong F \oplus (M \times \mathbb{R}^q)$, then $p(E) = p(F)$. This follows from (23.7.1) and 2.

(2) If for a vector bundle E for some k the bundle $\overbrace{E \oplus \cdots \oplus E}^{k} \oplus (M \times \mathbb{R}^l)$ is trivial, then $p(E) = 1$ since $p(E)^k = 1$.

(3) Let (E, p, M) be a vector bundle over a compact oriented manifold M. For $j_i \in \mathbb{N}_0$ we put

$$\lambda_{j_1,\dots,j_r}(E) := \int_M p_1(E)^{j_1} \dots p_r(E)^{j_r} \in \mathbb{R},$$

where the integral is set to be 0 on each degree which is not equal to $\dim M$. Then these *Pontryagin numbers* are indeed integers, see [Milnor-Stasheff, ??]. For example we have

$$\lambda_{j_1,\dots,j_r}(T(\mathbb{C}P^n)) = \binom{2n+1}{j_1}\dots\binom{2n+1}{j_r}.$$

23.9. The trace coefficients. For a matrix $A \in \mathfrak{gl}(n,\mathbb{R}) = L(\mathbb{R}^n,\mathbb{R}^n)$ the *trace coefficients* are given by

$$\operatorname{tr}_k^n(A) := \operatorname{Trace}(A^k) = \operatorname{Trace}(\overbrace{A\circ\dots\circ A}^{k}).$$

Obviously tr_k^n is an invariant polynomial, homogeneous of degree k. To a direct sum of two matrices $A \in \mathfrak{gl}(n)$ and $B \in \mathfrak{gl}(m)$ it reacts clearly by

$$\operatorname{tr}_k^{n+m}\begin{pmatrix} A & 0 \\ 0 & B\end{pmatrix} = \operatorname{Trace}\begin{pmatrix} A^k & 0 \\ 0 & B^k\end{pmatrix} = \operatorname{tr}_k^n(A) + \operatorname{tr}_k^m(B).$$

The tensor product (sometimes also called Kronecker product) of A and B is given by $A \otimes B = (A^i_j B^k_l)_{(i,k),(j,l)\in n\times m}$ in terms of the canonical bases. Since we have $\operatorname{Trace}(A\otimes B) = \sum_{i,k} A^i_i B^k_k = \operatorname{Trace}(A)\operatorname{Trace}(B)$, we also get

$$\begin{aligned}\operatorname{tr}_k^{nm}(A\otimes B) &= \operatorname{Trace}((A\otimes B)^k) = \operatorname{Trace}(A^k\otimes B^k) = \operatorname{Trace}(A^k)\operatorname{Trace}(B^k)\\ &= \operatorname{tr}_k^n(A)\operatorname{tr}_k^m(B).\end{aligned}$$

Lemma. *The trace coefficients and the characteristic coefficients are connected by the following recursive equation:*

$$c_k^n(A) = \tfrac{1}{k}\sum_{j=0}^{k-1}(-1)^{k-j-1}c_j^n(A)\operatorname{tr}_{k-j}^n(A).$$

Proof. For a matrix $A \in \mathfrak{gl}(n)$ let us denote by $C(A)$ the matrix of the signed algebraic complements of A (also called the classical adjoint), i. e.

(1) $$C(A)^i_j = (-1)^{i+j}\det\begin{pmatrix} A & \begin{matrix}\text{without } i\text{-th column,}\\ \text{without } j\text{-th row}\end{matrix}\end{pmatrix}$$

Then Cramer's rule reads

(2) $$A.C(A) = C(A).A = \det(A).\mathbb{I},$$

and the derivative of the determinant is given by

(3) $$d\det(A)X = \operatorname{Trace}(C(A)X).$$

Note that $C(A)$ is a homogeneous matrix valued polynomial of degree $n-1$ in A. We define now matrix valued polynomials $a_k(A)$ by

$$C(A+t\mathbb{I}) = \sum_{k=0}^{n-1} a_k(A)t^{n-k-1}. \tag{4}$$

We claim that for $A \in \mathfrak{gl}(n)$ and $k = 0, 1, \dots, n-1$ we have

$$a_k(A) = \sum_{j=0}^{k} (-1)^j c^n_{k-j}(A)A^j. \tag{5}$$

We prove this in the following way: from (2) we have

$$(A+t\mathbb{I})C(A+t\mathbb{I}) = \det(A+t\mathbb{I})\mathbb{I},$$

and we insert (4) and (23.6.1) to get in turn

$$(A+t\mathbb{I})\sum_{k=0}^{n-1} a_k(A)t^{n-k-1} = \sum_{j=0}^{n} c^n_j(A)t^{n-j}\mathbb{I}$$

$$\sum_{k=0}^{n-1} A.a_k(A)t^{n-k-1} + \sum_{k=0}^{n-1} a_k(A)t^{n-k} = \sum_{j=0}^{n} c^n_j(A)t^{n-j}\mathbb{I}$$

We put $a_{-1}(A) := 0 =: a_n(A)$ and compare coefficients of t^{n-k} in the last equation to get the recursion formula

$$A.a_{k-1}(A) + a_k(A) = c^n_k(A)\mathbb{I}$$

which immediately leads to to the desired formula (5), even for $k = 0, 1, \dots, n$. If we start this computation with the two factors in (2) reversed we get $A.a_k(A) = a_k(A).A$. Note that (5) for $k = n$ is exactly the *Caley-Hamilton equation*

$$0 = a_n(A) = \sum_{j=0}^{n} c^n_{n-j}(A)A^j.$$

We claim that

$$\operatorname{Trace}(a_k(A)) = (n-k)c^n_k(A). \tag{6}$$

We use (3) for the proof:

$$\begin{aligned}
\tfrac{\partial}{\partial t}\big|_0 (\det(A+t\mathbb{I})) &= d\det(A+t\mathbb{I})\ \tfrac{\partial}{\partial t}\big|_0 (A+t\mathbb{I}) = \operatorname{Trace}(C(A+t\mathbb{I})\mathbb{I}) \\
&= \operatorname{Trace}\left(\sum_{k=0}^{n-1} a_k(A)t^{n-k-1}\right) = \sum_{k=0}^{n-1} \operatorname{Trace}(a_k(A))t^{n-k-1}. \\
\tfrac{\partial}{\partial t}\big|_0 (\det(A+t\mathbb{I})) &= \tfrac{\partial}{\partial t}\big|_0 \left(\sum_{k=0}^{n} c^n_k(A)t^{n-k}\right) \\
&= \sum_{k=0}^{n} (n-k)c^n_k(A)t^{n-k-1}.
\end{aligned}$$

Comparing coefficients leads to the result (6).

Now we may prove the lemma itself by the following computation:

$$\begin{aligned}
(n-k)c^n_k(A) &= \operatorname{Trace}(a_k(A)) \quad \text{by (6)}\\
&= \operatorname{Trace}\left(\sum_{j=0}^{k}(-1)^j c^n_{k-j}(A)A^j\right) \quad \text{by (5)}\\
&= \sum_{j=0}^{k}(-1)^j c^n_{k-j}(A)\operatorname{Trace}(A^j)\\
&= n\,c^n_k(A) + \sum_{j=1}^{k}(-1)^j c^n_{k-j}(A)\operatorname{tr}^n_j(A).\\
c^n_k(A) &= -\tfrac{1}{k}\sum_{j=1}^{k}(-1)^j c^n_{k-j}(A)\operatorname{tr}^n_j(A)\\
&= \tfrac{1}{k}\sum_{j=0}^{k-1}(-1)^{k-j-1} c^n_j(A)\operatorname{tr}^n_{k-j}(A). \quad \square
\end{aligned}$$

23.10. The trace classes. Let (E,p,M) be a real vector bundle. Then the trace classes are given by

(1) $$\operatorname{tr}_k(E) := \left(\frac{-1}{2\pi\sqrt{-1}}\right)^{2k}\operatorname{Cw}(\operatorname{tr}^{\dim E}_{2k}, E)\in H^{4k}(M,\mathbb{R}).$$

Between the trace classes and the Pontryagin classes there are the following relations for $k\ge 1$

(2) $$p_k(E) = \frac{-1}{2k}\sum_{j=0}^{k-1}p_j(E)\wedge\operatorname{tr}_{k-j}(E),$$

which follows directly from lemma (23.9) above.

The inhomogeneous cohomology class

(3) $$\operatorname{tr}(E) = \sum_{k=0}^{\infty}\frac{1}{(2k)!}\operatorname{tr}_k(E) = \operatorname{Cw}(\operatorname{Trace}\circ\exp, E)$$

is called the *Pontryagin character* of E. In the second expression we use the smooth invariant function $\operatorname{Trace}\circ\exp : \mathfrak{gl}(n)\to\mathbb{R}$ which is given by

$$\operatorname{Trace}(\exp(A)) = \operatorname{Trace}\left(\sum_{k\ge 0}\frac{A^k}{k!}\right) = \sum_{k\ge 0}\frac{1}{k!}\operatorname{Trace}(A^k).$$

Of course one should first take the Taylor series at 0 of it and then take the Chern-Weil class of each homogeneous part separately.

Theorem. *Let (E_i, p, M) be vector bundles over the same base manifold M. Then we have*

(4) $\operatorname{tr}(E_1 \oplus E_2) = \operatorname{tr}(E_1) + \operatorname{tr}(E_2)$.
(5) $\operatorname{tr}(E_1 \otimes E_2) = \operatorname{tr}(E_1) \wedge \operatorname{tr}(E_2)$.
(6) $\operatorname{tr}(g^* E) = g^* \operatorname{tr}(E)$ *for any smooth mapping* $g : N \to M$.

Clearly stably equivalent vector bundles have equal Pontryagin characters. Statements (4) and (5) say that one may view the Pontryagin character as a ring homomorphism from the real K-theory into cohomology,

$$\operatorname{tr} : K_{\mathbb{R}}(M) \to H^{4*}(M; \mathbb{R}).$$

Statement (6) says, that it is even a natural transformation.

Proof. (4) This can be proved in the same way as (23.7.1), but we indicate another method which will be used also in the proof of (5) below. Covariant derivatives for E_1 and E_2 induce a covariant derivative on $E_1 \oplus E_2$ by $\nabla_X^{E_1 \oplus E_2}(s_1, s_2) = (\nabla_X^{E_1} s_1, \nabla_X^{E_2}, s_2)$. For the curvature operators we clearly have

$$R^{E_1 \oplus E_2} = R^{E_1} \oplus R^{E_2} = \begin{pmatrix} R^{E_1} & 0 \\ 0 & R^{E_2} \end{pmatrix}$$

So the result follows from (23.9) with the help of (23.5).

(5) We have an induced covariant derivative on $E_1 \otimes E_2$ given by $\nabla_X^{E_1 \otimes E_2} s_1 \otimes s_2 = (\nabla_X^{E_1} s_1) \otimes s_2 + s_1 \otimes (\nabla_X^{E_2} s_2)$. Then for the curvatures we get obviously $R^{E_1 \otimes E_2}(X, Y) = R^{E_1}(X, Y) \otimes Id_{E_2} + Id_{E_1} \otimes R^{E_2}(X, Y)$. The two summands of the last expression commute, so we get

$$(R^{E_1} \otimes Id_{E_2} + Id_{E_1} \otimes R^{E_2})^{\circ_\wedge, k} = \sum_{j=0}^{k} \binom{k}{j} (R^{E_1})^{\circ_\wedge, j} \otimes_\wedge (R^{E_2})^{\circ_\wedge, k-j},$$

where the product involved is given as in

$$(R^E \circ_\wedge R^E)(X_1, \dots, X_4) = \tfrac{1}{2!2!} \sum_\sigma \operatorname{sign}(\sigma) R^E(X_{\sigma 1}, X_{\sigma 2}) \circ R^E(X_{\sigma 3}, X_{\sigma 4}),$$

which makes $(\Omega(M, L(E, E)), \circ_\wedge)$ into a graded associative algebra. The next computation takes place in a commutative subalgebra of it:

$$\begin{aligned}
\operatorname{tr}(E_1 \otimes E_2) &= [\operatorname{Trace} \exp(R^{E_1} \otimes Id_{E_2} + Id_{E_1} \otimes R^{E_2})]_{H(M)} \\
&= [\operatorname{Trace}(\exp(R^{E_1}) \otimes_\wedge \exp(R^{E_2}))]_{H(M)} \\
&= [\operatorname{Trace}(\exp(R^{E_1})) \wedge \operatorname{Trace}(\exp(R^{E_2}))]_{H(M)} \\
&= \operatorname{tr}(E_1) \wedge \operatorname{tr}(E_2).
\end{aligned}$$

(6) This is a general fact. $\square$

23.11. The Pfaffian coefficient. Let (V, g) be a real Euclidian vector space of dimension n, with a positive definite inner product g. Then for each p we have an induced inner product on $\Lambda^p V$ which is given by

$$\langle x_1 \wedge \dots \wedge x_p, y_1 \wedge \dots \wedge y_p \rangle_g = \det(g(x_i, y_j)_{i,j}).$$

Moreover the inner product g, when viewed as a linear isomorphism $g : V \to V^*$, induces an isomorphism $\beta : \Lambda^2 V \to L_{g,\,\text{skew}}(V, V)$ which is given on decomposable forms by $\beta(x \wedge y)(z) = g(x, z)y - g(y, z)x$. We also have

$$\beta^{-1}(A) = A \circ g^{-1} \in L_{\text{skew}}(V^*, V) = \{B \in L(V^*, V) : B^t = -B\} \cong \Lambda^2 V, \text{ where}$$
$$B^t : V^* \xrightarrow{B^*} V^{**} \xrightarrow{\cong} V.$$

Now we assume that V is of even dimension n and is oriented. Then there is a unique element $e \in \Lambda^n V$ which is positive and normed: $\langle e, e \rangle_g = 1$. We define

$$\operatorname{Pf}^g(A) := \frac{1}{n!}\langle e, \overbrace{\beta^{-1}(A) \wedge \dots \wedge \beta^{-1}(A)}^{n/2} \rangle_g, \qquad A \in \mathfrak{so}(n, \mathbb{R}).$$

This is a homogeneous polynomial of degree $n/2$ on $\mathfrak{so}(n, \mathbb{R})$. Its polarisation is the $n/2$-linear symmetric functional

$$\operatorname{Pf}^g(A_1, \dots, A_{n/2}) = \frac{1}{n!}\langle e, \beta^{-1}(A_1) \wedge \dots \wedge \beta^{-1}(A_{n/2}) \rangle_g.$$

Lemma.

(1) *If $U \in O(V, g)$ then $\operatorname{Pf}^g(U.A.U^{-1}) = \det(U)\operatorname{Pf}^g(A)$, so Pf^g is invariant under the adjoint action of $SO(V, g)$.*

(2) *If $X \in L_{g,\,\text{skew}}(V, V) = \mathfrak{o}(V, g)$ then we have*

$$\sum_{i=1}^{n/2} \operatorname{Pf}^g(A_1, \dots, [X, A_i], \dots, A_{n/2}) = 0.$$

Proof. (1) We have $U \in O(V, g)$ if and only if $g(Ux, Uy) = g(x, y)$. For $g : V \to V^*$ this means $U^* g U = g$ and $U^{-1} g^{-1} (U^{-1})^* = g^{-1}$, so we get $\beta^{-1}(UAU^{-1}) = UAU^{-1} g^{-1} = UAg^{-1}U^* = \Lambda^2(U)\beta^{-1}(A)$ and in turn:

$$\begin{aligned}
\operatorname{Pf}^g(UAU^{-1}) &= \frac{1}{n!}\langle e, \Lambda^n(U)(\beta^{-1}(A) \wedge \dots \wedge \beta^{-1}(A)) \rangle_g \\
&= \frac{1}{n!}\det(U)\langle \Lambda^n(U)e, \Lambda^n(U)(\beta^{-1}(A) \wedge \dots \wedge \beta^{-1}(A)) \rangle_g \\
&= \frac{1}{n!}\det(U)\langle e, \beta^{-1}(A) \wedge \dots \wedge \beta^{-1}(A) \rangle_g \\
&= \det(U)\operatorname{Pf}^g(A).
\end{aligned}$$

(2) This follows from (1) by differentiation, see the beginning of the proof of (23.3). □

23.12. The Pfaffian class. Let (E,p,M,V) be a vector bundle which is fiber oriented and of even fiber dimension. If we choose a fiberwise Riemannian metric on E, we in fact reduce the linear frame bundle of E to the oriented orthonormal one $SO(\mathbb{R}^n,E)$. On the Lie algebra $\mathfrak{o}(n,\mathbb{R})$ of the structure group $SO(n,\mathbb{R})$ the Pfaffian form Pf of the standard inner product is an invariant, $\operatorname{Pf}\in I^{n/2}(SO(n,\mathbb{R}))$. We define the *Pfaffian class* of the oriented bundle E by

$$\operatorname{Pf}(E):=\left(\frac{-1}{2\pi\sqrt{-1}}\right)^{n/2}\frac{1}{(n/2)!}\operatorname{Cw}(\operatorname{Pf},SO(\mathbb{R}^n,E))\in H^n(M).$$

It does not depend on the choice of the Riemannian metric on E, since for any two fiberwise Riemannian metrics g_1 and g_2 on E there is an isometric vector bundle isomorphism $f:(E,g_1)\to(E,g_2)$ covering the identity of M, which pulls a $SO(n)$-connection for (E,g_2) to an $SO(n)$-connection for (E,g_1). So the two Pfaffian classes coincide since then $\operatorname{Pf}^1\circ(f^*\Omega_2\otimes_\wedge\dots\otimes_\wedge f^*\Omega_2)=\operatorname{Pf}^2\circ(\Omega_2\otimes_\wedge\dots\otimes_\wedge\Omega_2)$.

Theorem. *The Pfaffian class of oriented even dimensional vector bundles has the following properties:*

(1) $\operatorname{Pf}(E)^2=(-1)^{n/2}p_{n/2}(E)$ *where n is the fiber dimension of E.*
(2) $\operatorname{Pf}(E_1\oplus E_2)=\operatorname{Pf}(E_1)\wedge\operatorname{Pf}(E_2)$
(3) $\operatorname{Pf}(g^*E)=g^*\operatorname{Pf}(E)$ *for smooth $g:N\to M$.*

Proof. This is left as an exercise for the reader. □

23.13. Chern classes. Let (E,p,M) be a complex vector bundle over the smooth manifold M. So the structure group is $GL(n,\mathbb{C})$ where n is the fiber dimension. Recall now the explanation of the characteristic coefficients c^n_k in (23.6) and insert complex numbers everywhere. Then we get the characteristic coefficients $c^n_k\in I^k(GL(n,\mathbb{C}))$, which are just the extensions of the real ones to the complexification. We define then the *Chern classes* by

$$c_k(E):=\left(\frac{-1}{2\pi\sqrt{-1}}\right)^k\operatorname{Cw}(c_k^{\dim E},E)\in H^{2k}(M;\mathbb{R}). \tag{1}$$

The *total Chern class* is again the inhomogeneous cohomology class

$$c(E):=\sum_{k=0}^{\dim_\mathbb{C}E}c_k(E)\in H^{2*}(M;\mathbb{R}). \tag{2}$$

It has the following properties:

$$c(\bar E)=(-1)^{\dim_\mathbb{C}E}c(E) \tag{3}$$

$$c(E_1\oplus E_2)=c(E_1)\wedge c(E_2) \tag{4}$$

$$c(g^*E)=g^*c(E)\quad\text{for smooth } g:N\to M \tag{5}$$

One can show (see [Milnor-Stasheff, 1974]) that (3), (4), (5), and the following normalisation determine the total Chern class already completely: The total Chern class of the canonical complex line bundle over S^2 (the square root of the tangent bundle with respect to the tensor product) is $1+\omega_{S^2}$, where ω_{S^2} is the canonical volume form on S^2 with total volume 1.

Lemma. *Then Chern classes are real cohomology classes.*

Proof. We choose a hermitian metric on the complex vector bundle E, i. e. we reduce the structure group from $GL(n,\mathbb{C})$ to $U(n)$. Then the curvature Ω of a $U(n)$-principal connection has values in the Lie algebra $\mathfrak{u}(n)$ of skew hermitian matrices A with $A^* = -A$. But then we have $c_k^n(-\sqrt{-1}A) \in \mathbb{R}$ since $\overline{\det_{\mathbb{C}}(-\sqrt{-1}A + t\mathbb{I})} = \det_{\mathbb{C}}(\overline{-\sqrt{-1}A + t\mathbb{I}}) = \det_{\mathbb{C}}(-\sqrt{-1}A + t\mathbb{I})$. □

23.14. The Chern character. The *trace classes of a complex vector bundle* are given by

$$\operatorname{tr}_k(E) := \left(\frac{-1}{2\pi\sqrt{-1}}\right)^k \operatorname{Cw}(\operatorname{tr}_k^{\dim E}, E) \in H^{2k}(M,\mathbb{R}). \tag{1}$$

They are also real cohomology classes, and we have $\operatorname{tr}_0(E) = \dim_{\mathbb{C}} E$, the fiber dimension of E, and $\operatorname{tr}_1(E) = c_1(E)$. In general we have the following recursive relation between the Chern classes and the trace classes:

$$c_k(E) = \frac{-1}{k}\sum_{j=0}^{k-1} c_j(E) \wedge \operatorname{tr}_{k-j}(E), \tag{2}$$

which follows directly from lemma (23.9). The inhomogeneous cohomology class

$$\operatorname{ch}(E) := \sum_{k\ge 0} \frac{1}{k!}\operatorname{tr}_k(E) \in H^{2*}(M,\mathbb{R}) \tag{3}$$

is called the *Chern character* of the complex vector bundle E. With the same methods as for the Pontryagin character one can show that the Chern character satisfies the following properties:

$$\operatorname{ch}(E_1 \oplus E_2) = \operatorname{ch}(E_1) + \operatorname{ch}(E_2) \tag{4}$$

$$\operatorname{ch}(E_1 \otimes E_2) = \operatorname{ch}(E_1) \wedge \operatorname{ch}(E_2) \tag{5}$$

$$\operatorname{ch}(g^* E) = g^* \operatorname{ch}(E) \tag{6}$$

From these it clearly follows that the Chern character can be viewed as a ring homomorphism from complex K-theory into even cohomology,

$$\operatorname{ch} : K_{\mathbb{C}}(M) \to H^{2*}(M,\mathbb{R}),$$

which is natural.

Finally we remark that the Pfaffian class of the underlying real vector bundle of a complex vectorbundle E of complex fiber dimension n coincides with the Chern class $c_n(E)$. But there is a new class, the Todd class, see below.

23.15. The Todd class. On the vector space $\mathfrak{gl}(n,\mathbb{C})$ of all complex $(n\times n)$-matrices we consider the smooth function

$$f(A) := \det_{\mathbb{C}}\left(\sum_{k=0}^{\infty}\frac{(-1)^k}{(k+1)!}A^k\right). \tag{1}$$

It is the unique smooth function which satisfies the functional equation

$$\det(A).f(A) = \det(\mathbb{I}-\exp(-A)).$$

Clearly f is invariant under $\operatorname{Ad}(GL(n,\mathbb{C}))$ and $f(0)=1$, so we may consider the invariant smooth function, defined near 0, $\operatorname{Td}:\mathfrak{gl}(n,\mathbb{C})\supset U\to\mathbb{C}$, which is given by $\operatorname{Td}(A)=1/f(A)$. It is uniquely defined by the functional equation

$$\begin{aligned}\det(A) &= \operatorname{Td}(A)\det(\mathbb{I}-\exp(-A))\\ \det(\tfrac12 A)\det(\exp(\tfrac12 A)) &= \operatorname{Td}(A)\det(\sinh(\tfrac12 A)).\end{aligned}$$

The *Todd class* of a complex vector bundle is then given by

$$\begin{aligned}\operatorname{Td}(E) &= \left[GL(\mathbb{C}^n,E)[\operatorname{Td}]\left(\sum_{k\ge0}\left(\frac{-1}{2\pi\sqrt{-1}}R^E\right)^{\otimes_\wedge,k}\right)\right]_{H^{2*}(M,\mathbb{R})} \\ &= \operatorname{Cw}(\operatorname{Td},E).\end{aligned} \tag{2}$$

The Todd class is a real cohomology class since for $A\in\mathfrak{u}(n)$ we have $\operatorname{Td}(-A) = \operatorname{Td}(A^*) = \overline{\operatorname{Td}(A)}$. Since $\operatorname{Td}(0)=1$, the Todd class $\operatorname{Td}(E)$ is an invertible element of $H^{2*}(M,\mathbb{R})$.

23.16. The Atiyah-Singer index formula (roughly). Let E_i be complex vector bundles over a compact manifold M, and let $D:\Gamma(E_1)\to\Gamma(E_2)$ be an elliptic pseudodifferential operator of order p. Then for appropriate Sobolev completions D prolongs to a bounded Fredholm operator between Hilbert spaces $D:\mathcal{H}^{d+p}(E_1)\to\mathcal{H}^d(E_2)$. Its *index* $\operatorname{index}(D)$ is defined as the dimension of the kernel minus dimension of the cokernel, which does not depend on d if it is high enough. The Atiyah-Singer index formula says that

$$\operatorname{index}(D) = (-1)^{\dim M}\int_{TM}\operatorname{ch}(\sigma(D))\operatorname{Td}(TM\otimes\mathbb{C}),$$

where $\sigma(D)$ is a virtual vector bundle (with compact support) on $TM\setminus 0$, a formal difference of two vector bundles, the so called symbol bundle of D.

See [Boos, 1977] for a rather unprecise introduction, [Shanahan, 1978] for a very short introduction, [Gilkey, 1984] for an analytical treatment using the heat kernel method, [Lawson, Michelsohn, 1989] for a recent treatment and the papers by Atiyah and Singer for the real thing.

Special cases are The Gauss-Bonnet-Chern formula, and the Riemann-Roch-Hirzebruch formula.

24. Jets

Jet spaces or jet bundles consist of the invariant expressions of Taylor developments up to a certain order of smooth mappings between manifolds. Their invention goes back to Ehresmann [Ehresmann, 1951]. We could have treated them from the beginning and could have mixed them into every chapter; but it is also fine to have all results collected in one place.

24.1. Contact. Recall that smooth functions $f, g : \mathbb{R} \to \mathbb{R}$ are said to have *contact of order* k at 0 if all their values and all derivatives up to order k coincide.

Lemma. *Let $f, g : M \to N$ be smooth mappings between smooth manifolds and let $x \in M$. Then the following conditions are equivalent.*

(1) *For each smooth curve $c : \mathbb{R} \to M$ with $c(0) = x$ and for each smooth function $h \in C^\infty(M)$ the two functions $h \circ f \circ c$ and $h \circ g \circ c$ have contact of order k at 0.*
(2) *For each chart (U, u) of M centered at x and each chart (V, v) of N with $f(x) \in V$ the two mappings $v \circ f \circ u^{-1}$ and $v \circ g \circ u^{-1}$, defined near 0 in $\mathbb{R}^m$, with values in $\mathbb{R}^n$, have the same Taylor development up to order k at 0.*
(3) *For some charts (U, u) of M and (V, v) of N with $x \in U$ and $f(x) \in V$ we have*
$$\frac{\partial^{|\alpha|}}{\partial u^\alpha}\Big|_x (v \circ f) = \frac{\partial^{|\alpha|}}{\partial u^\alpha}\Big|_x (v \circ g)$$
for all multi indices $\alpha \in \mathbb{N}^m$ with $0 \le |\alpha| \le k$.
(1) *$T^k_x f = T^k_x g$, where T^k is the k-th iterated tangent bundle functor.*

Proof. This is an easy exercise in Analysis.

24.2. Definition. If the equivalent conditions of lemma (24.1) are satisfied, we say that f and g have the same *k-jet at x* and we write $j^k f(x)$ or $j^k_x f$ for the resulting equivalence class and call it the *k -jet at x* of f; x is called the *source* of the k-jet, $f(x)$ is its *target*.

The space of all k-jets of smooth mappings from M to N is denoted by $J^k(M, N)$. We have the *source mapping* $\alpha : J^k(M, N) \to M$ and the *target mapping* $\beta : J^k(M, N) \to N$, given by $\alpha(j^k f(x)) = x$ and $\beta(j^k f(x)) = f(x)$. We will also write $J^k_x(M, N) := \alpha^{-1}(x)$, $J^k(M, N)_y := \beta^{-1}(y)$, and $J^k_x(M, N)_y := J^k_x(M, N) \cap J^k(M, N)_y$ for the spaces of jets with source x, target y, and both, respectively. For $l < k$ we have a canonical surjective mapping $\pi^k_l : J^k(M, N) \to J^l(M, N)$, given by $\pi^k_l(j^k f(x)) := j^l f(x)$. This mapping respects the fibers of α and β and $\pi^k_0 = (\alpha, \beta) : J^k(M, N) \to M \times N$.

24.3. Jets on vector spaces. Now we look at the case $M=\mathbb{R}^m$ and $N=\mathbb{R}^n$. Let $f:\mathbb{R}^m\to\mathbb{R}^n$ be a smooth mapping. Then by (24.1.3) the k-jet $j^kf(x)$ of f ant x has a canonical representative, namely the Taylor polynomial of order k of f at x:

$$\begin{aligned} f(x+y) &= f(x)+df(x).y+\frac{1}{2!}d^2f(x)y^2+\dots+\frac{1}{k!}d^kf(x).y^k+o(|y|^k)\\ &=: f(x)+\operatorname{Tay}^k_xf(y)+o(|y|^k)\end{aligned}$$

Here y^k is short for $(y,y,\dots,y)$, k-times. The 'Taylor polynomial without constant'

$$\operatorname{Tay}^k_xf:y\mapsto\operatorname{Tay}^k_x(y):=df(x).y+\frac{1}{2!}d^2f(x).y^2+\dots+\frac{1}{k!}d^kf(x).y^k$$

is an element of the linear space

$$P^k(m,n):=\bigoplus_{j=1}^k L^j_{sym}(\mathbb{R}^m,\mathbb{R}^n),$$

where $L^j_{sym}(\mathbb{R}^m,\mathbb{R}^n)$ is the vector space of all j-linear symmetric mappings $\mathbb{R}^m\times\dots\times\mathbb{R}^m\to\mathbb{R}^n$, where we silently use the total polarization of polynomials. Conversely each polynomial $p\in P^k(m,n)$ defines a k-jet $j^k_0(y\mapsto z+p(x+y))$ with arbitrary source x and target z. So we get canonical identifications $J^k_x(\mathbb{R}^m,\mathbb{R}^n)_z\cong P^k(m,n)$ and

$$J^k(\mathbb{R}^m,\mathbb{R}^n)\cong\mathbb{R}^m\times\mathbb{R}^n\times P^k(m,n).$$

If $U\subset\mathbb{R}^m$ and $V\subset\mathbb{R}^n$ are open subsets then clearly $J^k(U,V)\cong U\times V\times P^k(m,n)$ in the same canonical way.

For later uses we consider now the *truncated composition*

$$\bullet:P^k(m,n)\times P^k(p,m)\to P^k(p,n),$$

where $p\bullet q$ is just the polynomial $p\circ q$ without all terms of order $>k$. Obviously it is a polynomial, thus real analytic mapping. Now let $U\subset\mathbb{R}^m$, $V\subset\mathbb{R}^n$, and $W\subset\mathbb{R}^p$ be open subsets and consider the fibered product

$$\begin{aligned} J^k(U,V)\times_U J^k(W,U) &= \{\,(\sigma,\tau)\in J^k(U,V)\times J^k(W,U):\alpha(\sigma)=\beta(\tau)\,\}\\ &= U\times V\times W\times P^k(m,n)\times P^k(p,m).\end{aligned}$$

Then the mapping

$$\begin{gathered}\gamma:J^k(U,V)\times_U J^k(W,U)\to J^k(W,V),\\ \gamma(\sigma,\tau)=\gamma((\alpha(\sigma),\beta(\sigma),\bar\sigma),(\alpha(\tau),\beta(\tau),\bar\tau))=(\alpha(\tau),\beta(\sigma),\bar\sigma\bullet\bar\tau),\end{gathered}$$

is a real analytic mapping, called the *fibered composition of jets.*

Let U, $U' \subset \mathbb{R}^m$ and $V \subset \mathbb{R}^n$ be open subsets and let $g : U' \to U$ be a smooth diffeomorphism. We define a mapping $J^k(g,V) : J^k(U,V) \to J^k(U',V)$ by $J^k(g,V)(j^k f(x)) = j^k(f \circ g)(g^{-1}(x))$. Using the canonical representation of jets from above we get $J^k(g,V)(\sigma) = \gamma(\sigma, j^k g(g^{-1}(x)))$ or $J^k(g,V)(x,y,\bar\sigma) = (g^{-1}(x), y, \bar\sigma \bullet \operatorname{Tay}^k_{g^{-1}(x)} g)$. If g is a C^p diffeomorphism then $J^k(g,V)$ is a C^{p-k} diffeomorphism. If $g' : U'' \to U'$ is another diffeomorphism, then clearly $J^k(g',V) \circ J^k(g,V) = J^k(g \circ g', V)$ and $J^k(\quad, V)$ is a contravariant functor acting on diffeomorphisms between open subsets of $\mathbb{R}^m$. Since the truncated composition $\bar\sigma \mapsto \bar\sigma \bullet \operatorname{Tay}^k_{g^{-1}(x)} g$ is linear, the mapping $J^k_x(g,\mathbb{R}^n) := J^k(g,\mathbb{R}^n)|J^k_x(U,\mathbb{R}^n) : J^k_x(U,\mathbb{R}^n) \to J^k_{g^{-1}(x)}(U',\mathbb{R}^n)$ is also linear.

If more generally $g : M' \to M$ is a diffeomorphism between manifolds the same formula as above defines a bijective mapping $J^k(g,N) : J^k(M,N) \to J^k(M',N)$ and clearly $J^k(\quad, N)$ is a contravariant functor defined on the category of manifolds and diffeomorphisms.

Now let $U \subset \mathbb{R}^m$, $V \subset \mathbb{R}^n$, and $W \subset \mathbb{R}^p$ be open subsets and let $h : V \to W$ be a smooth mapping. Then we define $J^k(U,h) : J^k(U,V) \to J^k(U,W)$ by $J^k(U,h)(j^k f(x)) = j^k(h \circ f)(x)$ or equivalently by

$$J^k(U,h)(x,y,\bar\sigma) = (x, h(y), \operatorname{Tay}^k_y h \bullet \bar\sigma).$$

If h is C^p, then $J^k(U,h)$ is C^{p-k}. Clearly $J^k(U, \quad)$ is a covariant functor acting on smooth mappings between open subsets of finite dimensional vector spaces. The mapping $J^k_x(U,h)_y : J^k_x(U,V)_y \to J^k(U,W)_{h(y)}$ is linear if and only if the mapping $\bar\sigma \mapsto \operatorname{Tay}^k_y h \bullet \bar\sigma$ is linear, so if h is affine or if $k = 1$.

If $h : N \to N'$ is a smooth mapping between manifolds we have by the same prescription a mapping $J^k(M,h) : J^k(M,N) \to J^k(M,N')$ and $J^k(M, \quad)$ turns out to be a functor on the category of manifolds and smooth mappings.

24.4. The differential group G^k_m. The k-jets at 0 of diffeomorphisms of $\mathbb{R}^m$ which map 0 to 0 form a group under truncated composition, which will be denoted by $GL^k(m,\mathbb{R})$ or G^k_m for short, and will be called the *differential group of order* k. Clearly an arbitrary 0-respecting k-jet $\sigma \in P^k(m,m)$ is in G^k_m if and only if its linear part is invertible, thus

$$G^k_m = GL^k(m,\mathbb{R}) = GL(m) \oplus \bigoplus_{j=2}^{k} L^j_{\text{sym}}(\mathbb{R}^m,\mathbb{R}^m) =: GL(m) \times P^k_2(m),$$

where we put $P^k_2(m) = \bigoplus_{j=2}^k L^j_{\text{sym}}(\mathbb{R}^m,\mathbb{R}^m)$ for the space of all polynomial mappings without constant and linear term of degree $\le k$. Since the truncated composition is a polynomial mapping, G^k_m is a Lie group, and the mapping $\pi^k_l : G^k_m \to G^l_m$ is a homomorphism of Lie groups, so $\ker(\pi^k_l) = \bigoplus_{j=l+1}^k L^j_{\text{sym}}(\mathbb{R}^m,\mathbb{R}^m) =: P^k_{l+1}(m)$ is a normal subgroup for all l. The exact sequence of groups

$$\{e\} \to P^k_{l+1}(m) \to G^k_m \to G^l_m \to \{e\}$$

splits if and only if $l = 1$; only then we have a semidirect product.

24.5. Theorem. *If M and N are smooth manifolds, the following results hold.*

(1) $J^k(M,N)$ *is a smooth manifold (it is of class C^{r-k} if M and N are of class C^r); a canonical atlas is given by all charts $(J^k(U,V), J^k(u^{-1},v))$, where (U,u) is a chart on M and (V,v) is a chart on N.*

(2) $(J^k(M,N),(\alpha,\beta),M\times N,P^k(m,n),G^k_m\times G^k_n)$ *is a fiber bundle with structure group, where $m = dimM$, $n = dimN$, and where $(\gamma,\chi)\in G^k_m\times G^k_n$ acts on $\sigma\in P^k(m,n)$ by $(\gamma,\chi).\sigma = \chi\bullet\sigma\bullet\gamma^{-1}$.*

(3) *If $f : M\to N$ is a smooth mapping then $j^kf : M\to J^k(M,N)$ is also smooth (it is C^{r-k} if f is C^r), sometimes called the k-jet extension of f. We have $\alpha\circ j^kf = Id_M$ and $\beta\circ j^kf = f$.*

(4) *If $g : M'\to M$ is a (C^r-) diffeomorphism then also the induced mapping $J^k(g,N) : J^k(M,N)\to J^k(M',N)$ is a (C^{r-k}-) diffeomorphism.*

(5) *If $h : N\to N'$ is a (C^r-) mapping then $J^k(M,h) : J^k(M,N)\to J^k(M,N')$ is a (C^{r-k}-) mapping. $J^k(M,\quad)$ is a covariant functor from the category of smooth manifolds and smooth mappings into itself which maps each of the following classes of mappings into itself: immersions, embeddings, closed embeddings, submersions, surjective submersions, fiber bundle projections. Furthermore $J^k(\quad,\quad)$ is a contra- covariant bifunctor.*

(6) *The projections $\pi^k_l : J^k(M,N)\to J^l(M,N)$ are smooth and natural, i.e. they commute with the mappings from (4) and (5).*

(7) $(J^k(M,N),\pi^k_l,J^l(M,N),P^k_{l+1}(m,n))$ *are fiber bundles for all l. The bundle $(J^k(M,N),\pi^k_{k-1},J^{k-1}(M,N),L^k_{\text{sym}}(\mathbb{R}^m,\mathbb{R}^n))$ is an affine bundle. The first jet space $J^1(M,N)$ is a vector bundle, it is isomorphic to the bundle $(L(TM,TN),(\pi_M,\pi_N),M\times N)$. Moreover we have $J^1_0(\mathbb{R},N) = TN$ and $J^1(M,\mathbb{R})_0 = T^*M$.*

Proof. We use (24.3) heavily. Let (U_γ,u_γ) be an atlas of M and let $(V_\varepsilon,v_\varepsilon)$ be an atlas of N. Then $J^k(u_\gamma^{-1},v_\varepsilon) : (\alpha,\beta)^{-1}(U_\gamma\times V_\varepsilon)\to J^k(u_\gamma(U_\gamma),v_\varepsilon(V_\varepsilon))$ is a bijective mapping and the chart change looks like

$$J^k(u_\gamma^{-1},v_\varepsilon)\circ J^k(u_\delta^{-1},v_\nu)^{-1} = J^k(u_\delta\circ u_\gamma^{-1},v_\varepsilon\circ v_\nu^{-1})$$

by the functorial properties of $J^k(\quad,\quad)$. $J^k(M,N)$ is Hausdorff in the identification topology, since it is a fiber bundle and the usual argument for gluing fiber bundles applies. So (1) follows.

Now we make this manifold atlas into a fiber bundle by using as charts

$$\begin{aligned}(U_\gamma\times V_\varepsilon),\psi_{(\gamma,\varepsilon)} : J^k(M,N)|U_\gamma\times V_\varepsilon &\to U_\gamma\times V_\varepsilon\times P^k(m,n),\\ \psi_{(\gamma,\varepsilon)}(\sigma) &= (\alpha(\sigma),\beta(\sigma),J^k_{\alpha(\sigma)}(u_\gamma^{-1},v_\varepsilon)_{\beta(\sigma)}.\end{aligned}$$

We then get as transition functions

$$\begin{aligned}\psi_{(\gamma,\varepsilon)}\psi_{(\delta,\nu)}(x,y,\bar\sigma) &= (x,y,J^k_{u_\delta(x)}(u_\delta\circ u_\gamma^{-1},v_\varepsilon\circ v_\nu^{-1})(\bar\sigma))\\ &= \big(x,y,\operatorname{Tay}^k_{v_\nu(y)}(v_\varepsilon\circ v_\nu^{-1})\bullet\bar\sigma\bullet\operatorname{Tay}^k_{u_\gamma(x)}(u_\delta\circ u_\gamma^{-1})\big),\end{aligned}$$

and (2) follows.

(3), (4), and (6) are obvious from (24.3), mainly by the functorial properties of $J^k(\quad,\quad)$.

(5). We will show later that these assertions hold in a much more general situation, see the chapter on product preserving functors. It is clear from (24.3) that $J^k(M,h)$ is a smooth mapping. The rest follows by looking at special chart representations of h and the induced chart representations for $J^k(M,h)$.

It remains to show (7) and here we concentrate on the affine bundle. Let $a_1+a\in GL(n)\times P^k_2(n,n)$, $\sigma+\sigma_k\in P^{k-1}(m,n)\oplus L^k_{\text{sym}}(\mathbb{R}^m,\mathbb{R}^n)$, and $b_1+b\in GL(m)\times P^k_2(m,m)$, then the only term of degree k containing σ_k in $(a+a_k)\bullet(\sigma+\sigma_k)\bullet(b+b_k)$ is $a_1\circ\sigma_k\circ b_1^k$, which depends linearly on σ_k. To this the degree k-components of compositions of the lower order terms of σ with the higher order terms of a and b are added, and these may be quite arbitrary. So an affine bundle results.

We have $J^1(M,N)=L(TM,TN)$ since both bundles have the same transition functions. Finally we have $J^1_0(\mathbb{R},N)=L(T_0\mathbb{R},TN)=TN$, and $J^1(M,\mathbb{R})_0=L(TM,T_0\mathbb{R})=T^*M$ □

24.6. Frame bundles and natural bundles.. Let M be a manifold of dimension m. We consider the jet bundle $J^1_0(\mathbb{R}^m,M)=L(T_0\mathbb{R}^m,TM)$ and the open subset $invJ^1_0(\mathbb{R}^m,M)$ of all invertible jets. This is visibly equal to the linear frame bundle of TM as treated in (21.11).

Note that a mapping $f:\mathbb{R}^m\to M$ is locally invertible near 0 if and only if $j^1f(0)$ is invertible. A jet σ will be called *invertible* if its order 1-part $\pi^k_1(\sigma)\in J^1_0(\mathbb{R}^m,M)$ is invertible. Let us now consider the open subset $invJ^k_0(\mathbb{R}^m,M)\subset J^k_0(\mathbb{R}^m,M)$ of all invertible jets and let us denote it by P^kM. Then by (21.2) we have a principal fiber bundle (P^kM,π_M,M,G^k_m) which is called the *k-th order frame bundle* of the manifold M. Its principal right action r can be described in several ways. By the fiber composition of jets:

$$r=\gamma: invJ^k_0(\mathbb{R}^m,\mathbb{R}^m)\times invJ^k_0(\mathbb{R}^m,M)=G^k_m\times P^kM\to P^kM;$$

or by the functorial property of the jet bundle:

$$r^{j^kg(0)}=invJ^k_0(g,M)$$

for a local diffeomorphism $g:\mathbb{R}^m,0\to\mathbb{R}^m,0$.

If $h:M\to M'$ is a local diffeomorphism, the induced mapping $J^k_0(\mathbb{R}^m,h)$ maps the open subset P^kM into P^kM'. By the second description of the principal right action this induced mapping is a homomorphism of principal fiber bundles which we will denote by $P^k(h):P^kM\to P^kM'$. Thus P^k becomes a covariant functor from the category $\mathcal{M}f_m$ of m-dimensional manifolds and local diffeomorphisms into the category of all principal fiber bundles with structure group G^k_m over m-dimensional manifolds and homomorphisms of principal fiber bundles covering local diffeomorphisms.

If we are given any smooth left action $\ell : G^k_m \times S \to S$ on some manifold S, the associated bundle construction from theorem (21.7) gives us a fiber bundle $P^kM[S,\ell] = P^kM \times_{G^k_m} S$ over M for each m-dimensional manifold M; by (21.9.3) this describes a functor $P^k(\quad)[S,\ell]$ from the category $\mathcal{M}f_m$ into the category of all fiber bundles over m-dimensional manifolds with standard fiber S and G^k_m-structure, and homomorphisms of fiber bundles covering local diffeomorphisms. These bundles are also called *natural bundles* or *geometric objects*.

24.7. Theorem. *If (E, p, M, S) is a fiber bundle, let us denote by $J^k(E) \to M$ the space of all k-jets of sections of E. Then we have:*

(1) *$J^k(E)$ is a closed submanifold of $J^k(M,E)$.*
(2) *The first jet bundle $J^1(E) \to M \times E$ is an affine subbundle of the vector bundle $J^1(M,E) = L(TM, TE)$, in fact we have $J^1(E) = \{\, \sigma \in L(TM,TE) : Tp \circ \sigma = Id_{TM} \,\}$.*
(3) *$(J^k(E), \pi^k_{k-1}, J^{k-1}(E))$ is an affine bundle.*
(4) *If (E, p, M) is a vector bundle, then $(J^k(E), \alpha, M)$ is also a vector bundle. If $\phi : E \to E'$ is a homomorphism of vector bundles covering the identity, then $J^k(\varphi)$ is of the same kind.*

Proof. (1). By (24.5.5) the mapping $J^k(M,p)$ is a submersion, thus $J^k(E) = J^k(M,p)^{-1}(j^k(Id_M))$ is a submanifold. (2) is clear. (3) and (4) are seen by looking at appropriate canonical charts. $\square$

CHAPTER VI
Symplectic Geometry and Hamiltonian Mechanics

25. Symplectic Geometry and Classical Mechanics

25.1. Motivation. A particle with mass $m > 0$ moves in a potential $V(q)$ along a curve $q(t)$ in $\mathbb{R}^3$ in such a way that Newton's second law is satisfied: $m\ddot{q}(t) = -\operatorname{grad} V(q(t))$. Let us consider the the quantity $p_i := m \cdot \dot{q}^i$ as an independent variable. It is called the i-th *momentum*. Let us define the energy function (as the sum of the kinetic and potential energy) by

$$E(q,p) := \frac{1}{2m}|p|^2 + V(q) = \frac{m|\dot{q}|^2}{2} + V(q).$$

Then $m\ddot{q}(t) = -\operatorname{grad} V(q(t))$ is equivalent to

$$\begin{cases} \dot{q}^i = \frac{\partial E}{\partial p_i}, \\ \dot{p}_i = -\frac{\partial E}{\partial q^i}, \qquad i = 1,2,3, \end{cases}$$

which are *Hamilton's equations* of motion. In order to study this equation for a general energy function $E(q,p)$ we consider the matrix

$$J = \begin{pmatrix} 0 & \mathbb{I}_{\mathbb{R}^3} \\ -\mathbb{I}_{\mathbb{R}^3} & 0 \end{pmatrix}.$$

Then the equation is equivalent to $\dot{u}(t) = J \cdot \operatorname{grad} E(u(t))$, where $u = (q,p) \in \mathbb{R}^6$. In complex notation, where $z^i = q^i + \sqrt{-1}\,p_i$, this is equivalent to $\dot{z}^i = -2\sqrt{-1}\frac{\partial E}{\partial \bar{z}^i}$. Consider the *Hamiltonian vector field* $H_E := J \cdot \operatorname{grad} E$ associated to the energy function E, then we have $\dot{u}(t) = H_E(u(t))$, so the orbit of the particle with initial position and momentum $(q_0, p_0) = u_0$ is given by $u(t) = \operatorname{Fl}^{H_E}_t(u_0)$.

Let us now consider the *symplectic structure*

$$\omega(x,y) = \sum_{i=1}^{3}(x^i y^{3+i} - x^{3+i} y^i) = (x|Jy) \quad \text{ for } x,y \in \mathbb{R}^6.$$

Then the Hamiltonian vector field H_E is given by

$$\begin{aligned}\omega(H_E(u),v) &= (H_E|Jv) = (J\,\mathrm{grad}\,E(u)|Jv) = \\ &= (J^\top J\,\mathrm{grad}\,E(u)|v) = (\mathrm{grad}\,E(u)|v) = dE(u)v\end{aligned}$$

The Hamiltonian vector field is therefore the 'gradient of E with respect to the symplectic structure ω; we write $H_E = \mathrm{grad}^\omega E$.

How does this equation react to coordinate transformations? So let $f : \mathbb{R}^3\times\mathbb{R}^3 \to \mathbb{R}^3\times\mathbb{R}^3$ be a (local) diffeomorphism. We consider the energy $E\circ f$ and put $u = f(w)$. Then

$$\begin{aligned}\omega(\mathrm{grad}^\omega(E\circ f)(w),v) &= d(E\circ f)(w)v = dE(f(w)).df(w)v \\ &= \omega(\mathrm{grad}^\omega E(f(w)), df(w)v) = \omega(df(w)\,df(w)^{-1}\,\mathrm{grad}^\omega E(f(w)), df(w)v) \\ &= \omega(df(w)\,(f^*\,\mathrm{grad}^\omega E)(w), df(w)v) = (f^*\omega)((f^*\,\mathrm{grad}^\omega E)(w),v).\end{aligned}$$

So we see that $f^*\,\mathrm{grad}^\omega E = \mathrm{grad}^\omega(E\circ f)$ if and only if $f^*\omega = \omega$, i.e. $df(w) \in Sp(3,\mathbb{R})$ for all w. Such diffeomorphisms are called *symplectomorphisms*. By (3.14) we have $\mathrm{Fl}_t^{f^*\,\mathrm{grad}^\omega E} = f^{-1}\circ\mathrm{Fl}_t^{\mathrm{grad}^\omega E}\circ f$ in any case.

25.2. Lemma. *(E. Cartan) Let V be a real finite dimensional vector space, and let $\omega\in\Lambda^2V^*$ be a 2-form on V. Consider the linear mapping $\check\omega : V\to V^*$ given by $\langle\check\omega(v),w\rangle = \omega(v,w)$.*

If $\omega\neq 0$ then the rank of the linear mapping $\check\omega : V\to V^*$ is $2p$, and there exist linearly independent $l^1,\dots,l^{2p}\in V^*$ which form a basis of $\check\omega(V)\subset V^*$ such that $\omega = \sum_{k=1}^p l^{2k-1}\wedge l^{2k}$. Furthermore, l^2 can be chosen arbitrarily in $\check\omega(V)\setminus 0$.

Proof. Let $v_1,\dots,v_n$ be a basis of V and let $v^1,\dots,v^n$ be the dual basis of V^*. Then $\omega = \sum_{i<j}\omega(v_i,v_j)v^i\wedge v^j =: \sum_{i<j}a_{ij}\,v^i\wedge v^j$. Since $\omega\neq 0$, not all $a_{ij}=0$. Suppose that $a_{12}\neq 0$. Put

$$l^1 = \frac{1}{a_{12}}\check\omega(v^1) = \frac{1}{a_{12}}i(v_1)\omega = \frac{1}{a_{12}}i(v_1)\Big(\sum_{i<j}a_{ij}\,v^i\wedge v^j\Big) = v^2 + \frac{1}{a_{12}}\sum_{j=3}^n a_{1j}\,v^j,$$

$$l^2 = \check\omega(v_2) = i(v_2)\omega = i(v_2)\Big(\sum_{i<j}a_{ij}\,v^i\wedge v^j\Big) = -a_{12}v^1 + \sum_{j=3}^n a_{2j}\,v^j.$$

So, $l^1, l^2, v^3,\dots,v^n$ is still a basis of V^*. Put $\omega_1 := \omega - l^1\wedge l^2$. Then

$$\begin{aligned}i_{v_1}\omega_1 &= i_{v_1}\omega - i_{v_1}l^1\wedge l^2 + l^1\wedge i_{v_1}l^2 = a_{12}l^1 - 0 - a_{12}l^1 = 0,\\ i_{v_2}\omega_1 &= i_{v_2}\omega - i_{v_2}l^1\wedge l^2 + l^1\wedge i_{v_2}l^2 = l^2 - l^2 + 0 = 0\end{aligned}$$

So the 2-form ω_1 belongs to the subalgebra of ΛV^* generated by $v^3, v^4,\dots,v^n$. If $\omega_1 = 0$ then $\omega = l^1\wedge l^2$. If $\omega_1\neq 0$ we can repeat the procedure and get the form of ω.

If $l = \check\omega(v)\in\check\omega(V)\subset V^*$ is arbitrary but $\neq 0$, there is some $w\in V$ with $\langle l,w\rangle = \omega(v,w)\neq 0$. Choose a basis $v_1,\dots,v_n$ of V with $v_1 = w$ and $v_2 = v$. Then $l^2 = i(v_2)\omega = i(v)\omega = l$. □

25.3. Corollary. *Let $\omega \in \Lambda^2 V^*$ and let $2p = \operatorname{rank}(\check{\omega} : V \to V^*)$.*
Then p is the maximal number k such that $\omega^{\wedge k} = \omega \wedge \dots \wedge \omega \neq 0$.

Proof. By (25.2) we have $\omega^{\wedge p} = p!\, l^1 \wedge l^2 \wedge \dots \wedge l^{2p}$ and $\omega^{\wedge(2p+1)} = 0$. □

25.4. Symplectic vector spaces. A symplectic form on a vector space V is a 2-form $\omega \in \Lambda^2 V^*$ such that $\check{\omega} : V \to V^*$ is an isomorphism. Then $\dim(V) = 2n$ and there is a basis $l^1, \dots, l^{2n}$ of V^* such that $\omega = \sum_{i=1}^n l^i \wedge l^{n+i}$, by (25.2).

For a linear subspace $W \subset V$ we define the *symplectic orthogonal* by $W^{\omega\perp} = W^\perp := \{v \in V : \omega(w, v) = 0 \text{ for all } w \in W\}$; which coincides with the annihilator (or polar) $\check{\omega}(W)^\circ = \{v \in V : \langle \check{\omega}(w), v\rangle = 0 \text{ for all } w \in W\}$ in V.

Lemma. *For linear subspaces $W, W_1, W_2 \subset V$ we have:*
1. $W^{\perp\perp} = W$.
2. $\dim(W) + \dim(W^\perp) = \dim(V) = 2n$.
3. $\check{\omega}(W^\perp) = W^\circ$ *and* $\check{\omega}(W) = (W^\perp)^\circ$ *in* V^*.
4. *For two linear subspace $W_1, W_2 \subset V$ we have: $W_1 \subseteq W_2 \Leftrightarrow W_1^\perp \supseteq W_2^\perp$, $(W_1 \cap W_2)^\perp = W_1^\perp + W_2^\perp$, and $(W_1 + W_2)^\perp = W_1^\perp \cap W_2^\perp$.*
5. $\dim(W_1 \cap W_2) - \dim(W_1^\perp \cap W_2^\perp) = \dim W_1 + \dim W_2 - 2n$.

Proof. (1) - (4) are obvious, using duality and the annihilator. (5) can be seen as follows. By (4) we have

$$\dim(W_1 \cap W_2)^\perp = \dim(W_1^\perp + W_2^\perp) = \dim(W_1^\perp) + \dim(W_2^\perp) - \dim(W_1^\perp \cap W_2^\perp),$$
$$\begin{aligned} \dim(W_1 \cap W_2) &= 2n - \dim(W_1 \cap W_2)^\perp \qquad \text{by (2)} \\ &= 2n - \dim(W_1^\perp) - \dim(W_2^\perp) + \dim(W_1^\perp \cap W_2^\perp) \\ &= \dim(W_1) + \dim(W_2) - 2n + \dim(W_1^\perp \cap W_2^\perp). \quad \square \end{aligned}$$

A linear subspace $W \subseteq V$ is called:

isotropic	if	$W \subseteq W^\perp$	$\Rightarrow \dim(W) \le n$
coisotropic	if	$W \supseteq W^\perp$	$\Rightarrow \dim(W) \ge n$
Lagrangian	if	$W = W^\perp$	$\Rightarrow \dim(W) = n$
symplectic	if	$W \cap W^\perp = 0$	$\Rightarrow \dim(W) =$ even.

25.5. Example. Let W be a vector space with dual W^*. Then $(W \times W^*, \omega)$ is a symplectic vector space where $\omega((v, v^*), (w, w^*)) = \langle w^*, v\rangle - \langle v^*, w\rangle$. Choose a basis $w_1, \dots, w_n$ of $W = W^{**}$ and let $w^1, \dots, w^n$ be the dual basis. Then $\omega = \sum_i w^i \wedge w_i$. The two subspace $W \times 0$ and $0 \times W^*$ are Lagrangian.

Consider now a symplectic vector space (V, ω) and suppose that $W_1, W_2 \subseteq V$ are two Lagrangian subspaces such that $W_1 \cap W_2 = 0$. Then $\omega : W_1 \times W_2 \to \mathbb{R}$ is a duality pairing, so we may identify W_2 with W_1^* via ω. Then (V, ω) is isomorphic to $W_1 \times W_1^*$ with the symplectic structure described above.

25.6. Let $\mathbb{R}^{2n} = \mathbb{R}^n \times (\mathbb{R}^n)^*$ with the standard symplectic structure ω from (25.5). Recall from (4.7) the Lie group $Sp(n,\mathbb{R})$ of symplectic automorphisms of $(\mathbb{R}^{2n},\omega)$,

$$Sp(n,\mathbb{R}) = \{A \in L(\mathbb{R}^{2n},\mathbb{R}^{2n}) : A^\top J A = J\}, \qquad \text{where } J = \begin{pmatrix} 0 & \mathbb{I}_{\mathbb{R}^n} \\ -\mathbb{I}_{\mathbb{R}^n} & 0 \end{pmatrix}.$$

Let $(\quad|\quad)$ be the standard inner product on $\mathbb{R}^{2n}$ and let $\mathbb{R}^{2n} \cong \sqrt{-1}\mathbb{R}^n \oplus \mathbb{R}^n = \mathbb{C}^n$, where the scalar multiplication by $\sqrt{-1}$ is given by $J\binom{x}{y} = \binom{-y}{x}$. Then we have:

$$\omega\left(\tbinom{x}{y}, \tbinom{x'}{y'}\right) = \langle y', x\rangle - \langle y, x'\rangle = \left(\tbinom{x}{y}\Big|\, \tbinom{y'}{-x'}\right) = \left(\tbinom{x}{y}\Big|\, J\tbinom{x'}{y'}\right) = (x^T, y^T) J \begin{pmatrix} x' \\ y' \end{pmatrix}.$$

$J^2 = -\mathbb{I}_{R^{2n}}$ implies $J \in Sp(n,\mathbb{R})$, and $J^\top = -J = J^{-1}$ implies $J \in O(2n,\mathbb{R})$. We consider now the Hermitian inner product $h : \mathbb{C}^n \times \mathbb{C}^n \to \mathbb{C}$ given by

$$\begin{aligned}
h(u,v) :&= (u|v) + \sqrt{-1}\omega(u,v) = (u|v) + \sqrt{-1}(u|Jv) \\
h(v,u) &= (v|u) + \sqrt{-1}(v|Ju) = (u|v) + \sqrt{-1}(J^\top v|u) \\
&= (u|v) - \sqrt{-1}(u|Jv) = \overline{h(u,v)} \\
h(Ju,v) &= (Ju|v) + \sqrt{-1}(Ju|Jv) = \sqrt{-1}((u|J^\top Jv) - \sqrt{-1}(u|J^\top v)) \\
&= \sqrt{-1}((u|v) + \sqrt{-1}\omega(u,v)) = \sqrt{-1}h(u,v).
\end{aligned}$$

Lemma. *The subgroups $Sp(n,\mathbb{R})$, $O(2n,\mathbb{R})$, and $U(n)$ of $GL(2n,\mathbb{R})$ acting on $\mathbb{R}^{2n} \cong \mathbb{C}^n$ are related by*

$$O(2n,\mathbb{R}) \cap GL(n,\mathbb{C}) = Sp(n,\mathbb{R}) \cap GL(n,\mathbb{C}) = Sp(n,\mathbb{R}) \cap O(2n,\mathbb{R}) = U(n).$$

Proof. For $A \in GL(2n,\mathbb{R})$ (and all $u,v \in \mathbb{R}^{2n}$) we have in turn

$$\begin{aligned}
& h(Au,Av) = h(u,v) && \Leftrightarrow \quad A \in U(n) \\
& \left\{\begin{matrix} (Au|Av) = (u|v) & \text{(real part)} \\ \omega(Au,Av) = \omega(u,v) & \text{(imaginary part)} \end{matrix}\right\} && \Leftrightarrow \quad A \in O(2n,\mathbb{R}) \cap Sp(n,\mathbb{R}) \\
& \left\{\begin{matrix} (Au|Av) = (u|v) \\ JA = AJ \end{matrix}\right\} && \Leftrightarrow \quad A \in O(2n,\mathbb{R}) \cap GL(n,\mathbb{C}) \\
& \left\{\begin{matrix} JA = AJ \\ (Au|JAv) = (Au|AJv) = (u|Jv) \end{matrix}\right\} && \Leftrightarrow \quad A \in Sp(n,\mathbb{R}) \cap GL(n,\mathbb{C}) \quad \square
\end{aligned}$$

25.7. The Lagrange Grassmann manifold. Let $L(\mathbb{R}^{2n},\omega) = L(2n)$ denote the space of all Lagrangian linear subspaces of $\mathbb{R}^{2n}$; we call it the *Lagrange Grassmann* manifold. It is a subset of the Grassmannian $G(n,2n;\mathbb{R})$, see (21.5).

In the situation of (25.6) we consider a linear subspace $W \subset (\mathbb{R}^{2n},\omega)$ of dimension n. Then we have:

W is a Lagrangian subspace
$\Leftrightarrow \omega|W = 0 \quad \Leftrightarrow \quad (\quad|J(\quad))|W = 0$
$\Leftrightarrow J(W)$ is orthogonal to W with respect to $(\quad|\quad) = \mathrm{Re}(h)$

Thus the group $O(2n,\mathbb{R})\cap GL(n,\mathbb{C}) = U(n)$ acts transitively on the Lagrange Grassmann manifold $L(2n)$. The isotropy group of the Lagrangian subspace $\mathbb{R}^n\times 0$ is the subgroup $O(n,\mathbb{R})\subset U(n)$ consisting of all unitary matrices with all entries real. So by (5.11) we have $L(2n) = U(n)/O(n,\mathbb{R})$ is a compact homogenous space and a smooth manifold. For the dimension we have $\dim L(2n) = \dim U(n) - \dim O(n,\mathbb{R}) = (n + 2\frac{n(n-1)}{2}) - \frac{n(n-1)}{2} = \frac{n(n+1)}{2}$.

Which choices did we make in this construction? If we start with a general symplectic vector space (V,ω), we first fix a Lagrangian subspace L $(=\mathbb{R}^n\times 0)$, then we identify V/L with L^* via ω. Then we chose a positive inner product on L, transport it to L^* via ω and extend it to $L\times L^*$ by putting L and L^* orthogonal to each other. All these possible choices are homotopic to each other.

Finally we consider $\det_{\mathbb{C}} = \det : U(n)\to S^1\subset\mathbb{C}$. Then $\det(O(n)) = \{\pm 1\}$. So $\det^2 : U(n)\to S^1$ and $\det^2(O(n)) = \{1\}$. For $U\in U(n)$ and $A\in O(n,\mathbb{R})$ we have $\det^2(UA) = \det^2(U)\det^2(A) = \det^2(U)$, so this factors to a well defined smooth mapping $\det^2 : U(n)/O(n) = L(2n)\to S^1$.

Claim. The group $SU(n)$ acts (from the left) transitively on each fiber of $\det^2 : L(2n) = U(n)/O(n)\to S^1$.
Namely, for $U_1, U_2\in U(n)$ with $\det^2(U_1) = \det^2(U_2)$ we get $\det(U_1) = \pm\det(U_2)$. There exists $A\in O(n)$ such that $\det(U_1) = \det(U_2.A)$, thus $U_1(U_2A)^{-1}\in SU(n)$ and $U_1(U_2A)^{-1}U_2A\,O(n) = U_1\,O(n)$. The claim is proved.

Now $SU(n)$ is simply connected and each fiber of $\det^2 : U(n)/O(n)\to S^1$ is diffeomorphic to $SU(n)/SO(n)$ which again simply connected by the exact homotopy sequence of a fibration

$$\dots\to(0=\pi_1(SU(n)))\to\pi_1(SU(n)/SO(n))\to(\pi_0(SO(n))=0)\to\dots$$

Using again the exact homotopy sequence

$$\dots\to 0=\pi_1(SU(n)/SO(n))\to\pi_1(L(2n))\to\pi_1(S^1)\to\pi_0(SU(n)/SO(n))=0$$

we conclude that $\pi_1(L(2n)) = \pi_1(S^1) = \mathbb{Z}$. Thus also (by the Hurewicz homomorphism) we have $H^1(L(2n),\mathbb{Z}) = \mathbb{Z}$ and thus $H^1(L(2n),\mathbb{R}) = \mathbb{R}$.

Let $\frac{dz}{2\pi\sqrt{-1}z}|_{S^1} = \frac{xdy-ydx}{2\pi\sqrt{-1}}|_{S^1}\in\Omega^1(S^1)$ be a generator of $H^1(S^1,\mathbb{Z})$. Then the pullback $(\det^2)^*\frac{dz}{2\pi\sqrt{-1}z} = (\det^2)^*\frac{xdy-ydx}{2\pi\sqrt{-1}}\in\Omega^1(L(2n))$ is a generator of $H^1(L(2n))$. Its cohomology class is called the *Maslov-class.*

25.8. Symplectic manifolds, and their submanifolds. A *symplectic manifold* (M,ω) is a manifold M together with a 2-form $\omega\in\Omega^2(M)$ such that $d\omega = 0$ and $\omega_x\in\Lambda^2T_x^*M$ is a symplectic structure on T_xM for each $x\in M$. So $\dim(M)$ is even, $\dim(M) = 2n$, say. Moreover, $\omega^{\wedge n} = \omega\wedge\dots\wedge\omega$ is a volume form on M (nowhere zero), called the *Liouville volume*, which fixes also an orientation of M.

Among the submanifolds N of M we can single out those whose tangent spaces T_xN have special relations to the the symplectic structure ω_x on T_xM as listed in

(25.4): Thus submanifold N of M is called:

isotropic	if	$T_xN \subseteq T_xN^{\omega\perp}$ for each $x \in N$	$\Rightarrow \dim(N) \leq n$
coisotropic	if	$T_xN \supseteq T_xN^{\omega\perp}$ for each $x \in N$	$\Rightarrow \dim(N) \geq n$
Lagrangian	if	$T_xN = T_xN^{\omega\perp}$ for each $x \in N$	$\Rightarrow \dim(N) = n$
symplectic	if	$T_xN \cap T_xN^{\omega\perp} = 0$ for each $x \in N$	$\Rightarrow \dim(N) =$ even,

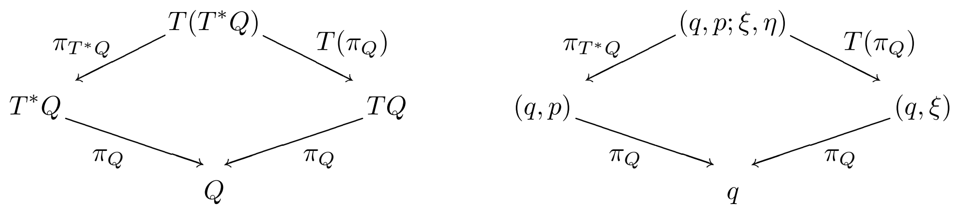
where for a linear subspace $W \subset T_xN$ the symplectic orthogonal is $W^{\omega\perp} = \{X \in T_xM : \omega_x(X,Y) = 0 \text{ for all } Y \in W\}$, as in (25.4).

25.9. The cotantent bundle. Consider the manifold $M = T^*Q$, where Q is a manifold. Recall that for any smooth $f : Q \to P$ which is locally a diffeomorphism we get a homomorphism of vector bundles $T^*f : T^Q \to T^*P$ covering f by $T_x^*f = ((T_xf)^{-1})^* : T_x^*Q \to T_{f(x)}^*P$.

There is a canonical 1-form $\theta = \theta_Q \in \Omega^1(T^*Q)$, called the *Liouville form* which is given by

$$\theta(X) = \langle \pi_{T^*Q}(X), T(\pi_Q)(X)\rangle, \qquad X \in T(T^*Q),$$

where we used the projections (and their local forms):



For a chart $q = (q^1, \dots, q^n) : U \to \mathbb{R}^n$ on Q, and the induced chart $T^*q : T^*U \to \mathbb{R}^n \times \mathbb{R}^n$, where $T_x^*q = (T_xq^{-1})^*$, we put $p_i := \langle e_i, T^*q(\quad)\rangle : T^*U \to \mathbb{R}$. Then $(q^1, \dots, q^n, p_1, \dots, p_n) : T^*U \to \mathbb{R}^n \times (\mathbb{R}^n)^*$ are the canonically induced coordinates. In these coordinates we have

$$\theta_Q = \sum_{i=1}^n \Big(\theta_Q(\tfrac{\partial}{\partial q^i})dq^i + \theta_Q(\tfrac{\partial}{\partial p_i})dp_i\Big) = \sum_{i=1}^n p_i\, dq^i + 0,$$

since $\theta_Q(\frac{\partial}{\partial q^i}) = \theta_{\mathbb{R}^n}(q,p;e_i,0) = \langle p, e_i\rangle = p_i$.

Now we define the *canonical symplectic structure* $\omega_Q = \omega \in \Omega^2(T^*Q)$ by

$$\omega_Q := -d\theta_Q \overset{\text{locally}}{=} \sum_{i=1}^n dq^i \wedge dp_i.$$

Note that $\check\omega(\frac{\partial}{\partial q^i}) = dp_i$ and $\check\omega(\frac{\partial}{\partial p_i}) = -dq^i$.

Lemma. *The 1-form $\theta_Q \in \Omega^1(T^*Q)$ has the following unversal property, and is uniquely determined by it:*

Any 1-form $\varphi \in \Omega^1(Q)$ is a smooth section $\varphi : Q \to T^*Q$ and for the pullback we have $\varphi^*\theta_Q = \varphi \in \Omega^1(Q)$. Moreover, $\varphi^*\omega_Q = -d\varphi \in \Omega^2(Q)$.

The 1-form θ_Q is natural in $Q \in \mathcal{M}f_n$: For any local diffeomorphism $f : Q \to P$ the local diffeomorphism $T^*f : T^*Q \to T^*P$ satisfies $(T^*f)^*\theta_P = \theta_Q$, and a fortiori $(T^*f)^*\omega_P = \omega_Q$.

In this sense θ_Q is a *universal 1-form*, or a *universal connection*, and ω_Q is the *universal curvature*, for $\mathbb{R}^1$-principal bundles over Q. Compare with section (22).

Proof. For a 1-form $\varphi \in \Omega^1(Q)$ we have

$$\begin{aligned}(\varphi^*\theta_Q)(X_x) &= (\theta_Q)_{\varphi_x}(T_x\varphi.X_x) = \varphi_x(T_{\varphi_x}\pi_Q.T_x\varphi.X_x)\\ &= \varphi_x(T_x(\pi_Q \circ \varphi).X_x) = \varphi_x(X_x).\end{aligned}$$

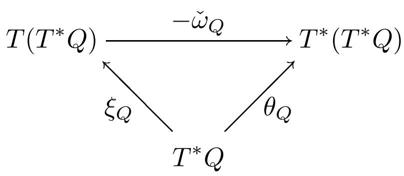
Thus $\varphi^*\theta_Q = \varphi$. Clearly this equation describes θ_Q uniquely. For ω we have $\varphi^*\omega_Q = -\varphi^*d\theta_Q = -d\varphi^*\theta_Q = -d\varphi$.

For a local diffeomorphism $f : Q \to P$, for $\alpha \in T^*_xQ$, and for $X_\alpha \in T_\alpha(T^*Q)$ we compute as follows:

$$\begin{aligned}((T^*f)^*\theta_P)_\alpha(X_\alpha) &= (\theta_P)_{T^*f.\alpha}(T_\alpha(T^*f).X_\alpha) = (T^*f.\alpha)(T(\pi_P).T(T^*f).X_\alpha)\\ &= (\alpha \circ T_xf^{-1})(T(\pi_P \circ T^*f).X_\alpha) = \alpha.T_xf^{-1}.T(f \circ \pi_Q).X_\alpha\\ &= \alpha(T(\pi_Q).X_\alpha) = \theta_Q(X_\alpha). \quad \square\end{aligned}$$

25.10. Lemma. *Let $\varphi : T^*Q \to T^*P$ be a (globally defined) local diffeomorphism such that $\varphi^*\theta_P = \theta_Q$. Then there exists a local diffeomorphism $f : Q \to P$ such that $\varphi = T^*f$.*

Proof. Let $\xi_Q = -\check{\omega}^{-1} \circ \theta_Q \in \mathfrak{X}(T^*Q)$ be the so called *Liouville vector field.*



Then locally $\xi_Q = \sum_{i=1}^n p_i \frac{\partial}{\partial p_i}$. Its flow is given by $\mathrm{Fl}_t^{\xi_Q}(\alpha) = e^t.\alpha$. Since $\varphi^*\theta_P = \theta_Q$ we also have that the Liouville vector field ξ_Q and ξ_P are φ-dependent. Since $\xi_Q = 0$ exactly at the zero section we have $\varphi(0_Q) \subseteq 0_P$, so there is a smooth mapping $f : Q \to P$ with $0_P \circ f = \varphi \circ 0_Q : Q \to T^*P$. By (3.14) we have $\varphi \circ \mathrm{Fl}_t^{\xi_Q} = \mathrm{Fl}_t^{\xi_P} \circ \varphi$, so the image of φ of the closure of a flow line of ξ_Q is contained in the closure of a flow line of ξ_P. For $\alpha_x \in T^*_xQ$ the closure of the flow line is

$[0,\infty).\alpha_x$ and $\varphi(0_x) = 0_{f(x)}$, thus $\varphi([0,\infty).\alpha_x) \subset T^*_{f(x)}P$, and φ is fiber respecting: $\pi_P \circ \varphi = f \circ \pi_Q : T^*Q \to P$. Finally, for $X_\alpha \in T_\alpha(T^*Q)$ we have

$$\begin{aligned}
\alpha(T_\alpha\pi_Q.X_\alpha) &= \theta_Q(X_\alpha) = (\varphi^*\theta_P)(X_\alpha) = (\theta_P)_{\varphi(\alpha)}(T_\alpha\varphi.X_\alpha)\\
&= (\varphi(\alpha))(T_{\varphi(\alpha)}\pi_P.T_\alpha\varphi.X_\alpha) = (\varphi(\alpha))(T_\alpha(\pi_P\circ\varphi).X_\alpha)\\
&= (\varphi(\alpha))(T_\alpha(f\circ\pi_Q).X_\alpha) = (\varphi(\alpha))(Tf.T_\alpha\pi_Q.X_\alpha), \qquad \text{thus}\\
\alpha &= \varphi(\alpha)\circ T_{\pi_Q(\alpha)}f\\
\varphi(\alpha) &= \alpha\circ T_{\pi_Q(\alpha)}f^{-1} = (T_{\pi_Q(\alpha)}f^{-1})^*(\alpha) = T^*f(\alpha). \quad \square
\end{aligned}$$

25.11. Time dependent vector fields. Let f_t be curve of diffeomorphism on a manifold M locally defined for each t, with $f_0 = \mathrm{Id}_M$, as in (3.6). We define two time dependent vector fields

$$\xi_t(x) := (T_xf_t)^{-1}\tfrac{\partial}{\partial t}f_t(x), \qquad \eta_t(x) := (\tfrac{\partial}{\partial t}f_t)(f_t^{-1}(x)).$$

Then $T(f_t).\xi_t = \frac{\partial}{\partial t}f_t = \eta_t\circ f_t$, so ξ_t and η_t are f_t-related.

Lemma. *In this situation, for $\omega\in\Omega^k(M)$ we have:*

(1) $i_{\xi_t}\, f_t^*\,\omega = f_t^*\, i_{\eta_t}\,\omega$.
(2) $\frac{\partial}{\partial t}f_t^*\omega = f_t^*\mathcal{L}_{\eta_t}\omega = \mathcal{L}_{\xi_t}\, f_t^*\,\omega$.

Proof. (1) is by computation:

$$\begin{aligned}
(i_{\xi_t}\, f_t^*\,\omega)_x(X_2,\dots,X_k) &= (f_t^*\,\omega)_x(\xi_t(x),X_2,\dots,X_k) =\\
&= \omega_{f_t(x)}(T_xf_t.\xi_t(x),T_xf_t.X_2,\dots,T_xf_t.X_k) =\\
&= \omega_{f_t(x)}(\eta_t(f_t(x)),T_xf_t.X_2,\dots,T_xf_t.X_k) = (f_t^*\, i_{\eta_t}\,\omega)_x(X_2,\dots,X_k).
\end{aligned}$$

(2) We put $\bar\eta\in\mathfrak{X}(\mathbb{R}\times M)$, $\bar\eta(t,x) = (\partial_t,\eta_t(x))$. We recall from (3.30) the evolution operator for η_t:

$$\Phi^\eta:\mathbb{R}\times\mathbb{R}\times M\to M, \quad \tfrac{\partial}{\partial t}\Phi^\eta_{t,s}(x) = \eta_t(\Phi^\eta_{t,s}(x)), \quad \Phi^\eta_{s,s}(x) = x,$$

which satisfies

$$(t,\Phi^\eta_{t,s}(x)) = \mathrm{Fl}^{\bar\eta}_{t-s}(s,x), \quad \Phi^\eta_{t,s} = \Phi^\eta_{t,r}\circ\Phi^\eta_{r,s}(x).$$

Since f_t satisfies $\frac{\partial}{\partial t}f_t = \eta_t\circ f_t$ and $f_0 = \mathrm{Id}_M$, we may conclude that $f_t = \Phi^\eta_{t,0}$, or $(t,f_t(x)) = \mathrm{Fl}^{\bar\eta}_t(0,x)$, so $f_t = \mathrm{pr}_2\circ\mathrm{Fl}^{\bar\eta}_t\circ\mathrm{ins}_0$. Thus

$$\tfrac{\partial}{\partial t}f_t^*\omega = \tfrac{\partial}{\partial t}(\mathrm{pr}_2\circ\mathrm{Fl}^{\bar\eta}_t\circ\mathrm{ins}_0)^*\omega = \mathrm{ins}_0^*\,\tfrac{\partial}{\partial t}(\mathrm{Fl}^{\bar\eta}_t)^*\,\mathrm{pr}_2^*\,\omega = \mathrm{ins}_0^*(\mathrm{Fl}^{\bar\eta}_t)^*\mathcal{L}_{\bar\eta}\,\mathrm{pr}_2^*\,\omega.$$

For time dependent vector fields X_i on M we have, using (7.6):

$$\begin{aligned}
(\mathcal{L}_{\bar\eta}\,\mathrm{pr}_2^*\,\omega)&(0\times X_1,\dots,0\times X_k)|_{(t,x)} = \bar\eta((\mathrm{pr}_2^*\,\omega)(0\times X_1,\dots))|_{(t,x)} -\\
&- \textstyle\sum_i(\mathrm{pr}_2^*\,\omega)(0\times X_1,\dots,[\bar\eta,0\times X_i],\dots,0\times X_k)|_{(t,x)}\\
&= (\partial_t,\eta_t(x))(\omega(X_1,\dots,X_k)) - \textstyle\sum_i\omega(X_1,\dots,[\eta_t,X_i],\dots,X_k)|_x\\
&= (\mathcal{L}_{\eta_t}\omega)_x(X_1,\dots,X_k).
\end{aligned}$$

This implies for $X_i \in T_xM$

$$\begin{aligned}(\tfrac{\partial}{\partial t} f_t^*\omega)_x(X_1,\dots,X_k) &= (\operatorname{ins}_0^*(\operatorname{Fl}_t^{\bar\eta})^*\mathcal{L}_{\bar\eta}\operatorname{pr}_2^*\omega)_x(X_1,\dots,X_k)\\ &= ((\operatorname{Fl}_t^{\bar\eta})^*\mathcal{L}_{\bar\eta}\operatorname{pr}_2^*\omega)_{(0,x)}(0\times X_1,\dots,0\times X_k)\\ &= (\mathcal{L}_{\bar\eta}\operatorname{pr}_2^*\omega)_{(t,f_t(x))}(0_t\times T_xf_t.X_1,\dots,0_t\times T_xt_x.X_k)\\ &= (\mathcal{L}_{\eta_t}\omega)_{f_t(x)}(T_xf_t.X_1,\dots,T_xt_x.X_k)\\ &= (f_t^*\mathcal{L}_{\eta_t}\omega)_x(X_1,\dots,X_k),\end{aligned}$$

which proves the first part of (2). The second part now follows by using (1):

$$\begin{aligned}\tfrac{\partial}{\partial t} f_t^*\omega &= f_t^*\mathcal{L}_{\eta_t}\omega = f_t^*(di_{\eta_t}+i_{\eta_t}d)\omega = d\,f_t^*\,i_{\eta_t}\omega + f_t^*\,i_{\eta_t}d\omega\\ &= d\,i_{\xi_t}\,f_t^*\,\omega + i_{\xi_t}\,f_t^*\,d\omega = d\,i_{\xi_t}\,f_t^*\,\omega + i_{\xi_t}\,d\,f_t^*\,\omega = \mathcal{L}_{\xi_t}\,f_t^*\,\omega. \quad\square\end{aligned}$$

25.12. Surfaces. Let M be an orientable 2-dimensional manifold. Let $\omega \in \Omega^2(M)$ be a volume form on M. Then $d\omega = 0$, so (M,ω) is a symplectic manifold. There are not many different symplectic structures on M if M is compact, since we have:

25.13. Theorem. *(J. Moser) Let M be a connected compact oriented manifold. Let $\omega_0, \omega_1 \in \Omega^{\dim M}(M)$ be two volume forms (both > 0).*
If $\int_M \omega_0 = \int_M \omega_1$ then there is a diffeomorphism $f : M \to M$ such that $f^*\omega_1 = \omega_0$.

Proof. Put $\omega_t := \omega_0 + t(\omega_1 - \omega_0)$ for $t \in [0,1]$, then each ω_t is a volume form on M since these form a convex set.

We look for a curve of diffeomorphisms $t \mapsto f_t$ with $f_t^*\omega_t = \omega_0$; then $\frac{\partial}{\partial t}(f_t^*\omega_t) = 0$. Since $\int_M(\omega_1 - \omega_0) = 0$ we have $[\omega_1 - \omega_0] = 0 \in H^m(M)$, so $\omega_1 - \omega_0 = d\psi$ for some $\psi \in \Omega^{m-1}(M)$. Put $\eta_t := (\frac{\partial}{\partial t} f_t) \circ f_t^{-1}$, then by (25.11) we have:

$$\begin{aligned}0 &\overset{\text{wish}}{=} \tfrac{\partial}{\partial t}(f_t^*\omega_t) = f_t^*\mathcal{L}_{\eta_t}\omega_t + f_t^*\tfrac{\partial}{\partial t}\omega_t = f_t^*(\mathcal{L}_{\eta_t}\omega_t + \omega_1 - \omega_0)\\ 0 &\overset{\text{wish}}{=} \mathcal{L}_{\eta_t}\omega_t + \omega_1 - \omega_0 = di_{\eta_t}\omega_t + i_{\eta_t}d\omega_t + d\psi = di_{\eta_t}\omega_t + d\psi\end{aligned}$$

We can choose η_t uniquely by $i_{\eta_t}\omega_t = -\psi$, since ω_t is non degenerate for all t. Then the evolution operator $f_t = \Phi^\eta_{t,0}$ exists for $t \in [0,1]$ since M is compact, by (3.30). We have, using (25.11.2),

$$\tfrac{\partial}{\partial t}(f_t^*\omega_t) = f_t^*(\mathcal{L}_{\eta_t}\omega_t + d\psi) = f_t^*(di_{\eta_t}\omega_t + d\psi) = 0,$$

so $f_t^*\omega_t = \text{ constant } = \omega_0$. $\square$

25.14. Coadjoint orbits of a Lie group. Let G be a Lie group with Lie algebra $\mathfrak{g}$ and dual space $\mathfrak{g}^*$, and consider the adjoint representation $\operatorname{Ad} : G \to GL(\mathfrak{g})$. The *coadjoint representation* $\operatorname{Ad}^* : G \to GL(\mathfrak{g}^*)$ is then given by $\operatorname{Ad}^*(g)\alpha := \alpha \circ \operatorname{Ad}(g^{-1}) = \operatorname{Ad}(g^{-1})^*(\alpha)$. For $\alpha \in \mathfrak{g}^*$ we consider the coadjoint orbit $G.\alpha \subset \mathfrak{g}^*$ which is diffeomorphic to the homogenous space G/G_α, where G_α is the isotropy group $\{g \in G : \operatorname{Ad}^*(g)\alpha = \alpha\}$ at α.

As in (5.12), for $X \in \mathfrak{g}$ we consider the fundamental vector field $\zeta_X = -\operatorname{ad}(X)^* \in \mathfrak{X}(\mathfrak{g}^*)$ of the coadjoint action. For any $Y \in \mathfrak{g}$ we consider the linear function $\operatorname{ev}_Y : \mathfrak{g}^* \to \mathbb{R}$. The Lie derivative of the fundamental vector field ζ_X on the function ev_Y is then given by

$$\text{(1)} \qquad \mathcal{L}_{\zeta_X} \operatorname{ev}_Y = -d\operatorname{ev}_Y \circ \operatorname{ad}(X)^* = -\operatorname{ev}_Y \circ \operatorname{ad}(X)^* = \operatorname{ev}_{[Y,X]}, \qquad X, Y \in \mathfrak{g},$$

Note that the tangent space to the orbit is given by $T_\beta(G.\alpha) = \{\zeta_X(\beta) : X \in \mathfrak{g}\}$. Now we define the symplectic structure on the orbit $O = G.\alpha$ by

$$\text{(2)} \qquad \begin{aligned} &(\omega_O)_\alpha(\zeta_X, \zeta_Y) = \alpha([X,Y]) = \langle \alpha, [X,Y]\rangle, \qquad \alpha \in \mathfrak{g}^*, \quad X, Y \in \mathfrak{g}. \\ &\omega_O(\zeta_X, \zeta_Y) = \operatorname{ev}_{[X,Y]} \end{aligned}$$

Theorem. *(Kirillov, Kostant, Souriau) If G is a Lie group then any coadjoint orbit $O \subset \mathfrak{g}^*$ carries a canonical symplectic structure ω_O which is invariant under the coadjoint action of G.*

Proof. First we claim that for $X \in \mathfrak{g}$ we have $X \in \mathfrak{g}_\alpha = \{Z \in \mathfrak{g} : \zeta_Z(\alpha) = 0\}$ if and only if $\alpha([X, \quad]) = (\omega_O)_\alpha(\zeta_X, \quad) = 0$. Indeed, for $Y \in \mathfrak{g}$ we have

$$\begin{aligned} \langle \alpha, [X,Y]\rangle &= \langle \alpha, \tfrac{\partial}{\partial t}\big|_0 \operatorname{Ad}(\exp(tX))Y\rangle = \tfrac{\partial}{\partial t}\big|_0 \langle \alpha, \operatorname{Ad}(\exp(tX))Y\rangle \\ &= \tfrac{\partial}{\partial t}\big|_0 \langle \operatorname{Ad}^*(\exp(-tX))\alpha, Y\rangle = -\langle \zeta_X(\alpha), Y\rangle = 0. \end{aligned}$$

This shows that ω_O as defined in (2) is well defined, and also non-degenerate along each orbit.

Now we show that $d\omega_O = 0$, using (2):

$$\begin{aligned} (d\omega_O)(\zeta_X, \zeta_Y, \zeta_Z) &= \sum_{\text{cyclic}} \zeta_X\, \omega_O(\zeta_Y, \zeta_Z) - \sum_{\text{cyclic}} \omega_O([\zeta_X, \zeta_Y], \zeta_Z) \\ &= \sum_{\text{cyclic}} \zeta_X \operatorname{ev}_{[Y,Z]} - \sum_{\text{cyclic}} \omega_O(\zeta_{-[X,Y]}, \zeta_Z) \qquad \text{now use (1)} \\ &= \sum_{\text{cyclic}} \operatorname{ev}_{[[Y,Z],X]} + \sum_{\text{cyclic}} \operatorname{ev}_{[[X,Y],Z]} = 0 \qquad \text{by Jacobi.} \end{aligned}$$

Finally we show that ω_O is G-invariant: For $g \in G$ we have

$$\begin{aligned} ((Ad^*(g))^*\omega_O)_\alpha(\zeta_X(\alpha), \zeta_Y(\alpha)) &= (\omega_O)_{Ad^*(g)\alpha}(T(Ad^*(g)).\zeta_X(\alpha), T(Ad^*(g)).\zeta_Y(\alpha)) \\ &= (\omega_O)_{Ad^*(g)\alpha}(\zeta_{\operatorname{Ad}(g)X}(Ad^*(g)\alpha), \zeta_{\operatorname{Ad}(g)Y}(Ad^*(g)\alpha)), \qquad \text{by (5.12.2),} \\ &= (Ad^*(g)\alpha)([\operatorname{Ad}(g)X, \operatorname{Ad}(g)Y]) \\ &= (\alpha \circ \operatorname{Ad}(g^{-1}))(\operatorname{Ad}(g)[X,Y]) = \alpha([X,Y]) = (\omega_O)_\alpha(\zeta_X, \zeta_Y). \quad \square \end{aligned}$$

25.15. Theorem. *(Darboux) Let (M,ω) be a symplectic manifold of dimension $2n$. Then for each $x\in M$ there exists a chart (U,u) of M centered at x such that $\omega|U=\sum_{i=1}^n du^i\wedge du^{n+i}$. So each symplectic manifold is locally symplectomorphic to a cotangent bundle.*

Proof. Take any chart $(U,u:U\to u(U)\subset\mathbb{R}^{2n})$ centered at x. Choose linear coordinates on $\mathbb{R}^{2n}$ in such a way that $\omega_x=\sum_{i=1}^n du^i\wedge du^{n+i}|_x$ at x only. Then $\omega_0=\omega|U$ and $\omega_1=\sum_{i=1}^n du^i\wedge du^{n+i}$ are two symplectic structures on the open set $U\subset M$ which agree at x. Put $\omega_t:=\omega_0+t(\omega_1-\omega_0)$. By making U smaller if necessary we may assume that ω_t is a symplectic structure for all $t\in[0,1]$.

We want to find a curve of diffeomorphisms f_t near x with $f_0=\operatorname{Id}$ such that $f_t(x)=x$ and $f_t^*\omega_t=\omega_0$. Then $\frac{\partial}{\partial t}f_t^*\omega_t=\frac{\partial}{\partial t}\omega_0=0$. We may assume that U is contractible, thus $H^2(U)=0$, so $d(\omega_1-\omega_0)=0$ implies that $\omega_1-\omega_0=d\psi$ for some $\psi\in\Omega^1(U)$. By adding a constant form (in the chart on U) we may assume that $\psi_x=0$. So we get for the time dependent vector field $\eta_t=\frac{\partial}{\partial t}f_t\circ f_t^{-1}$, using (25.11.2),

$$0=\tfrac{\partial}{\partial t}f_t^*\omega_t=f_t^*(\mathcal{L}_{\eta_t}\omega_t+\tfrac{\partial}{\partial t}\omega_t)=f_t^*(d\,i_{\eta_t}\omega_t+i_{\eta_t}d\omega_t+\omega_1-\omega_0)=f_t^*\,d(i_{\eta_t}\omega_t+\psi)$$

We can now prescribe η_t uniquely by $i_{\eta_t}\omega_t=-\psi$, since ω_t is non-degenerate on x. Moreover $\eta_t(x)=0$ since $\psi_x=0$. On a small neighborhood of x the left evolution operator f_t of η_t exists for all $t\in[0,1]$, and then clearly $\frac{\partial}{\partial t}(f_t^*\omega_t)=0$, so $f_t^*\omega_t=\omega_0$ for all $t\in[0,1]$. □

25.16. Relative Poincaré Lemma. *Let M be a smooth manifold, let $N\subset M$ be a submanifold, and let $k\geq 0$. Let ω be a closed $(k+1)$-form on M which vanishes when pulled back to N. Then there exists a k-form φ on an open neighborhood U of N in M such that $d\varphi=\omega|U$ and $\varphi=0$ along N. If moreover $\omega=0$ along N (on $\bigwedge^k TM|N$), then we may choose φ such that the first derivatives of φ vanish on N.*

Proof. By restricting to a tubular neighborhood of N in M, we may assume that $p:M=:E\to N$ is a smooth vector bundle and that $i:N\to E$ is the zero section of the bundle. We consider $\mu:\mathbb{R}\times E\to E$, given by $\mu(t,x)=\mu_t(x)=tx$, then $\mu_1=\operatorname{Id}_E$ and $\mu_0=i\circ p:E\to N\to E$. Let $\xi\in\mathfrak{X}(E)$ be the vertical vector field $\xi(x)=\operatorname{vl}(x,x)=\frac{\partial}{\partial t}\big|_0(x+tx)$, then $\operatorname{Fl}^\xi_t=\mu_{e^t}$. So locally for t near $(0,1]$ we have

$$\begin{aligned}\tfrac{d}{dt}\mu_t^*\omega&=\tfrac{d}{dt}(\operatorname{Fl}^\xi_{\log t})^*\omega=\tfrac{1}{t}(\operatorname{Fl}^\xi_{\log t})^*\mathcal{L}_\xi\omega \text{ by (25.11) or (6.16)}\\&=\tfrac{1}{t}\mu_t^*(i_\xi d\omega+di_\xi\omega)=\tfrac{1}{t}d\mu_t^*i_\xi\omega.\end{aligned}$$

For $x\in E$ and $X_1,\dots,X_k\in T_xE$ we may compute

$$\begin{aligned}(\tfrac{1}{t}\mu_t^*i_\xi\omega)_x(X_1,\dots,X_k)&=\tfrac{1}{t}(i_\xi\omega)_{tx}(T_x\mu_t.X_1,\dots,T_x\mu_t.X_k)\\&=\tfrac{1}{t}\omega_{tx}(\xi(tx),T_x\mu_t.X_1,\dots,T_x\mu_t.X_k)\\&=\omega_{tx}(\operatorname{vl}(tx,x),T_x\mu_t.X_1,\dots,T_x\mu_t.X_k).\end{aligned}$$

So if $k \geq 0$, the k-form $\frac{1}{t}\mu_t^* i_\xi \omega$ is defined and smooth in (t,x) for all t near $[0,1]$ and describes a smooth curve in $\Omega^k(E)$. Note that for $x \in N = 0_E$ we have $(\frac{1}{t}\mu_t^* i_\xi \omega)_x = 0$, and if $\omega = 0$ along N, then $\frac{1}{t}\mu_t^* i_\xi \omega$ vanishes of second order along N. Since $\mu_0^*\omega = p^* i^* \omega = 0$ and $\mu_1^*\omega = \omega$, we have

$$\begin{aligned} \omega = \mu_1^*\omega - \mu_0^*\omega &= \int_0^1 \tfrac{d}{dt}\mu_t^*\omega dt \\ &= \int_0^1 d(\tfrac{1}{t}\mu_t^* i_\xi\omega)dt = d\left(\int_0^1 \tfrac{1}{t}\mu_t^* i_\xi \omega dt\right) =: d\varphi. \end{aligned}$$

If $x \in N$, we have $\varphi_x = 0$, and also the last claim is obvious from the explicit form of φ. $\square$

25.17. Lemma. *Let M be a smooth finite dimensional manifold, let $N \subset M$ be a submanifold, and let ω_0 and ω_1 be symplectic forms on M which are equal along N (on $\bigwedge^2 TM|N$).*

Then there exist a diffeomorphism $f : U \to V$ between two open neighborhoods U and V of N in M which satisfies $f|N = \mathrm{Id}_N$, $Tf|(TM|N) = \mathrm{Id}_{TM|N}$, and $f^*\omega_1 = \omega_0$.

Proof. Let $\omega_t = \omega_0 + t(\omega_1 - \omega_0)$ for $t \in [0,1]$. Since the restrictions of ω_0 and ω_1 to $\Lambda^2 TM|N$ are equal, there is an open neighborhood U_1 of N in M such that ω_t is a symplectic form on U_1, for all $t \in [0,1]$. If $i : N \to M$ is the inclusion, we also have $i^*(\omega_1 - \omega_0) = 0$, and by assumption $d(\omega_1 - \omega_0) = 0$. Thus by lemma (25.16) there is a smaller open neighborhood U_2 of N such that $\omega_1|U_2 - \omega_0|U_2 = d\varphi$ for some $\varphi \in \Omega^1(U_2)$ with $\varphi_x = 0$ for $x \in N$, such that also all first derivatives of φ vanish along N.

Let us now consider the time dependent vector field $X_t := -(\omega_t{}^\vee)^{-1} \circ \varphi$ given by $i_{X_t}\omega_t = \varphi$, which vanishes together with all first derivatives along N. Let f_t be the curve of local diffeomorphisms with $\frac{\partial}{\partial t} f_t = X_t \circ f_t$, then $f_t|N = \mathrm{Id}_N$ and $Tf_t|(TM|N) = \mathrm{Id}$. There is a smaller open neighborhood U of N such that f_t is defined on U for all $t \in [0,1]$. Then by (5.13) we have

$$\begin{aligned} \tfrac{\partial}{\partial t}(f_t^*\omega_t) &= f_t^*\mathcal{L}_{X_t}\omega_t + f_t^*\tfrac{\partial}{\partial t}\omega_t = f_t^*(di_{X_t}\omega_t + \omega_1 - \omega_0) \\ &= f_t^*(-d\varphi + \omega_1 - \omega_0) = 0, \end{aligned}$$

so $f_t^*\omega_t$ is constant in t, equals $f_0^*\omega_0 = \omega_0$, and finally $f_1^*\omega_1 = \omega_0$ as required. $\square$

25.18. Lemma. *(MOVE next 3 lemmas later after S.6) (Ehresmann) Let (V,ω) be a symplectic vector space of real dimension $2n$, and let g be a nondegenerate symmetric bilinear form on V. Let $K := \check{g}^{-1} \circ \check{\omega} : V \to V^* \to V$ so that $g(Kv,w) = \omega(v,w)$.*

Then $K \in GL(V)$ and the following properties are equivalent:

1. *$K^2 = -\mathrm{Id}_V$, so K is a complex structure.*
2. *$\omega(Kv,Kw) = \omega(v,w)$, so $K \in Sp(V,\omega)$.*
3. *$g(Kv,Kw) = g(v,w)$, so $K \in O(V,g)$.*

If these conditions are satisfied we say that any pair of the triple ω, g, J is *compatible.*

Proof. Starting from the definition we have in turn:

$$\begin{aligned} g(Kv,w) &= \langle \check g K(v), w\rangle = \langle \check g \check g^{-1}\check\omega(v), w\rangle = \langle \check\omega(v), w\rangle = \omega(v,w),\\ \omega(Kv,Kw) &= g(K^2v,Kw) = g(Kw,K^2v) = \omega(w,K^2v) = -\omega(K^2v,w),\\ g(K^2v,w) &= \omega(Kv,w) = -\omega(w,Kv) = -g(Kw,Kv) = -g(Kv,Kw). \end{aligned}$$

The second line shows that (1) $\Leftrightarrow$ (2), and the third line shows that (1) $\Leftrightarrow$ (3).

25.19. The exponential mapping for self adjoint operators. (?????MOVE later to exercises for section 4).

Let V be an Euclidean vector space with positive definite inner product $(\quad|\quad)$ (or a Hermitian vector space over $\mathbb{C}$). Let $S(V)$ be the vector space of all symmetric (or self-adjoint) linear operatores on V. Let $S^+(V)$ be the open subset of all positive definite symmetric operators A, so that $(Av|v) > 0$ for $v \neq 0$. Then the exponential mapping $\exp : A \mapsto e^A = \sum_{k=0}^\infty \frac{1}{k!}A^k$ maps $S(V)$ into $S^+(V)$.

Lemma. $\exp : S(V) \to S^+(V)$ *is a diffeomorphism.*

Proof. We start with a complex Hermitian vector space V. Let $\mathbb{C}^+ := \{\lambda\in\mathbb{C} : \operatorname{Re}(\lambda) > 0\}$, and let $\log : \mathbb{C}^+ \to \mathbb{C}$ be given by $\log(\lambda) = \int_{[1,\lambda]} z^{-1}\,dz$, where $[1,\lambda]$ denotes the line segment from 1 to λ.

Let $B \in S^+(V)$. Then all eigenvalues of B are real and positive. We chose a (positively oriented) circle $\gamma\subset\mathbb{C}^+$ such that all eigenvalues of B are contained in the interior of γ. We consider $\lambda\mapsto \log(\lambda)(\lambda\operatorname{Id}_V - B)^{-1}$ as a meromorphic function in $\mathbb{C}^+$ with values in the real vector space $\mathbb{C}\otimes S(V)$, and we define

$$\log(B) := \frac{1}{2\pi\sqrt{-1}}\int_\gamma \log(\lambda)(\lambda\operatorname{Id}_V - B)^{-1}\,d\lambda \quad B\in S^+(V).$$

We shall see that this does not depend on the choice of γ. We may use the same choice of the curve γ for all B in an open neighborhood in $S^+(V)$, thus $\log(B)$ is real analytic in B.

We claim that $\log = \exp^{-1}$. If $B\in S^+(V)$ then B has eigenvalues $\lambda_i > 0$ with eigenvectors v_i forming an orthonormal basis of V, so that $Bv_i = \lambda_i v_i$. Thus $(\lambda\operatorname{Id}_V - B)^{-1}v_i = \frac{1}{\lambda-\lambda_i}v_i$ for $\lambda\neq\lambda_i$, and

$$(\log B)v_i = \Big(\frac{1}{2\pi\sqrt{-1}}\int_\gamma \frac{\log\lambda}{\lambda-\lambda_i}\,d\lambda\Big)\,v_i = \log(\lambda_i)v_i$$

by Cauchy's integral formula. Thus $\log(B)$ does not depend on the choice of γ and $\exp(\log(B))v_i = e^{\log(\lambda_i)}v_i = \lambda_i\,v_i = Bv_i$ for all i. Thus $\exp\circ\log = \operatorname{Id}_{S^+(V)}$. Similarly one sees that $\log\circ\exp = \operatorname{Id}_{S(V)}$.

Now let V be a real Euclidean vector space. Let $V^{\mathbb{C}} = \mathbb{C}\otimes V$ be the complexified Hermitian vector space. If $B : V\to V$ is symmetric then $j(B) := B^{\mathbb{C}} = \operatorname{Id}_{\mathbb{C}}\otimes B :$

$V^{\mathbb{C}} \to V^{\mathbb{C}}$ is self adjoint. Thus we have an embedding of real vector spaces $j : S(V) \to S(V^{\mathbb{C}})$. The eigenvalues of $j(B)$ are the same as the eigenvalues of B, thus j restricts to an embedding $j : S^+(V) \to S^+(V^{\mathbb{C}})$. By definition the left hand one of the two following diagrams commutes and thus also the right hand one:

$$\begin{array}{ccc} S(V) & \xrightarrow{\ j\ } & S(V^{\mathbb{C}}) \\ {\scriptstyle \exp}\downarrow & & \downarrow{\scriptstyle \exp^{\mathbb{C}}} \\ S^+(V) & \xrightarrow{\ j\ } & S^+(V^{\mathbb{C}}) \end{array} \qquad \begin{array}{ccc} S(V) & \xrightarrow{\ j\ } & S(V^{\mathbb{C}}) \\ {\scriptstyle d\exp(B)}\downarrow & & \downarrow{\scriptstyle d\exp^{\mathbb{C}}(B)} \\ S(V) & \xrightarrow{\ j\ } & S(V^{\mathbb{C}}) \end{array}$$

Thus $d\exp(B) : S(V) \to S(V)$ is injective for each B, thus a linear isomorphism, and by the inverse function theorem $\exp : S(V) \to S^+(V)$ is locally a diffeomorphism and is injective by the diagram. It is also surjective: for $B \in S^+(V)$ we have $Bv_i = \lambda_i v_i$ for an orthonormal basis v_i, where $\lambda_i > 0$. Let $A \in S(V)$ be given by $Av_i = \log(\lambda_i)\, v_i$, then $\exp(A) = B$. $\square$

25.20. Lemma. *(Polar decomposition) Let (V, g) be an Euclidean real vector space (positive definite). Then we have a real analytic diffeomorphism*

$$GL(V) \cong S^+(V, g) \times O(V, g),$$

thus each $A \in GL(V)$ decomposes uniquely and real analytically as $A = B.U$ where B is $g-$ symmetric and g-positive definite and $U \in O(V, g)$.

Furthermore, let ω be a symplectic structure on V, let $A = \check{g}^{-1} \circ \check{\omega} \in GL(V)$, and let $A = BJ$ be the polar decomposition. Then A is g-skew symmetric, J is a complex structure, and the non-degenerate symmetric inner product $g_1(v, w) = \omega(v, Jw)$ is positive definite.

Proof. The decomposition $A = BU$, if it exists, must satisfy $AA^\top = BUU^\top B^\top = B^2$. By (25.19) the exponential mapping $X \mapsto e^X$ is a real analytic diffeomorphism $\exp : S(V, g) \to S^+(V, g)(V)$ from the real vector space of g-symmetric operators in V onto the submanifold of g-symmetric positive definite operators in $GL(V)$, with inverse $B \mapsto \log(B)$. The operator $AA^\top$ is g-symmetric and positive definite. Thus we may put $B := \sqrt{AA^\top} = \exp(\frac{1}{2}\log(AA^\top)) \in S^+(V, g)$. Moreover, B commutes with $AA^\top$. Let $U := B^{-1}A$. Then $UU^\top = B^{-1}AA^\top(B^{-1})^\top = \mathrm{Id}_V$, so $U \in O(V, g)$.

If we are also given a symplectic structure ω we have $g(Av, w) = \omega(v, w) = -\omega(w, v) = -g(Aw, v) = -g(v, Aw)$, thus $A^\top = -A$. This implies that $B = \exp(\frac{1}{2}\log(AA^\top)) = \exp(\frac{1}{2}\log(-A^2))$ commutes with A, thus also $J = B^{-1}A$ commutes with A and thus with B. Since $B^\top = B$ we get $J^{-1} = J^\top = (B^{-1}A)^\top = A^\top(B^{-1})^\top = -AB^{-1} = -B^{-1}A = -J$, thus J is a complex structure. Moreover, we have

$$\omega(Jv, Jw) = g(AJv, Jw) = g(JAv, Jw) = g(Av, w) = \omega(v, w),$$

thus by (25.18) the symplectic form ω and the complex structure J are compatible, and the symmetric (by (25.18)) bilinear form g_1 defined by $g_1(v, w) = \omega(v, Jw)$ is positive definite: $g_1(v, v) = \omega(v, Jv) = g(Av, Jv) = g(BJv, Jv) > 0$ since B is positive definite. $\square$

25.21. Relative Darboux' Theorem. *(Weinstein) Let (M,ω) be a symplectic manifold, and let $L\subset M$ be a Lagrangian submanifold.*

Then there exists a tubular neighborhood U of L in M, an open neigborhood V of the zero section 0_L in T^*L and a symplectomorphism

$$(T^*L,\omega_L)\supset(V,\omega_L)\xrightarrow{\varphi}(U,\omega|U)\subset(M,\omega)$$

such that $\varphi\circ 0_L: L\to V\to M$ is the embedding $L\subset M$.

Moreover, suppose that for the Lagrangian subbundle TL in the sympletic vector bundle $TM|L\to L$ we are given a complementary Lagrangian subbundle $E\to L$, then the symplectomorphism φ may be chosen in such a way that $T_{0_x}\varphi.V_{0_x}(T^*L)=E_{\varphi(0_x)}$ for $x\in L$

Proof. The tangent bundle $TL\to L$ is a Lagrangian subbundle of the symplectic vector bundle $TM|L\to L$.

Claim. There exists a Lagrangian complementary vector bundle $E\to L$ in the symplectic vector bundle $TM|L$. Namely, we choose a fiberwise Riemannian metric g in the vector bundle $TM|L\to L$, consider the vector bundle homomorphism $A=\check g^{-1}\check\omega: TM|L\to T^*M|L\to TM|L$ and its polar decomposition $A=BJ$ with respect to g as explained in lemma (25.20). Then J is a fiberwise complex structure, and $g_1(u,v):=\omega(u,Jv)$ defines again a positive definite fiberwise Riemannian metric. Since $g_1(J\ \ ,\ \ )=\omega(\ \ ,\ \ )$ vanishes on TL, the Lagrangian subbundle $E=JTL\subset TM|L$ is g_1-orthogonal to TL, thus a complement.

We may use either the constructed or the given Lagrangian complement to TL in what follows.

The symplectic structure ω induces a duality pairing between the vector bundles E and TL, thus we may identify $(TM|L)/TL\cong E\to L$ with the cotangent bundle T^*L by $\langle X_x,\check\omega(Y_x)\rangle=\omega(X_x,Y_x)$ for $x\in L$, $X_x\in T_xL$ and $Y_x\in E_x$.

Let $\psi:=\exp^g\circ\check\omega^{-1}: T^*L\to M$ where $\exp^g$ is any geodesic exponential mapping on TM restricted to E. Then ψ is a diffeomorphism from a neighborhood V of the zero section in T^*L to a tubular neighborhood U of L in M, which equals the embedding of L along the zero section.

Let us consider the pullback $\psi^*\omega$ and compare it with ω_L on V. For $0_x\in 0_L$ we have $T_{0_x}V=T_xL\oplus T_x^*L\cong T_xL\oplus E_x$. The linear subspace T_xL is Lagrangian for both ω_L and $\psi^*\omega$ since L is a Lagrange submanifold. The linear subspace T_x^*L is also Lagrangian for ω_L, and for $\psi^*\omega$ since E was a Lagrangian bundle. Both $(\omega_L)_{0_x}$ and $(\psi^*\omega)_{0_x}$ induce the same duality between T_xL and T_x^*L since the identification $E_x\cong T_x^*L$ was via ω_x. Thus ω_L equals $\psi^*\omega$ along the zero section.

Finally, by lemma (25.17) the identity of the zero section extends to a diffeomorphism ρ on a neighborhood with $\rho^*\psi^*\omega=\omega_L$. The diffeomorphism $\varphi=\psi\circ\rho$ then satisfies the theorem. $\square$

25.22. The Poisson bracket. Let (M,ω) be a symplectic manifold. For $f \in C^\infty(M)$ the *Hamiltonian vector field* or *symplectic gradient* $H_f = \operatorname{grad}^\omega(f) \in \mathfrak{X}(M)$ is defined by any of the following equivalent prescriptions:

(1) $$i(H_f)\omega = df, \quad H_f = \check\omega^{-1}df, \quad \omega(H_f, X) = X(f) \text{ for } X \in TM.$$

For two functions $f,g \in C^\infty(M)$ we define their *Poisson bracket* $\{f,g\}$ by

(2) $$\begin{aligned}\{f,g\} : &= i(H_f)i(H_g)\omega = \omega(H_g,H_f)\\ &= H_f(g) = \mathcal{L}_{H_f}g = dg(H_f) \in C^\infty(M).\end{aligned}$$

Let us furthermore put

(3) $$\mathfrak{X}(M,\omega) := \{X \in \mathfrak{X}(M) : \mathcal{L}_X\omega = 0\}$$

and call this the space of *locally Hamiltonian vector fields* or *ω-respecting vector fields.*

Theorem. *Let (M,ω) be a symplectic manifold.*

Then $(C^\infty(M), \{\ \ ,\ \ \})$ is a Lie algebra which also satisfies $\{f,gh\} = \{f,g\}h + g\{f,h\}$, i.e. $\operatorname{ad}_f = \{f,\ \ \}$ is a derivation of $(C^\infty(M),\cdot)$.

Moreover, there is an exact sequence of Lie algebras and Lie algebra homomorphisms

$$\begin{array}{ccccccccc} 0 \longrightarrow & H^0(M) & \xrightarrow{\ \alpha\ } & C^\infty(M) & \xrightarrow{\ H = \operatorname{grad}^\omega\ } & \mathfrak{X}(M,\omega) & \xrightarrow{\ \gamma\ } & H^1(M) & \longrightarrow 0\\ & 0 & & \{\ ,\ \} & & [\ ,\ ] & & 0 & \end{array}$$

where the brackets are written under the spaces, where α is the embedding of the space of all locally constant functions, and where $\gamma(X) := [i_X\omega] \in H^1(M)$.

The whole situation behaves invariantly (resp. equivariantly) under the pullback by symplectomorphisms $\varphi : M \to M$: For example $\varphi^*\{f,g\} = \{\varphi^*f, \varphi^*g\}$, $\varphi^*(H_f) = H_{\varphi^*f}$, and $\varphi^*\gamma(X) = \gamma(\varphi^*X)$. Consequently for $X \in \mathfrak{X}(M,\omega)$ we have $\mathcal{L}_X\{f,g\} = \{\mathcal{L}_Xf,g\} + \{f,\mathcal{L}_Xg\}$, and $\gamma(\mathcal{L}_XY) = 0$.

Proof. The operator H takes values in $\mathfrak{X}(M,\omega)$ since

$$\mathcal{L}_{H_f}\omega = i_{H_f}\,d\omega + d\,i_{H_f}\,\omega = 0 + ddf = 0.$$

$H(\{f,g\}) = [H_f,H_g]$ since by (7.9) and (7.7) we have

$$\begin{aligned}i_{H(\{f,g\})}\omega &= d\{f,g\} = d\mathcal{L}_{H_f}g = \mathcal{L}_{H_f}dg - 0 = \mathcal{L}_{H_f}i_{H_g}\omega - i_{H_g}\mathcal{L}_{H_f}\omega\\ &= [\mathcal{L}_{H_f}, i_{H_g}]\omega = i_{[H_f,H_g]}\omega.\end{aligned}$$

The sequence is exact at $H^0(M)$ since the embedding α of the locally constant functions is injective.

The sequence is exact at $C^\infty(M)$: For a locally constant function function c we have $H_c = \check\omega^{-1}dc = \check\omega^{-1}0 = 0$. If $H_f = \check\omega^{-1}df = 0$ for $f \in C^\infty(M)$ then $df = 0$, so f is locally constant.

The sequence is exact at $\mathfrak{X}(M,\omega)$: For $X \in \mathfrak{X}(M,\omega)$ we have $di_X\omega = i_X\omega + i_X d\omega = \mathcal{L}_X\omega = 0$, thus $\gamma(X) = [i_X\omega] \in H^1(M)$ is well defined. For $f \in C^\infty(M)$ we have $\gamma(H_f) = [i_{H_f}\omega] = [df] = 0 \in H^1(M)$. If $X \in \mathfrak{X}(M,\omega)$ with $\gamma(X) = [i_X\omega] = 0 \in H^1(M)$ then $i_X\omega = df$ for some $f \in \Omega^0(M) = C^\infty(M)$, but then $X = H_f$.

The sequence is exact at $H^1(M)$: The mapping γ is surjective since for $\varphi \in \Omega^1(M)$ with $d\varphi = 0$ we may consider $X := \check\omega^{-1}\varphi \in \mathfrak{X}(M)$ which satisfies $\mathcal{L}_X\omega = i_X d\omega + di_X\omega = 0 + d\varphi = 0$ and $\gamma(X) = [i_X\omega] = [\varphi] \in H^1(M)$.

The Poisson bracket $\{\quad,\quad\}$ is a Lie bracket and $\{f,gh\} = \{f,g\}h + g\{f,h\}$:

$$\begin{aligned}
\{f,g\} &= \omega(H_g,H_f) = -\omega(H_f,H_g) = \{g,f\}\\
\{f,\{g,h\}\} &= \mathcal{L}_{H_f}\mathcal{L}_{H_g}h = [\mathcal{L}_{H_f},\mathcal{L}_{H_g}]h + \mathcal{L}_{H_g}\mathcal{L}_{H_f}h\\
&= \mathcal{L}_{[H_f,H_g]}h + \{g,\{f,h\}\} = \mathcal{L}_{H_{\{f,g\}}}h + \{g,\{f,h\}\}\\
&= \{\{f,g\},h\} + \{g,\{f,h\}\}\\
\{f,gh\} &= \mathcal{L}_{H_f}(gh) = \mathcal{L}_{H_f}(g)h + g\mathcal{L}_{H_f}(h) = \{f,g\}h + g\{f,h\}.
\end{aligned}$$

All mappings in the sequence are Lie algebra homomorphisms: For local constants $\{c_1,c_2\} = H_{c_1}c_2 = 0$. For H we already checked. For $X, Y \in \mathfrak{X}(M,\omega)$ we have

$$i_{[X,Y]}\omega = [\mathcal{L}_X, i_Y]\omega = \mathcal{L}_X i_Y\omega - i_Y\mathcal{L}_X\omega = di_Xi_Y\omega + i_X di_Y\omega - 0 = di_Xi_Y\omega,$$

thus $\gamma([X,Y]) = [i_{[X,Y]}\omega] = 0 \in H^1(M)$.

Let us now transform the situation by a symplectomorphism $\varphi : M \to M$ via pullback. Then

$$\begin{aligned}
&\varphi^*\omega = \omega \quad\Leftrightarrow\quad (T\varphi)^*\circ\check\omega\circ T\varphi = \check\omega\\
&\Rightarrow H_{\varphi^*f} = \check\omega^{-1}d\,\varphi^*f = \check\omega^{-1}(\varphi^*df) = (T\varphi^{-1}\circ\check\omega^{-1}\circ(T\varphi^{-1})^*)\circ((T\varphi)^*\circ df\circ\varphi)\\
&\qquad = (T\varphi^{-1}\circ\check\omega^{-1}\circ df\circ\varphi) = \varphi^*(H_f)\\
&\varphi^*\{f,g\} = \varphi^*(dg(H_f)) = (\varphi^*dg)(\varphi^*H_f) = d(\varphi^*g)(H_{\varphi^*f}) = \{\varphi^*f,\varphi^*g\}.
\end{aligned}$$

The assertions about the Lie derivative follow by applying $\mathcal{L}_X = \frac{\partial}{\partial t}\big|_0 (\mathrm{Fl}^X_t)^*$. $\square$

25.23. Basic example. In the situation of (25.1), where $M = T^*\mathbb{R}^n$ with $\omega = \omega_{\mathbb{R}^n} = -d\theta_{\mathbb{R}^n} = \sum_{i=1}^n dq^i\wedge dp_i$, we have

$$\begin{gathered}
\check\omega : T(T^*\mathbb{R}^n)\to T^*(T^*\mathbb{R}^n),\quad \check\omega(\partial_{q^i}) = dp_i,\quad \check\omega(\partial_{p^i}) = -dq_i,\\
H_f = \check\omega^{-1}.df = \check\omega^{-1}\Big(\textstyle\sum_i\Big(\frac{\partial f}{\partial q^i}dq^i + \frac{\partial f}{\partial p_i}dp_i\Big)\Big) = \sum_i\Big(\frac{\partial f}{\partial p_i}\frac{\partial}{\partial q^i} - \frac{\partial f}{\partial q^i}\frac{\partial}{\partial p_i}\Big)\\
\{f,g\} = H_f g = \textstyle\sum_i\Big(\frac{\partial f}{\partial p_i}\frac{\partial g}{\partial q^i} - \frac{\partial f}{\partial q^i}\frac{\partial g}{\partial p_i}\Big)\\
\{p_i,p_j\} = 0,\quad \{q^i,q^j\} = 0,\quad \{q^i,p_j\} = -\delta^i_j.
\end{gathered}$$

25.24. Kepler's laws: elementary approach. Here we give first an elementary approach to the derivation of Kepler's laws.

Let us choose the orthonormal coordinate system in the oriented Euclidean space $\mathbb{R}^3$ with standard inner product $(\quad|\quad)$ and vector product $q \times q'$ in such a way that the sun with mass M is at $0 \in \mathbb{R}^3$. The planet now moves in a force field F on an orbit $q(t)$ according to Newton's law

$$F(q(t)) = m\ddot{q}(t). \tag{1}$$

(2) *If the force field is centripetal, $F(q) = -f(q)\,q$ for $f \geq 0$, then the angular momentum $q(t) \times \dot{q}(t) = J$ is a constant vector,* since

$$\partial_t(q \times \dot{q}) = \dot{q} \times \dot{q} + q \times \ddot{q} = 0 + \tfrac{1}{m} f(q)\, q \times q = 0.$$

Thus the planet moves in the plane orthogonal to the angular momentum vector J and we may choose coordinates such that this is the plane $q^3 = 0$. Let $z = q^1 + iq^2 = re^{i\varphi}$ then

$$J = \begin{pmatrix} 0 \\ 0 \\ j \end{pmatrix} = z \times \dot{z} = \begin{pmatrix} q^1 \\ q^2 \\ 0 \end{pmatrix} \times \begin{pmatrix} \dot{q}^1 \\ \dot{q}^2 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ q^1\dot{q}^2 - q^2\dot{q}^1 \end{pmatrix}$$
$$j = q^1\dot{q}^2 - q^2\dot{q}^1 = \operatorname{Im}(\bar{z}.\dot{z}) = \operatorname{Im}(re^{-i\varphi}(\dot{r}e^{i\varphi} + ir\dot{\varphi}e^{i\varphi})) = \operatorname{Im}(r\dot{r} + ir^2\dot{\varphi}) = r^2\dot{\varphi}.$$

(3) *Thus in a centripetal force field area is swept out at a constant rate $j = r^2\dot{\varphi}$ (2nd law of Kepler, 1602, published 1606),* since

$$\begin{aligned} \operatorname{Area}(t_1, t_2) &= \int_{\varphi(t_1)}^{\varphi(t_2)} \int_0^{r(\varphi)} r\, dr\, d\varphi = \int_{\varphi(t_1)}^{\varphi(t_2)} \tfrac{1}{2} r(\varphi)^2 d\varphi \\ &= \int_{t_1}^{t_2} \tfrac{1}{2} r(\varphi(t))^2 \dot{\varphi}(t)\, dt = \tfrac{j}{2}(t_2 - t_1). \end{aligned}$$

Now we specify the force field. According to Newton's law of gravity the sun acts on a planet of mass m at the point $0 \neq q \in \mathbb{R}^3$ by the force

$$F(q) = -G\frac{Mm}{|q|^3} q = -\operatorname{grad} U(q), \qquad U(q) = -G\frac{Mm}{|q|}, \tag{4}$$

where $G = 6,67 \cdot 10^{-11}\, Nm^2kg^{-2}$ is the gravitational constant and U is the gravitational potential. We consider now the energy function (compare with (25.1)) along the orbit as the sum of the kinetic and the potential energy

$$E(t) := \frac{m}{2}|\dot{q}(t)|^2 + U(q(t)) = \frac{m}{2}|\dot{q}(t)|^2 - G\frac{Mm}{|q(t)|} \tag{5}$$

which is constant along the orbit, since

$$\partial_t E(t) = m(\ddot{q}(t)|\dot{q}(t)) + (\operatorname{grad} U(q(t))|\dot{q}(t)) = 0.$$

We have in the coordinates specified above for the velocity $v = |\dot q|$

$$v^2 = |\dot q|^2 = \operatorname{Re}(\bar{\dot z}\dot z) = \operatorname{Re}((\dot r e^{-i\varphi} - ir\dot\varphi e^{-i\varphi})(\dot r e^{i\varphi} + ir\dot\varphi e^{i\varphi})) = \dot r^2 + r^2\dot\varphi^2.$$

We look now for a solution in the form $r = r(\varphi)$. From (3) we have $\dot\varphi = j/r^2$ so that

$$v^2 = \dot r^2 + r^2\dot\varphi^2 = \left(\frac{dr}{d\varphi}\right)^2 \dot\varphi^2 + r^2\dot\varphi^2 = \left(\frac{dr}{d\varphi}\right)^2 \frac{j^2}{r^4} + \frac{j^2}{r^2}.$$

Plugging into the conservation of energy (5) we get

$$\left(\frac{dr}{d\varphi}\right)^2 \frac{j^2}{r^4} + \frac{j^2}{r^2} - 2GM\frac{1}{r(t)} = \gamma = \text{ constant.}$$

$$\frac{1}{r^4}\left(\frac{dr}{d\varphi}\right)^2 = \frac{\gamma}{j^2} + \frac{2GM}{j^2}\frac{1}{r(t)} - \frac{1}{r^2} \tag{6}$$

Excluding the catastrophe of the planet falling into the sun we may assume that always $r \neq 0$ and substitute

$$u(\varphi) = \frac{1}{r(\varphi)}, \quad \frac{du}{d\varphi} = -\frac{1}{r^2}\frac{dr}{d\varphi}$$

into (6) to obtain

$$\left(\frac{du}{d\varphi}\right)^2 = \frac{\gamma}{j^2} + \frac{2GM}{j^2}u - u^2 = \frac{G^2M^2}{j^4}\left(1 + \frac{\gamma j^2}{G^2M^2}\right) - \left(u - \frac{GM}{j^2}\right)^2,$$

$$\left(\frac{du}{d\varphi}\right)^2 = \frac{\varepsilon^2}{p^2} - \left(u - \frac{1}{p}\right)^2, \qquad \text{where } p := \frac{j^2}{GM}, \quad \varepsilon := \sqrt{1 + \frac{\gamma j^2}{G^2M^2}} \tag{7}$$

are parameters suitable to describe conic sections.

If $\varepsilon = 0$ then $(\frac{du}{d\varphi})^2 = -(u - \frac{1}{p})^2$ so that both sides have to be zero: $u = 1/p$ or $r = p =$ constant and the planet moves on a circle.

If $\varepsilon > 0$ then (7) becomes

$$\frac{du}{d\varphi} = \sqrt{\frac{\varepsilon^2}{p^2} - \left(u - \frac{1}{p}\right)^2}, \qquad d\varphi = \frac{du}{\sqrt{\frac{\varepsilon^2}{p^2} - \left(u - \frac{1}{p}\right)^2}}$$

$$\begin{aligned}
\varphi + C &= \int d\varphi = \int \frac{du}{\sqrt{\frac{\varepsilon^2}{p^2} - \left(u - \frac{1}{p}\right)^2}}, \qquad w = u - \frac{1}{p} \\
&= \int \frac{dw}{\sqrt{\frac{\varepsilon^2}{p^2} - w^2}} = \frac{p}{\varepsilon}\int \frac{dw}{\sqrt{1 - (\frac{pw}{\varepsilon})^2}}, \qquad z = \frac{pw}{\varepsilon} \\
&= \int \frac{dz}{\sqrt{1 - z^2}} = \arcsin(z) = \arcsin\left(\frac{pw}{\varepsilon}\right) = \arcsin\left(\frac{pu - 1}{\varepsilon}\right).
\end{aligned}$$

This implies

$$\sin(\varphi + C) = \frac{pu - 1}{\varepsilon}, \qquad u = \frac{1 + \varepsilon \sin(\varphi + C)}{p}$$
$$r = \frac{1}{u} = \frac{p}{1 + \varepsilon \sin(\varphi + C)}.$$

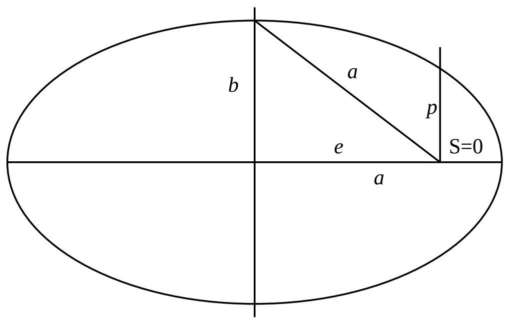
We choose the parameter C such that the minimal distance $\frac{p}{1+\varepsilon}$ of the planet from the sun (its *perihel*) is attained at $\varphi = 0$ so that $\sin(C) = 1$ or $C = \pi/2$; then $\sin(\varphi + \pi/2) = \cos(\varphi)$ and the *planetary orbit* is described by the equation

(8) $$r = \frac{p}{1 + \varepsilon \cos\varphi}, \qquad p > 0, \quad \varepsilon \geq 0.$$

Equation (8) *describes a conic section in polar coordinates with one focal point at 0. We have:*

A circle for $\varepsilon = 0$.
An ellipse for $0 \leq \varepsilon < 1$.
A parabola for $\varepsilon = 1$.
The left branch of a hyperbola for $\varepsilon > 1$.

The ellipse with the right hand focal point at at 0:



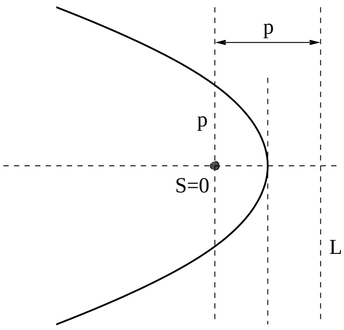
$$\frac{(q_1 + e)^2}{a^2} + \frac{{q_2}^2}{b^2} = 1,$$
$$e = \sqrt{a^2 - b^2},$$
$$\frac{(r\cos\varphi + e)^2}{a^2} + \frac{r^2 \sin^2\varphi}{b^2} = 1$$
$$(b^2 - a^2) r^2 \cos^2\varphi +$$
$$+ 2b^2 r \sqrt{a^2 - b^2} \cos\varphi +$$
$$+ a^2 r^2 - b^4 = 0.$$

Solving for $\cos\varphi$ we get

$$\cos\varphi = \frac{-2b^2 r\sqrt{a^2 - b^2} \pm \sqrt{4b^4 r^2 (a^2 - b^2) + 4(a^2 - b^2) r^2 (a^2 r^2 - b^4)}}{-2(a^2 - b^2) r^2}$$
$$= \frac{-2b^2 re \pm 2r^2 ea}{-2r^2 e^2} = \frac{b^2}{re} \pm \frac{a}{e}, \qquad \text{thus} \qquad \frac{b^2}{re} = \cos\varphi \pm \frac{a}{e}$$
$$r = \frac{b^2}{e(\cos\varphi \pm \frac{a}{e})} = \frac{b^2}{e\frac{a}{e}(\pm 1 + \frac{e}{a}\cos\varphi)} = \frac{\frac{b^2}{a}}{\pm 1 + \frac{e}{a}\cos\varphi}$$

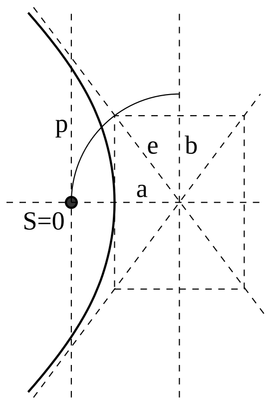
Put $p = b^2/a$ and $0 \leq \varepsilon = \sqrt{1 - b^2/a^2} = e/a \leq 1$ and note that $r > 0$ to obtain the desired equation (8) $r = \frac{p}{1+\varepsilon\cos\varphi}$.

The parabola with focal point at 0:



$$
\begin{aligned}
{q_2}^2 &= -2p(q_1 - \frac{p}{2}) = -2pq_1 + p^2,\\
r^2(1-\cos^2\varphi) &= -2pr\cos\varphi + p^2,\\
r^2\cos^2\varphi - 2pr\cos\varphi + p^2 - r^2 &= 0\\
\cos\varphi &= \frac{2pr \pm \sqrt{4p^2r^2 - 4r^2(p^2-r^2)}}{2r^2}\\
&= \frac{p\pm r}{r} = \frac{p}{r} \pm 1\\
r &= \frac{p}{1+\cos\varphi} \qquad > 0.
\end{aligned}
$$

The hyperbola with left hand focal point at 0:



$$
\begin{aligned}
&\frac{(q_1-e)^2}{a^2} - \frac{{q_2}^2}{b^2} = 1\\
&e = \sqrt{a^2+b^2}\\
&\frac{(r\cos\varphi - e)^2}{a^2} - \frac{r^2\sin^2\varphi}{b^2} = 1\\
&b^2r^2\cos^2\varphi - 2b^2r\sqrt{a^2+b^2}\cos\varphi +\\
&\qquad + a^2b^2 + b^4 - a^2r^2(1-\cos^2\varphi) = a^2b^2\\
&(b^2+a^2)r^2\cos^2\varphi -\\
&\qquad - 2b^2r\sqrt{a^2+b^2}\cos\varphi + b^4 - a^2r^2 = 0
\end{aligned}
$$

Solving again for $\cos\varphi$ we get

$$
\begin{aligned}
\cos\varphi &= \frac{2b^2r\sqrt{a^2+b^2} \pm \sqrt{4b^4r^2(a^2+b^2) - 4(a^2+b^2)r^2(b^4-a^2r^2)}}{2(a^2+b^2)r^2}\\
&= \frac{2b^2re \pm 2r^2ea}{2r^2e^2}
\end{aligned}
$$

Put $p = b^2/a$ and $\varepsilon = \sqrt{1+b^2/a^2} = e/a > 1$ and note that $r > 0$ to obtain the desired equation (8) $r = \frac{p}{1+\varepsilon\cos\varphi}$.

(Kepler's 3rd law) If T is the orbital periods of a planet on an elliptic orbits with major half axis a then:

$$\frac{T^2}{a^3} = \frac{(2\pi)^2}{GM}$$

is a constant depending only on the mass of the sun and not on the planet.

Let a and b be the major and minor half axes of an elliptic planetary orbit with period T. The area of this ellipse is $ab\pi$. But by (3) this area equals $ab\pi = jT/2$. In (7) we had $p = j^2/(GM)$, for an ellipse we have $p = b^2/a$, thus we get

$$\frac{j}{2}T = ab\pi = a^{3/2}p^{1/2}\pi = a^{3/2}\frac{j}{\sqrt{GM}}\pi, \qquad T = \frac{2\pi a^{3/2}}{\sqrt{GM}}, \qquad \frac{T^2}{a^3} = \frac{(2\pi)^2}{GM}.$$

25.25. Kepler's laws: The two body system as a completely integrable system. Here we start to treat the 2-body system with methods like Poisson bracket etc, as explained in (25.23). So the symplectic manifold (the *phase space*) is $T^*(\mathbb{R}^3 \setminus \{0\})$ with symplectic form $\omega = \omega_{\mathbb{R}^3} = -d\theta_{\mathbb{R}^3} = \sum_{i=1}^3 dq^i \wedge dp_i$. As in (25.1) we use the canonical coordinates q^i on $\mathbb{R}^3$ and $p_i := m \cdot \dot{q}^i$ on the cotangent fiber. The Hamiltonian function of the system is the energy from (25.24.5) written in these coordinates:

$$(1) \qquad E(q,p) := \frac{1}{2m}|p|^2 + U(q) = \frac{1}{2m}|p|^2 - G\frac{Mm}{|q|} = \frac{1}{2m}\sum p_i^2 - G\frac{Mm}{\sqrt{\sum (q^i)^2}}$$

The Hamiltonian vector field is then given by

$$H_E = \sum_{i=1}^3 \Big(\frac{\partial E}{\partial p_i}\frac{\partial}{\partial q^i} - \frac{\partial E}{\partial q^i}\frac{\partial}{\partial p_i}\Big) = \sum_{i=1}^3 \Big(\frac{1}{m}p_i\frac{\partial}{\partial q^i} - \frac{GMm}{|q|^3}q^i\frac{\partial}{\partial p_i}\Big)$$

The flow lines of this vector field can be expressed in terms of elliptic functions. Briefed by (25.24.2) we consider the 3 components of the vector product $J(q,p) = q \times p$ and we may compute that

$$\begin{gathered} J^1 = q^2p_3 - q^3p_2, \quad J^2 = -q^1p_3 + q^3p_1, \quad J^3 = q^1p_2 - q^2p_1, \\ \{E, J^i\} = 0, \quad \{J^i, J^k\} = 0, \quad \text{for } i,k = 1,2,3. \end{gathered}$$

Moreover the functions J^1, J^2, J^3 have linearly independent differentials on an open dense subset. Thus the 2 body system is a completely integrable system. The meaning of this will be explained later.

26. Completely integrable Hamiltonian systems

26.1. Introduction. The pioneers of analytical mechanics, Euler, Lagrange, Jacobi, Kowalewska, ... , were deeply interested in completely integrable systems, of which they discovered many examples: The motion of a rigid body with a fixed point in the three classical cases (Euler-Lagrange, Euler-Poisot, and Kowalewska cases), Kepler's system, the motion of a massive point in the gravitational field created by fixed attracting points, geodesics on an ellipsoid, etc. To analyze such systems Jacobi developed a method which now bears his name, based on a search for a complete integral of the first order partial differential equation associated with the Hamitonian system under consideration, called the Hamilton-Jacobi equation. Later it turned out, with many contributions by Poincaré, that complete integrability is very exceptional: A small perturbation of the Hamiltonian function can destroy it. Thus this topic fell in disrespect.

Later Kolmogorov, Arnold, and Moser showed that certain qualitative properties of completely integrable systems persist after perturbation: certain invariant tori on which the quasiperiodic motion of the non-perturbed, completely integrable system takes place survive the perturbation.

More recently it has been shown that certain nonlinear partial differential equations such as the Korteveg-de Vries equation $u_t + 3u_x u + a u_{xxx} = 0$ or the Camassa-Holm equation $u_t - u_{txx} = u_{xxx}.u + 2u_{xx}.u_x - 3u_x.u$ may be regarded as infinite dimensional ordinary differential equations which have many properties of completely integrable Hamiltonian systems. This started new very active research in completely integrable systems.

26.2. Completely integrable systems. Let (M, ω) be a symplectic manifold with $\dim(M) = 2n$ with a Hamiltonian function $h \in C^\infty(M)$.

(1) The *Hamiltonian system* (M, ω, h) is called *completely integrable* if there are n functions $f_1, \dots, f_n \in C^\infty(M)$ which

- are pairwise in involution: $\{f_i, f_j\} = 0$ for all i, j.
- are first integrals of the system: $\{h, f_i\} = 0$ for all i.
- are non degenerate: their differentials are linearly independent on a dense open subset of M.

We shall keep this notation throughout this section.

(2) The $n+1$ functions $h, f_1, \dots, f_n \in C^\infty(M)$ are pairwise in involution. At each point $x \in M$ the Hamiltonian fields $H_h(x), H_{f_1}(x), \dots, H_{f_n}(x)$ span an isotropic subset of $T_x M$ which has dimension $\le n$; thus they are linearly dependent. On the dense open subset $U \subseteq M$ where the differentials df_i are linearly independent, $dh(x)$ is a linear combination of $df_1(x), \dots, df_n(x)$. Thus *each $x \in U$ has an open neighborhood $V \subset U$ such that $h|V = \tilde h \circ (f_1, \dots, f_n)|V$ for a smooth local function on $\mathbb{R}^n$.* To see this note that the H_{f_i} span an integrable distribution of constant rank in U whose leaves are given by the connected components of the sets described by the equations $f_i = c_i$, c_i constant, for $i = 1, \dots, n$ of maximal rank. Since $\{h, f_i\} = 0$ the function h is constant along each leaf and thus factors locally over the mapping $f := (f_1, \dots, f_n) : U \to f(U) \subset \mathbb{R}^n$. The Hamiltonian vector field H_h is then a linear combination of the Hamiltonian fields H_{f_i},

$$H_h = \check\omega^{-1}(dh) = \check\omega^{-1}\Big(\sum_{i=1}^n \frac{\partial \tilde h}{\partial f_i}(f_1, \dots, f_n)\, df_i\Big) = \sum_{i=1}^n, \frac{\partial \tilde h}{\partial f_i}(f_1, \dots, f_n)\, H_{f_i}.$$

whose coefficients $\frac{\partial \tilde h}{\partial f_i}(f_1, \dots, f_n)$ depend only on the first integrals $f_1, \dots, f_n$. The f_i are constant along the flow lines of H_h since $\{h, f_i\} = 0$ implies $(\mathrm{Fl}^{H_h}_t)^* f_i = f_i$ and $(\mathrm{Fl}^{H_h}_t)^* H_{f_i} = H_{f_i}$. This last argument also shows that a trajectory of H_h intersecting U is completely contained in U. Therefore these coefficients $\frac{\partial \tilde h}{\partial f_i}(f_1, \dots, f_n)$ are constant along each trajectory of H_h which is contained in U.

(3) *The Hamiltonian vector fields $H_{f_1}, \dots, H_{f_n}$ span a smooth integrable distribution on M according to* (3.28), since $[H_{f_i}, H_{f_j}] = H_{\{f_i, f_j\}} = 0$ and $(\mathrm{Fl}^{H_{f_i}}_t)^* H_{f_j} = H_{f_j}$, so the dimension of the span is constant along each flow. So we have a foliation of jumping dimension on M: Each point of M lies in an initial submanifold which is

an integral manifold for the distribution spanned by the H_{f_i}. Each trajectory of H_h or of any H_{f_i} is completely contained in one of these leaves. The restriction of this foliation to the open set U is a foliation of U by Lagrangian submanifolds, whose leaves are defined by the equations $f_i = c_i$, $i = 1, \dots, n$, where the c_i are constants.

26.3. Lemma. [Arnold, 1978] *Let $\mathbb{R}^{2n} = \mathbb{R}^n \times \mathbb{R}^n$ be the standard symplectic vector space with standard basis e_i such that $\omega = \sum_{i=1}^n e^i \wedge e^{n+i}$. Let $W \subset \mathbb{R}^{2n}$ be a Lagrangian subspace.*

Then there is a partition $\{1, \dots, n\} = I \sqcup J$ such that the Lagrangian subspace U of $\mathbb{R}^{2n}$ spanned by the e_i for $i \in I$ and the e_{n+j} for $j \in J$, is a complement to W in $\mathbb{R}^{2n}$.

Proof. Let $k = \dim(W \cap (\mathbb{R}^n \times 0))$. If $k = n$ we may take $I = \emptyset$. If $k < n$ there exist $n - k$ elements $e_{i_1}, \dots, e_{i_{n-k}}$ of the basis $e_1, \dots, e_n$ of $\mathbb{R}^n \times 0$ which span a complement U' of $W \cap (\mathbb{R}^n \times 0)$ in $\mathbb{R}^n \times 0$. Put $I = \{i_1, \dots, i_{n-k}\}$ and let J be the complement. Let U'' be the span of the e_{n+j} for $j \in J$, and let $U = U' \oplus U''$. Then U is a Lagrangian subspace. We have

$$\mathbb{R}^n \times 0 = (W \cap (\mathbb{R}^n \times 0)) \oplus U', \quad W \cap (\mathbb{R}^n \times 0) \subset W, \quad U' = U \cap (\mathbb{R}^n \times 0) \subset U.$$

Thus $\mathbb{R}^n \times 0 \subset W + U$. Since $\mathbb{R}^n \times 0$, W, U are Lagrangian we have by (25.4.4)

$$W \cap U = W^\perp \cap U^\perp = (W + U)^\perp \subset (\mathbb{R}^n \times 0)^\perp = \mathbb{R}^n \times 0 \quad \text{thus}$$
$$W \cap U = (W \cap (\mathbb{R}^n \times 0)) \cap (U \cap (\mathbb{R}^n \times 0)) = W \cap (\mathbb{R}^n \times 0) \cap U' = 0,$$

and U is a complement of W. □

26.4. Lemma. *Let (M, ω) be a symplectic manifold of dimension $2n$, let $x \in M$. Suppose that $2n$ smooth functions $u^1, \dots, u^n, f_1, \dots, f_n$ are given near x, that their differentials are linearly independent, and that they satisfy the following properties:*

- *The submanifold defined by the equations $u^i = u^i(x)$ for $i = 1, \dots, n$, is Lagrangian.*
- *The functions $f_1, \dots, f_n$ are pairwise in involution: $\{f_i, f_j\} = 0$ for all i, j.*

Then on an open neighborhood U of x in M we may determine n other smooth functions $g_1, \dots, g_n$ such that

$$\omega|U = \sum_{i=1}^n df_i \wedge dg_i.$$

The determination of g_i uses exclusively the operations of integration, elimination (solving linear equations), and partial differentiation.

Proof. Without loss we may assume that $u_i(x) = 0$ for all i. There exists a contractible open neighborhood U of x in M such that $(u, f) := (u^1, \dots, u^n, f_1, \dots, f_n)$ is a chart defined on U, and such that each diffeomorphism $\psi_t(u, f) := (t\,u, f)$ is defined on the whole of U for t near $[0,1]$ and maps U into itself. Since ψ_0 maps U onto the Lagrange submanifold $N := \{y \in U : u_i(y) = 0 \text{ for } i = 1, \dots, n\}$ we have $\psi_0^*\omega = 0$. Using the homotopy invariance (9.4) we have

$$\omega|U = \psi_1^*\omega = \psi_0^*\omega + d\bar{h}(\omega) - \bar{h}(d\omega) = 0 + d\bar{h}\omega + 0,$$

where $\bar{h}(\omega) = \int_0^1 \operatorname{ins}_t^* i_{\partial_t}\psi^*\omega\, dt$ is from the proof of (9.4).

Since $f_1, \dots, f_n$ are pairwise in involution and have linearly independent differentials, $\omega|U$ belongs to the ideal in $\Omega^*(U)$ generated by $df_1, \dots, df_n$. This is a pointwise property. At $y \in U$ the tangent vectors $H_{f_1}(y), \dots, H_{f_n}(y)$ span a Lagrangian vector subspace L of T_yM with annihilator $L^o \subset T_y^*M$ spanned by $df_1(y), \quad, df_n(y)$. Choose a complementary Lagrangian subspace $W \subset T_yM$, see the proof of (25.21). Let $\alpha_1, \dots, \alpha_n \in T_y^*M$ be a basis of the annihilator W^o. Then $\omega_y = \sum_{i,j=1}^n \omega_{ij}\alpha_i \wedge df_j(y)$ since ω vanishes on L, on W, and induces a duality between L and W.

From the form of $\bar{h}(\omega)$ above we see that then also $\bar{h}(\omega)$ belongs to this ideal, since $\psi_t^* f_i = f_i$ for all i. Namely,

$$\bar{(}\omega) = \sum_{i,j=1}^n \int_0^1 \Big(\operatorname{ins}_t^*(\psi^*\omega_{ij}.\operatorname{ins}_t^*(i_{\partial_t}\psi^*\alpha_i).df_j\Big)dt =: \sum_{j=1}^n g_j\, df_j$$

for smooth functions g_i. Finally we remark that the determination of the components of ω in the chart (u, f) uses partial differentiations and eliminations, whereas the calculation of the components of $\bar{h}(\omega)$ uses integration. $\square$

26.5. Lemma. *Let (M, ω) be a symplectic manifold of dimension $2n$. We assume that the following data are known on an open subset U of M.*

- *A canonical system of local coordinates $(q^1, \dots, q^n, p_1, \dots, p_n)$ on U such that the symplectic form is given by $\omega|U = \sum_{i=1}^n dq^i \wedge dp_i$.*
- *Smooth functions $f_1, \dots, f_n$ which are pairwise in involution, $\{f_i, f_j\} = 0$ for all i, j, and whose differentials are linearly independent.*

Then each $x \in U$ admits an open neighborhood $V \subseteq U$ on which we can determine other smooth functions $g_1, \dots, g_n$ such that

$$\omega|_V = \sum_{i=1}^n df_i \wedge dg_i.$$

The determination of g_i uses exclusively the operations of integration, elimination (use of the implicit function theorem), and partial differentiation.

Proof. If the functions $q^1, \dots, q^n, f_1, \dots, f_n$ have linearly independent differentials at a point $x \in U$ the result follows from (26.4). In the general case we consider the Lagrangian subspace $L \subset T_xM$ spanned by $H_{f_1}(x), \dots, H_{f_n}(x)$. By lemma (26.3) there exists a partition $\{1, \dots, n\} = I \sqcup J$ such that the Langrangian subspace $W \subset T_xM$ spanned by $H_{q^i}(x)$ for $i \in I$ and $H_{p_j}(x)$ for $j \in J$, is complementary to L. Now the result follows from lemma (26.4) by calling u^k, $k = 1, \dots, n$ the functions q^i for $i \in I$ and p_j for $j \in J$. $\square$

26.6. Proposition. *Let (M,ω,h) be a Hamiltonian system on a symplectic manifold of dimension $2n$. We assume that the following data are known on an open subset U of M.*

- *A canonical system of local coordinates $(q^1,\dots,q^n,p_1,\dots,p_n)$ on U such that the symplectic form is given by $\omega|U=\sum_{i=1}^n dq^1\wedge dp_i$.*
- *A family $f=(f_1,\dots,f_n)$ of smooth first integrals for the Hamiltonian function h which are pairwise in involution, i.e. $\{h,f_i\}=0$ and $\{f_i,f_j\}=0$ for all i,j, and whose differentials are linearly independent.*

Then for each $x\in U$ the integral curve of H_h passing through x can be determined locally by using exclusively the operations of integration, elimination, and partial differentiation.

Proof. By lemma (26.5) there exists an open neighborhood V of x in U and functions $g_1,\dots,g_n\in C^\infty(V)$ such that $\omega|V=\sum_{i=1}^n df_i\wedge dg_i$. The determination uses only integration, partial differentiation, and elimination. We may choose V so small that $(f,g):=(f_1,\dots,f_n,g_1,\dots,g_n)$ is a chart on V with values in a cube in $\mathbb{R}^{2n}$.

We have already seen in (26.2.2) that $h|V=\tilde h\circ(f,g)$ where $\tilde h=h\circ(f,g)^{-1}$ is a smooth function on the cube which does not depend on the g_i. In fact $\tilde h$ may be determined by elimination since h is constant on the leaves of the foliation given by $f_i=c_i$, c_i constant.

The differential equation for the trajectories of H_h in V is given by

$$\dot f_k=\frac{\partial\tilde h}{\partial g_k}=0,\qquad \dot g_k=-\frac{\partial\tilde h}{\partial f_k},\qquad k=1,\dots,n,$$

thus the integral curve $\mathrm{Fl}_t^{H_h}(x)$ is given by

$$\begin{aligned}f_k(\mathrm{Fl}_t^{H_h}(x))&=f_k(x),\\ g_k(\mathrm{Fl}_t^{H_h}(x))&=g_k(x)-t\,\frac{\partial\tilde h}{\partial f_k}(f(x)),\end{aligned}\qquad k=1,\dots,n.\quad\square$$

26.7. Proposition. *Let (M,ω,h) be a Hamiltonian system with* $\dim(M)=2n$ *and let $f=(f_1,\dots,f_n)$ be a family first integrals of h which are pairwise in involution, $\{h,f_i\}=0$ and $\{f_i,f_j\}=0$ for all i,j. Suppose that all Hamiltonian vector fields H_{f_i} are complete. Then we have:*

(1) *The vector fields H_{f_i} are the infinitesimal generators of a smooth action $\ell:\mathbb{R}^n\times M\to M$ whose orbits are the isotropic leaves of the foliation with jumping dimension described in* (26.2.3) *and which can be described by*

$$\ell_{(t_1,\dots,t_n)}(x)=(\mathrm{Fl}_{t_1}^{H_{f_1}}\circ\dots\circ\mathrm{Fl}_{t_n}^{H_{f_n}})(x).$$

Each orbit is invariant under the flow of H_h.

(2) *(Liouville's theorem) If $a\in f(M)\subset\mathbb{R}^n$ is a regular value of f and if $N\subseteq f^{-1}(a)$ is a connected component, then N is a Lagrangian submanifold and*

is an orbit of the action of $\mathbb{R}^n$ *which acts transitively and locally freely on* N*: For any point* $x \in N$ *the isotopy subgroup* $(\mathbb{R}^n)_x := \{t \in \mathbb{R}^n : \ell_t(x) = x\}$ *is a discrete subgroup of* $\mathbb{R}^n$*. Thus it is a lattice* $\sum_{i=1}^k 2\pi\mathbb{Z}\, v_i$ *generated by* $k = \operatorname{rank}(\mathbb{R}^n)_x$ *linearly independent vectors* $2\pi v_i \in \mathbb{R}^n$*. The orbit* N *is diffeomorphic to the quotient group* $\mathbb{R}^n/(\mathbb{R}^n)_x \cong \mathbb{T}^k \times \mathbb{R}^{n-k}$*, a product of the* k*-dimensional torus by an* $(n-k)$*-dimensional vector space.*

Moreover, there exist constants $(w_1, \dots, w_n) \in \mathbb{R}^n$ *such that the flow of the Hamiltonian* h *on* N *is given by* $\operatorname{Fl}_t^{H_h} = \ell_{(tw_1,\dots,tw_n)}$*. If we use coordinates* $(b_1 \mod 2\pi, \dots, b_k \mod 2\pi, b_{k+1}, \dots, b_n)$ *corresponding to the diffeomorphic description* $N \cong \mathbb{T}^k \times \mathbb{R}^{n-k}$ *the flow of* h *is given by*

$$\begin{aligned}\operatorname{Fl}_t^{H_h}&(b_1 \bmod 2\pi, \dots, b_k \bmod 2\pi, b_{k+1}, \dots, b_n) =\\ &= (b_1 + tc_1 \bmod 2\pi, \dots, b_k + tc_k \bmod 2\pi, b_{k+1} + tc_{k+1}, \dots, b_n + tc_n)\end{aligned}$$

for constant c_i*. If* N *is compact so that* $k = n$*, this is called a quasiperiodic flow.*

Proof. The action ℓ is well defined since the complete vector fields H_{f_i} commute, see the proof of (3.17). Or we conclude the action directly from theorem (5.15). The rest of this theorem follows already from (26.2), or is obvious. The form of discrete subgroups of $\mathbb{R}^n$ is proved in the next lemma. □

26.8. Lemma. *Let* G *be a discrete subgroup of* $\mathbb{R}^n$*. Then* G *is the lattice* $\sum_{i=1}^k \mathbb{Z}\, v_i$ *generated by* $0 \le k = \operatorname{rank}(G) \le n$ *linearly independent vectors* $v_i \in \mathbb{R}^n$*.*

Proof. We use the standard Euclidean structure of $\mathbb{R}^n$. If $G \ne 0$ there is $0 \ne v \in G$. Let v_1 be the point in $\mathbb{R}v \cap G$ which is nearest to 0 but nonzero. Then $G \cap \mathbb{R}v = \mathbb{Z}v_1$: if there were $w \in G$ in one of the intervals $(m, m+1)v_1$ then $w - mv_1 \in \mathbb{R}v_1$ would be nonzero and closer to 0 than v_1.

If $G \ne \mathbb{Z}v_1$ there exists $v \in G \setminus \mathbb{R}v_1$. We will show that there exists a point v_2 in G with minimal distance to the line $\mathbb{R}v_2$ but not in the line. Suppose that the orthogonal projection $\operatorname{pr}_{\mathbb{R}v_1}(v)$ of v onto $\mathbb{R}v_1$ lies in the intervall $P = [m, m+1]v_1$ for $m \in \mathbb{Z}$, consider the cylinder $C = \{z \in \operatorname{pr}_{\mathbb{R}v_1}^{-1}(P) : \operatorname{dist}(z, P) \le \operatorname{dist}(v, P)\}$ and choose a point $v_2 \in G \setminus \mathbb{R}v_1$ in this cylinder nearest to P. Then v_2 has minimal distance to $\mathbb{R}v_1$ in $G \setminus (\mathbb{R}v_1)$ since any other point in G with smaller distance can be shifted into the cylinder C by adding some suitable mv_1.

Then $\mathbb{Z}v_1 + \mathbb{Z}v_2$ forms a lattice in the plane $\mathbb{R}v_1 + \mathbb{R}v_2$ which is partitioned into paralellograms $Q = \{a_1v_1 + a_2v_2 : m_i \le a_i < m_i + 1\}$ for $m_i \in \mathbb{Z}$. If there is a point $w \in G$ in one of these parallelograms Q then a suitable translate $w - n_1v_1 - n_2v_2$ would be nearer to $\mathbb{R}v_1$ than v_2. Thus $G \cap (\mathbb{R}v_1 + \mathbb{R}v_2) = \mathbb{Z}v_1 + \mathbb{Z}v_2$.

If there is a point of G outside this plane we may find as above a point v_3 of G with minimal distance to the plane, and by covering the 3-space $\mathbb{R}v_1 + \mathbb{R}v_2 + \mathbb{R}v_3$ with parallelepipeds we may show as above that $G \cap (\mathbb{R}v_1 + \mathbb{R}v_2 + \mathbb{R}v_3) = \mathbb{Z}v_1 + \mathbb{Z}v_2 + \mathbb{Z}v_3$, and so on. □

27. Extensions of Lie algebras and Lie groups

In this section we describe first the theory of semidirect products and central extensions of Lie algebras, later the more involved theory of general extensions with non-commutative kernels. For the latter we follow the presentation from [Alekseevsky, Michor, Ruppert, 2000], with special emphasis to connections with the (algebraic) theory of covariant exterior derivatives, curvature and the Bianchi identity in differential geometry (see section (27.3)). The results are due to [Hochschild, 1954], [Mori, 1953], [Shukla, 1966], and generalizations for Lie algebroids are in [Mackenzie, 1987].

The analogous result for super Lie algebras are available in [Alekseevsky, Michor, Ruppert, 2001].

The theory of group extensions and their interpretation in terms of cohomology is well known, see [Eilenberg, MacLane, 1947], [Hochschild, Serre, 1953], [Giraud, 1971], [Azcárraga, Izquierdo, 1995], e.g.

27.1. Extensions. An *extension* of a Lie algebra $\mathfrak{g}$ with kernel $\mathfrak{h}$ is an exact sequence of homomorphisms of Lie algebras:

$$0 \to \mathfrak{h} \xrightarrow{i} \mathfrak{e} \xrightarrow{p} \mathfrak{g} \to 0.$$

(1) This extension is called a *semidirect product* if we can find a section $s : \mathfrak{g} \to \mathfrak{e}$ which is a Lie algebra homomorphism. Then we have a representation of the Lie algebra $\alpha : \mathfrak{g} \to L(\mathfrak{h}, \mathfrak{h})$ which is given by $\alpha_X(H) = [s(X), H]$ where we suppress the injection i. It is a representation since $\alpha_{[X,Y]}H = [s([X,Y]), H] = [[s(X), s(Y)], H] = [s(X), [s(Y), H]] - [s(Y), [s(X, H)]] = (\alpha_X\alpha_Y - \alpha_Y\alpha_X)H$. This representation takes values in the Lie algebra $\operatorname{der}(\mathfrak{h})$ of derivations of $\mathfrak{h}$, so $\alpha : \mathfrak{g} \to \operatorname{der}(\mathfrak{h})$. From the data α, s we can reconstruct the extension $\mathfrak{e}$ since on $\mathfrak{h} \times \mathfrak{g}$ we have $[H + s(X), H' + s(X')] = [H, H'] + [s(X), H'] - [s(X'), H] + [X, X'] = [H, H'] + \alpha_X(H') - \alpha_{X'}(H) + [X, X']$.

(2) The extension is called *central extension* if $\mathfrak{h}$ or rather $i(\mathfrak{h})$ is in the center of $\mathfrak{e}$.

27.2. Describing extensions. Consider any exact sequence of homomorphisms of Lie algebras:

$$0 \to \mathfrak{h} \xrightarrow{i} \mathfrak{e} \xrightarrow{p} \mathfrak{g} \to 0.$$

Consider a linear mapping $s : \mathfrak{g} \to \mathfrak{e}$ with $p \circ s = \operatorname{Id}_{\mathfrak{g}}$. Then s induces mappings

$$\alpha : \mathfrak{g} \to \operatorname{der}(\mathfrak{h}), \qquad \alpha_X(H) = [s(X), H], \tag{1}$$

$$\rho : \textstyle\bigwedge^2 \mathfrak{g} \to \mathfrak{h}, \qquad \rho(X,Y) = [s(X), s(Y)] - s([X,Y]), \tag{2}$$

which are easily seen to satisfy

$$[\alpha_X, \alpha_Y] - \alpha_{[X,Y]} = \operatorname{ad}_{\rho(X,Y)} \tag{3}$$

$$\sum_{\text{cyclic}\{X,Y,Z\}} \Big(\alpha_X \rho(Y,Z) - \rho([X,Y],Z)\Big). = 0 \tag{4}$$

We can completely describe the Lie algebra structure on $\mathfrak{e} = \mathfrak{h} \oplus s(\mathfrak{g})$ in terms of α and ρ :

$$(5) \quad [H_1 + s(X_1), H_2 + s(X_2)] = \\ = ([H_1, H_2] + \alpha_{X_1} H_2 - \alpha_{X_2} H_1 + \rho(X_1, X_2)) + s[X_1, X_2]$$

and one can check that formula (5) gives a Lie algebra structure on $\mathfrak{h} \oplus s(\mathfrak{g})$, if $\alpha : \mathfrak{g} \to \operatorname{der}(\mathfrak{h})$ and $\rho : \bigwedge^2 \mathfrak{g} \to \mathfrak{h}$ satisfy (3) and (4).

27.3. Motivation: Lie algebra extensions associated to a principal bundle.

Let $\pi : P \to M = P/K$ be a principal bundle with structure group K, see section (21); i.e. P is a manifold with a free right action of a Lie group K and π is the projection on the orbit space $M = P/K$. Denote by $\mathfrak{g} = \mathfrak{X}(M)$ the Lie algebra of the vector fields on M, by $\mathfrak{e} = \mathfrak{X}(P)^K$ the Lie algebra of K-invariant vector fields on P and by $\mathfrak{h} = \mathfrak{X}_{\text{vert}}(P)^K$ the ideal of the K-invariant vertical vector fields of $\mathfrak{e}$. Geometrically, $\mathfrak{e}$ is the Lie algebra of infinitesimal automorphisms of the principal bundle P and $\mathfrak{h}$ is the ideal of infinitesimal automorphisms acting trivially on M, i.e. the Lie algebra of infinitesimal gauge transformations. We have a natural homomorphism $\pi_* : \mathfrak{e} \to \mathfrak{g}$ with the kernel $\mathfrak{h}$, i.e. $\mathfrak{e}$ is an extension of $\mathfrak{g}$ by means $\mathfrak{h}$.

Note that we have an additional structure of $C^\infty(M)$-module on $\mathfrak{g}, \mathfrak{h}, \mathfrak{e}$, such that $[X, fY] = f[X, Y] + (\pi_* X)fY$, where $X, Y \in \mathfrak{e}$, $f \in C^\infty(M)$. In particular, $\mathfrak{h}$ is a Lie algebra over $C^\infty(M)$. The extension

$$0 \to \mathfrak{h} \to \mathfrak{e} \to \mathfrak{g} \to 0$$

is also an extension of $C^\infty(M)$-modules.

Assume now that the section $s : \mathfrak{g} \to \mathfrak{e}$ is a homomorphism of $C^\infty(M)$-modules. Then it can be considered as a connection in the principal bundle π, see section (22), and the $\mathfrak{h}$-valued 2-form ρ as its curvature. In this sense we interpret the constructions from section (27.1) as follows in (27.4) below. The analogy with differential geometry has also been noticed by [Lecomte, 1985] and [Lecomte, 1994].

27.4. Geometric interpretation. Note that (27.2.2) looks like the Maurer-Cartan formula for the *curvature* on principal bundles of differential geometry (22.2.3)

$$\rho = ds + \tfrac{1}{2}[s, s]_\wedge,$$

where for an arbitrary vector space V the usual Chevalley differential, see (12.14.2), is given by

$$d : L^p_{\text{skew}}(\mathfrak{g}; V) \to L^{p+1}_{\text{skew}}(\mathfrak{g}; V)$$
$$d\varphi(X_0, \dots, X_p) = \sum_{i<j} (-1)^{i+j} \varphi([X_i, X_j], X_0, \dots, \widehat{X_i}, \dots, \widehat{X_j}, \dots, X_p)$$

and where for a vector space W and a Lie algebra $\mathfrak{f}$ the $\mathbb{N}$-graded (super) Lie bracket $[\quad,\quad]_\wedge$ on $L^*_{\text{skew}}(W, \mathfrak{f})$, see (22.2), is given by

$$[\varphi, \psi]_\wedge(X_1, \dots, X_{p+q}) = \frac{1}{p!\,q!}\sum_\sigma \operatorname{sign}(\sigma)\,[\varphi(X_{\sigma 1}, \dots, X_{\sigma p}), \psi(X_{\sigma(p+1)}, \dots)]_{\mathfrak{f}}.$$

Similarly formula (27.2.3) reads as

$$\operatorname{ad}_\rho = d\alpha + \tfrac{1}{2}[\alpha, \alpha]_\wedge.$$

Thus we view s as a *connection* in the sense of a *horizontal lift* of vector fields on the base of a bundle, and α as an *induced connection*, see (22.8). Namely, for every $\operatorname{der}(\mathfrak{h})$-module V we put

$$\begin{aligned} \alpha_\wedge &: L^p_{\text{skew}}(\mathfrak{g}; V) \to L^{p+1}_{\text{skew}}(\mathfrak{g}; V)\\ \alpha_\wedge\varphi(X_0, \dots, X_p) &= \sum_{i=0}^p (-1)^i \alpha_{X_i}(\varphi(X_0, \dots, \widehat{X_i}, \dots, X_p)). \end{aligned}$$

Then we have the *covariant exterior differential* (on the sections of an associated vector bundle, see (22.12))

(1) $$\delta_\alpha : L^p_{\text{skew}}(\mathfrak{g}; V) \to L^{p+1}_{\text{skew}}(\mathfrak{g}; V), \qquad \delta_\alpha\varphi = \alpha_\wedge\varphi + d\varphi,$$

for which formula (27.2.4) looks like the *Bianchi identity*, see (22.5.6), $\delta_\alpha\rho = 0$. Moreover one can prove by direct evaluation that another well known result from differential geometry holds, namely (22.5.9)

(2) $$\delta_\alpha\delta_\alpha(\varphi) = [\rho, \varphi]_\wedge, \quad \varphi \in L^p_{\text{skew}}(\mathfrak{g}; \mathfrak{h}).$$

If we change the linear section s to $s' = s + b$ for linear $b : \mathfrak{g} \to \mathfrak{h}$, then we get

(3) $$\alpha'_X = \alpha_X + \operatorname{ad}^{\mathfrak{h}}_{b(X)}$$

(4) $$\begin{aligned} \rho'(X, Y) &= \rho(X, Y) + \alpha_X b(Y) - \alpha_Y b(X) - b([X, Y]) + [bX, bY]\\ &= \rho(X, Y) + (\delta_\alpha b)(X, Y) + [bX, bY].\\ \rho' &= \rho + \delta_\alpha b + \tfrac{1}{2}[b, b]_\wedge. \end{aligned}$$

27.5. Theorem. *Let $\mathfrak{h}$ and $\mathfrak{g}$ be Lie algebras.*

Then isomorphism classes of extensions of $\mathfrak{g}$ over $\mathfrak{h}$, i.e. short exact sequences of Lie algebras $0 \to \mathfrak{h} \to \mathfrak{e} \to \mathfrak{g} \to 0$, modulo the equivalence described by the commutative diagram of Lie algebra homomorphisms

$$\begin{array}{ccccccccc} 0 & \longrightarrow & \mathfrak{h} & \longrightarrow & \mathfrak{e} & \longrightarrow & \mathfrak{g} & \longrightarrow & 0\\ & & \| & & {\scriptstyle\varphi}\downarrow & & \| & & \\ 0 & \longrightarrow & \mathfrak{h} & \longrightarrow & \mathfrak{e}' & \longrightarrow & \mathfrak{g} & \longrightarrow & 0, \end{array}$$

correspond bijectively to equivalence classes of data of the following form:

(1) *A linear mapping* $\alpha : \mathfrak{g} \to \operatorname{der}(\mathfrak{h})$,

(2) *a skew-symmetric bilinear mapping* $\rho : \mathfrak{g} \times \mathfrak{g} \to \mathfrak{h}$

such that

(3) $$[\alpha_X, \alpha_Y] - \alpha_{[X,Y]} = \operatorname{ad}_{\rho(X,Y)},$$

(4) $$\sum_{\text{cyclic}} \Big(\alpha_X \rho(Y,Z) - \rho([X,Y],Z) \Big) = 0 \qquad \textit{equivalently, } \delta_\alpha \rho = 0.$$

On the vector space $\mathfrak{e} := \mathfrak{h} \oplus \mathfrak{g}$ *a Lie algebra structure is given by*

(5) $$[H_1 + X_1, H_2 + X_2]_{\mathfrak{e}} = [H_1, H_2]_{\mathfrak{h}} + \alpha_{X_1} H_2 - \alpha_{X_2} H_1 + \rho(X_1, X_2) + [X_1, X_2]_{\mathfrak{g}},$$

the associated exact sequence is

$$0 \to \mathfrak{h} \xrightarrow{i_1} \mathfrak{h} \oplus \mathfrak{g} = \mathfrak{e} \xrightarrow{\mathrm{pr}_2} \mathfrak{g} \to 0.$$

Two data (α, ρ) *and* (α', ρ') *are equivalent if there exists a linear mapping* $b \colon \mathfrak{g} \to \mathfrak{h}$ *such that*

(6) $$\alpha'_X = \alpha_X + \operatorname{ad}^{\mathfrak{h}}_{b(X)},$$

(7) $$\rho'(X,Y) = \rho(X,Y) + \alpha_X b(Y) - \alpha_Y b(X) - b([X,Y]) + [b(X), b(Y)]$$
$$\rho' = \rho + \delta_\alpha b + \tfrac{1}{2}[b,b]_\wedge,$$

the corresponding isomorphism being

$$\mathfrak{e} = \mathfrak{h} \oplus \mathfrak{g} \to \mathfrak{h} \oplus \mathfrak{g} = \mathfrak{e}', \qquad H + X \mapsto H - b(X) + X.$$

Moreover, a datum (α, ρ) *corresponds to a split extension (a semidirect product) if and only if* (α, ρ) *is equivalent to to a datum of the form* $(\alpha', 0)$ *(then* α' *is a homomorphism). This is the case if and only if there exists a mapping* $b : \mathfrak{g} \to \mathfrak{h}$ *such that*

(8) $$\rho = -\delta_\alpha b - \tfrac{1}{2}[b,b]_\wedge.$$

Proof. Straigthforward computations. □

27.6. Corollary. [Lecomte, Roger, 1986] *Let* $\mathfrak{g}$ *and* $\mathfrak{h}$ *be Lie algebras such that* $\mathfrak{h}$ *has no center. Then isomorphism classes of extensions of* $\mathfrak{g}$ *over* $\mathfrak{h}$ *correspond bijectively to Lie homomorphisms*

$$\bar{\alpha} : \mathfrak{g} \to \operatorname{out}(\mathfrak{h}) = \operatorname{der}(\mathfrak{h}) / \operatorname{ad}(\mathfrak{h}).$$

Proof. If (α, ρ) is a datum, then the map $\bar\alpha : \mathfrak g \to \operatorname{der}(\mathfrak h)/\operatorname{ad}(\mathfrak h)$ is a Lie algebra homomorphism by (27.5.3). Conversely, let $\bar\alpha$ be given. Choose a linear lift $\alpha : \mathfrak g \to \operatorname{der}(\mathfrak h)$ of $\bar\alpha$. Since $\bar\alpha$ is a Lie algebra homomorphism and $\mathfrak h$ has no center, there is a uniquely defined skew symmetric linear mapping $\rho : \mathfrak g \times \mathfrak g \to \mathfrak h$ such that $[\alpha_X, \alpha_Y] - \alpha_{[X,Y]} = \operatorname{ad}_{\rho(X,Y)}$. Condition (27.5.4) is then automatically satisfied. For later use also, we record the simple proof:

$$\begin{aligned}
&\sum_{\text{cyclic} X,Y,Z} \Big[\alpha_X \rho(Y,Z) - \rho([X,Y],Z), H\Big] \\
&= \sum_{\text{cyclic} X,Y,Z} \Big(\alpha_X[\rho(Y,Z),H] - [\rho(Y,Z), \alpha_X H] - [\rho([X,Y],Z),H]\Big) \\
&= \sum_{\text{cyclic} X,Y,Z} \Big(\alpha_X[\alpha_Y,\alpha_Z] - \alpha_X\alpha_{[Y,Z]} - [\alpha_Y,\alpha_Z]\alpha_X + \alpha_{[Y,Z]}\alpha_X \\
&\qquad\qquad - [\alpha_{[X,Y]},\alpha_Z] + \alpha_{[[X,Y]Z]}\Big)H \\
&= \sum_{\text{cyclic} X,Y,Z} \Big([\alpha_X,[\alpha_Y,\alpha_Z]] - [\alpha_X, \alpha_{[Y,Z]}] - [\alpha_{[X,Y]},\alpha_Z] + \alpha_{[[X,Y]Z]}\Big)H = 0.
\end{aligned}$$

Thus (α, ρ) describes an extension by theorem (27.5). The rest is clear. □

27.7. Remarks. If $\mathfrak h$ has no center and $\bar\alpha : \mathfrak g \to \operatorname{out}(\mathfrak h) = \operatorname{der}(\mathfrak h)/\operatorname{ad}(\mathfrak h)$ is a given homomorphism, the extension corresponding to $\bar\alpha$ can be constructed in the following easy way: It is given by the pullback diagram

$$\begin{array}{ccccccccc}
0 & \longrightarrow & \mathfrak h & \longrightarrow & \operatorname{der}(\mathfrak h)\times_{\operatorname{out}(\mathfrak h)}\mathfrak g & \xrightarrow{\operatorname{pr}_2} & \mathfrak g & \longrightarrow & 0 \\
 & & \| & & \Big\downarrow{\scriptstyle \operatorname{pr}_1} & & \Big\downarrow{\scriptstyle \bar\alpha} & & \\
0 & \longrightarrow & \mathfrak h & \longrightarrow & \operatorname{der}(\mathfrak h) & \xrightarrow{\pi} & \operatorname{out}(\mathfrak h) & \longrightarrow & 0
\end{array}$$

where $\operatorname{der}(\mathfrak h)\times_{\operatorname{out}(\mathfrak h)}\mathfrak g$ is the Lie subalgebra

$$\operatorname{der}(\mathfrak h)\times_{\operatorname{out}(\mathfrak h)}\mathfrak g := \{(D,X) \in \operatorname{der}(\mathfrak h)\times\mathfrak g : \pi(D) = \bar\alpha(X)\} \subset \operatorname{der}(\mathfrak h)\times\mathfrak g.$$

We owe this remark to E. Vinberg.

If $\mathfrak h$ has no center and satisfies $\operatorname{der}(\mathfrak h) = \mathfrak h$, and if $\mathfrak h$ is normal in a Lie algebra $\mathfrak e$, then $\mathfrak e \cong \mathfrak h \oplus \mathfrak e/\mathfrak h$, since $\operatorname{Out}(\mathfrak h) = 0$.

27.8. Theorem. *Let $\mathfrak g$ and $\mathfrak h$ be Lie algebras and let*

$$\bar\alpha : \mathfrak g \to \operatorname{out}(\mathfrak h) = \operatorname{der}(\mathfrak h)/\operatorname{ad}(\mathfrak h)$$

be a Lie algebra homomorphism. Then the following are equivalent:

1. *For one (equivalently: any) linear lift $\alpha : \mathfrak g \to \operatorname{der}(\mathfrak h)$ of $\bar\alpha$ choose $\rho : \bigwedge^2 \mathfrak g \to \mathfrak h$ satisfying $([\alpha_X, \alpha_Y] - \alpha_{[X,Y]}) = \operatorname{ad}_{\rho(X,Y)}$. Then the $\delta_{\bar\alpha}$-cohomology class of $\lambda = \lambda(\alpha,\rho) := \delta_\alpha\rho : \bigwedge^3 \mathfrak g \to Z(\mathfrak h)$ in $H^3(\mathfrak g; Z(\mathfrak h))$ vanishes.*
2. *There exists an extension $0 \to \mathfrak h \to \mathfrak e \to \mathfrak g \to 0$ inducing the homomorphism $\bar\alpha$.*

If this is the case then all extensions $0 \to \mathfrak{h} \to \mathfrak{e} \to \mathfrak{g} \to 0$ *inducing the homomorphism* $\bar\alpha$ *are parameterized by* $H^2(\mathfrak{g}, (Z(\mathfrak{h}), \bar\alpha))$*, the second Chevalley cohomology space of* $\mathfrak{g}$ *with values in the center* $Z(\mathfrak{h})$*, considered as* $\mathfrak{g}$*-module via* $\bar\alpha$*.*

Proof. Using once more the computation in the proof of corollary (27.6) we see that $\operatorname{ad}(\lambda(X,Y,Z)) = \operatorname{ad}(\delta_\alpha\rho(X,Y,Z)) = 0$ so that $\lambda(X,Y,Z) \in Z(\mathfrak{h})$. The Lie algebra $\operatorname{out}(\mathfrak{h}) = \operatorname{der}(\mathfrak{h})/\operatorname{ad}(\mathfrak{h})$ acts on the center $Z(\mathfrak{h})$, thus $Z(\mathfrak{h})$ is a $\mathfrak{g}$-module via $\bar\alpha$, and $\delta_{\bar\alpha}$ is the differential of the Chevalley cohomology. Using (27.4.2) we see that

$$\delta_{\bar\alpha}\lambda = \delta_\alpha\delta_\alpha\rho = [\rho,\rho]_\wedge = -(-1)^{2\cdot 2}[\rho,\rho]_\wedge = 0,$$

so that $[\lambda] \in H^3(\mathfrak{g}; Z(\mathfrak{h}))$.

Let us check next that the cohomology class $[\lambda]$ does not depend on the choices we made. If we are given a pair (α,ρ) as above and we take another linear lift $\alpha' : \mathfrak{g} \to \operatorname{der}(\mathfrak{h})$ then $\alpha'_X = \alpha_X + \operatorname{ad}_{b(X)}$ for some linear $b : \mathfrak{g} \to \mathfrak{h}$. We consider

$$\rho' : \bigwedge^2 \mathfrak{g} \to \mathfrak{h}, \quad \rho'(X,Y) = \rho(X,Y) + (\delta_\alpha b)(X,Y) + [b(X), b(Y)].$$

Easy computations show that

$$[\alpha'_X, \alpha'_Y] - \alpha'_{[X,Y]} = \operatorname{ad}_{\rho'(X,Y)}$$
$$\lambda(\alpha,\rho) = \delta_\alpha\rho = \delta_{\alpha'}\rho' = \lambda(\alpha',\rho')$$

so that even the cochain did not change. So let us consider for fixed α two linear mappings

$$\rho,\rho' : \bigwedge^2 \mathfrak{g} \to \mathfrak{h}, \quad [\alpha_X, \alpha_Y] - \alpha_{[X,Y]} = \operatorname{ad}_{\rho(X,Y)} = \operatorname{ad}_{\rho'(X,Y)}.$$

Then $\rho - \rho' =: \mu : \bigwedge^2 \mathfrak{g} \to Z(\mathfrak{h})$ and clearly $\lambda(\alpha,\rho) - \lambda(\alpha,\rho') = \delta_\alpha\rho - \delta_\alpha\rho' = \delta_{\bar\alpha}\mu$.

If there exists an extension inducing $\bar\alpha$ then for any lift α we may find ρ as in (27.5) such that $\lambda(\alpha,\rho) = 0$. On the other hand, given a pair (α,ρ) as in (1) such that $[\lambda(\alpha,\rho)] = 0 \in H^3(\mathfrak{g}, (Z(\mathfrak{h}), \bar\alpha))$, there exists $\mu : \bigwedge^2 \mathfrak{g} \to Z(\mathfrak{h})$ such that $\delta_{\bar\alpha}\mu = \lambda$. But then

$$\operatorname{ad}_{(\rho-\mu)(X,Y)} = \operatorname{ad}_{\rho(X,Y)}, \quad \delta_\alpha(\rho - \mu) = 0,$$

so that $(\alpha, \rho-\mu)$ satisfy the conditions of (27.5) and thus define an extension which induces $\bar\alpha$.

Finally, suppose that (1) is satisfied, and let us determine how many extensions there exist which induce $\bar\alpha$. By (27.5) we have to determine all equivalence classes of data (α,ρ) as in (27.5). We may fix the linear lift α and one mapping $\rho : \bigwedge^2 \mathfrak{g} \to \mathfrak{h}$ which satisfies (27.5.3) and (27.5.4), and we have to find all ρ' with this property. But then $\rho - \rho' = \mu : \bigwedge^2 \mathfrak{g} \to Z(\mathfrak{h})$ and

$$\delta_{\bar\alpha}\mu = \delta_\alpha\rho - \delta_\alpha\rho' = 0 - 0 = 0$$

so that μ is a 2-cocycle. Moreover we may still pass to equivalent data in the sense of (27.5) using some $b : \mathfrak{g} \to \mathfrak{h}$ which does not change α, i.e. $b : \mathfrak{g} \to Z(\mathfrak{h})$. The corresponding ρ' is, by (27.5.7), $\rho' = \rho + \delta_\alpha b + \frac{1}{2}[b,b]_\wedge = \rho + \delta_{\bar\alpha} b$. Thus only the cohomology class of μ matters. □

27.9. Corollary. *Let $\mathfrak{g}$ and $\mathfrak{h}$ be Lie algebras such that $\mathfrak{h}$ is abelian. Then isomorphism classes of extensions of $\mathfrak{g}$ over $\mathfrak{h}$ correspond bijectively to the set of all pairs $(\alpha, [\rho])$, where $\alpha : \mathfrak{g} \to \mathfrak{gl}(\mathfrak{h}) = \operatorname{der}(\mathfrak{h})$ is a homomorphism of Lie algebras and $[\rho] \in H^2(\mathfrak{g}, \mathfrak{h})$ is a Chevalley cohomology class with coefficients in the $\mathfrak{g}$-module $\mathfrak{h}$ given by α.*

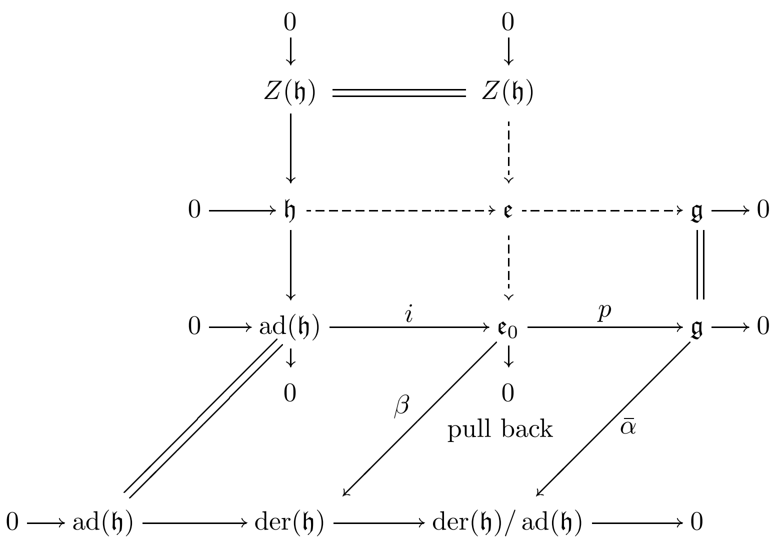
Isomorphism classes of central extensions correspond to elements $[\rho] \in H^2(\mathfrak{g}, \mathbb{R}) \otimes \mathfrak{h}$ (0 action of $\mathfrak{g}$ on $\mathfrak{h}$).

Proof. This is obvious from theorem (27.8). □

27.10. An interpretation of the class λ. Let $\mathfrak{h}$ and $\mathfrak{g}$ be Lie algebras and let a homomorphism $\bar{\alpha} : \mathfrak{g} \to \operatorname{der}(\mathfrak{h})/\operatorname{ad}(\mathfrak{h})$ be given. We consider the extension

$$0 \to \operatorname{ad}(\mathfrak{h}) \to \operatorname{der}(\mathfrak{h}) \to \operatorname{der}(\mathfrak{h})/\operatorname{ad}(\mathfrak{h}) \to 0$$

and the following diagram, where the bottom right hand square is a pullback (compare with remark (27.7)):



The left hand vertical column describes $\mathfrak{h}$ as a central extension of $\operatorname{ad}(\mathfrak{h})$ with abelian kernel $Z(\mathfrak{h})$ which is moreover killed under the action of $\mathfrak{g}$ via $\bar{\alpha}$; it is given by a cohomology class $[\nu] \in H^2(\operatorname{ad}(\mathfrak{h}); Z(\mathfrak{h}))^{\mathfrak{g}}$. In order to get an extension $\mathfrak{e}$ of $\mathfrak{g}$ with kernel $\mathfrak{h}$ as in the third row we have to check that the cohomology class $[\nu]$ is in the image of $i^* : H^2(\mathfrak{e}_0; Z(\mathfrak{h})) \to H^2(\operatorname{ad}(\mathfrak{h}); Z(\mathfrak{h}))^{\mathfrak{g}}$. It would be interesting to express this in terms of of the Hochschild-Serre exact sequence, see [Hochschild, Serre, 1953].

28. Poisson manifolds

28.1. Poisson manifolds. A *Poisson structure* on a smooth manifold M is a Lie bracket $\{\quad,\quad\}$ on the space of the vector space of smooth functions $C^\infty(M)$ satisfying also

$$\{f, gh\} = \{f, g\}h + g\{f, h\}. \tag{1}$$

This means that for each $f \in C^\infty(M)$ the mapping $\operatorname{ad}_f = \{f, \quad\}$ is a derivation of $(C^\infty(M), \cdot)$, so by (3.3) there exists a unique vector field $H(f) = H_f \in \mathfrak{X}(M)$ such that $\{f, h\} = H_f(h) = dh(H_f)$ holds for each $h \in C^\infty(M)$. We also have $H(fg) = f\,H_g + g\,H_f$ since $H_{fg}(h) = \{fg, h\} = f\{g, h\} + g\{f, h\} = (f\,H_g + g\,H_f)(h)$. Thus there exists a unique tensor field $P \in \Gamma(\bigwedge^2 TM)$ such that

$$\{f, g\} = H_f(g) = P(df, dg) = \langle df \wedge dg, P\rangle. \tag{2}$$

The choice of sign is motivated by the following. If ω is a symplectic form on M we consider, using (25.22):

$$\begin{aligned}
\breve\omega : TM \to T^*M, &\qquad \langle \breve\omega(X), Y\rangle = \omega(X, Y)\\
\check P = \breve\omega^{-1} : T^*M \to TM, &\qquad \langle \psi, \check P(\varphi)\rangle = P(\varphi, \psi)\\
H_f = \breve\omega^{-1}(df) = \check P(df), &\qquad i_{H_f}\omega = df\\
\{f, g\} = H_f(g) = i_{H_f}\,dg = i_{H_f} i_{H_g}\omega &= \omega(H_g, H_f)\\
= H_f(g) = \langle dg, H_f\rangle = \langle dg, \check P(df)\rangle &= P(df, dg).
\end{aligned}$$

28.2. Proposition. Schouten-Nijenhuis bracket. *Let M be a smooth manifold. We consider the space $\Gamma(\bigwedge TM)$ of multi vector fields on M. This space carries a graded Lie bracket for the grading $\Gamma(\bigwedge^{*+1} TM), * = -1, 0, 1, 2, \dots$, called the Schouten-Nijenhuis bracket, which is given by*

$$\begin{aligned}
(1)\quad & [X_1 \wedge \dots \wedge X_p, Y_1 \wedge \dots \wedge Y_q] =\\
&\quad = \sum_{i,j} (-1)^{i+j}[X_i, Y_j] \wedge X_1 \wedge \dots \widehat{X_i} \dots \wedge X_p \wedge Y_1 \wedge \dots \widehat{Y_j} \dots \wedge Y_q.\\
(2)\quad & [f, U] = -\bar\imath(df)U,
\end{aligned}$$

where $\bar\imath(df)$ is the insertion operator $\bigwedge^k TM \to \bigwedge^{k-1} TM$, the adjoint of $df \wedge (\quad) : \bigwedge^l T^*M \to \bigwedge^{l+1} T^*M$.

This bracket has the following properties: Let $U \in \Gamma(\bigwedge^u TM)$, $V \in \Gamma(\bigwedge^v TM)$, $W \in \Gamma(\bigwedge^w TM)$, and $f \in C^\infty(M, \mathbb{R})$. Then

$$[U, V] = -(-1)^{(u-1)(v-1)}[V, U] \tag{3}$$

$$[U, [V, W]] = [[U, V], W] + (-1)^{(u-1)(v-1)}[V, [U, W]] \tag{4}$$

$$[U, V \wedge W] = [U, V] \wedge W + (-1)^{(u-1)v} V \wedge [U, W] \tag{5}$$

$$[X, U] = \mathcal{L}_X U, \tag{6}$$

(7) *Let $P \in \Gamma(\bigwedge^2 TM)$. Then the skew-symmetric product $\{f,g\} := \langle df \wedge dg, P\rangle$ on $C^\infty(M)$ satisfies the Jacobi identity if and only if* $[P,P]=0$

[Schouten, 1940] found an expression for $(-1)^{u-1}[U,V]$ in terms of covariant derivatives which did not depend on the covariant derivative, [Nijenhuis, 1955] found that it satisfied the graded Jacobi identity. In [Lichnerowicz, 1977] the relation of the Schouten Nijenhuis-bracket to Poisson manifolds was spelled out. See also [Tulczyjew, 1974], [Michor, 1987] for the version presented here, and [Vaisman, 1994] for more information.

Proof. The bilinear mapping $\bigwedge^k\Gamma(TM)\times\bigwedge^l\Gamma(TM)\to\bigwedge^{k+l-1}\Gamma(TM)$ given by (1) factors over $\bigwedge^k\Gamma(TM)\to\bigwedge^k_{C^\infty(M)}\Gamma(TM)=\Gamma(\bigwedge^k TM)$ since we may easily compute that

$$[X_1\wedge\dots\wedge X_p, Y_1\wedge\dots\wedge fY_j\wedge\dots\wedge Y_q] = f[X_1\wedge\dots\wedge X_p, Y_1\wedge\dots\wedge Y_q]+ \\ +(-1)^p\bar\imath(df)(X_1\wedge\dots\wedge X_p)\wedge Y_1\wedge\dots\wedge Y_q.$$

So the bracket $[\quad,\quad]:\Gamma(\bigwedge^{k-1}TM)\times\Gamma(\bigwedge^{l-1}TM)\to\Gamma(\bigwedge^{k+l-1}TM)$ is a well defined operation. Properties (3)–(6) have to be checked by direct computations.

Property (7) can be seen as follows: We have

$$\{f,g\} = \langle df\wedge dg, P\rangle = \langle dg, \bar\imath(df)P\rangle = -\langle dg,[f,P]\rangle = [g,[f,P]]. \tag{8}$$

Now a straightforward computation involving the graded Jacobi identity and the graded skew symmetry of the Schouten-Nijenhuis bracket gives

$$[h,[g,[f,[P,P]]]] = -2(\{f,\{g,h\}\}+\{g,\{h,f\}\}+\{h,\{f,g\}\}).$$

Since $[h,[g,[f,[P,P]]]] = \langle df\wedge dg\wedge dh, [P,P]\rangle$ the result follows. □

28.3. Hamiltonian vector fields for Poisson structures. Let (M,P) be a Poisson manifold. As usual we denote by $\check P: T^*M\to TM$ the associated skew symmetric homomorphism of vector bundles. Let $\mathfrak X(M,P):=\{X\in\mathfrak X(M): L_XP=0\}$ be the *Lie algebra of infinitesimal automorphisms* of the Poisson structure. For $f\in C^\infty(M)$ we define the *Hamiltonian vector field* by

$$\operatorname{grad}^P(f) = H_f = \check P(df) = -[f,P] = -[P,f]\in\mathfrak X(M), \tag{1}$$

and we recall the relation between Poisson structure and Poisson bracket (28.1.2) and (28.2.8)

$$\{f,g\} = H_f(g) = P(df,dg) = \langle df\wedge dg, P\rangle = [g,[f,P]].$$

Lemma. *The Hamiltonian vector field mapping takes values in $\mathfrak{X}(M,P)$ and is a Lie algebra homomorphism*

$$(C^\infty(M), \{\quad,\quad\}_P) \xrightarrow{H=\operatorname{grad}^P} \mathfrak{X}(M,P).$$

Proof. For $f \in C^\infty(M)$ we have:

$$\begin{aligned} 0 = [f,[P,P]] &= [[f,P],P] - [P,[f,P]] = 2[[f,P],P], \\ \mathcal{L}_{H_f} P &= [H_f, P] = -[[f,P],P] = 0. \end{aligned}$$

For $f, g \in C^\infty(M)$ we get

$$\begin{aligned} [H_f, H_g] &= [[f,P],[g,P]] \\ &= [g,[[f,P],P]] - [[g,[f,P]],P] \\ &= [g, -\mathcal{L}_{H_f} P] - [\{f,g\},P] = 0 + H(\{f,g\}) \quad \square \end{aligned}$$

28.4. Theorem. *Let (M,P) be a Poisson manifold. Then $\check P(T^*M) \subseteq TM$ is an integrable smooth distribution (with jumping dimension) in the sense of* (3.23)*. On each leaf L (which is an initial submanifold of M by* (3.25)*) the Poisson structure P induces the inverse of a symplectic structure L.*

One says that the Poisson manifold M is stratified into symplectic leaves.

Proof. We use theorem (3.28). Consider the set $\mathcal{V} := \{\check P(df) = H_f = -[f,P] : f \in C^\infty(M)\} \subset \mathfrak{X}(\check P(T^*M))$ of sections of the distribution. The set $\mathcal{V}$ spans the distribution since through each point in T^*M we may find a form df. The set $\mathcal{V}$ is involutive since $[H_f, H_g] = H_{\{f,g\}}$. Finally we have to check that the dimension of $\check P(T^*M)$ is constant along flow lines of vector fields in $\mathcal{V}$, i.e., of vector fields H_f:

$$\begin{aligned} &\check P = (\mathrm{Fl}_t^{H_f})^* \check P = T(\mathrm{Fl}_{-t}^{H_f}) \circ \check P \circ (T\,\mathrm{Fl}_{-t}^{H_f})^* \qquad \text{since } \mathcal{L}_{H_f} P = 0, \\ &\implies \dim \check P(T^*_{\mathrm{Fl}_t^{H_f}(x)} M) = \text{constant in } t. \end{aligned}$$

So all assumptions of theorem (3.28) are satisfied and thus the distribution $P(T^*M)$ is integrable.

Now let L be a leaf of the distribution $P(T^*M)$, a maximal integral manifold. The 2-vector field $P|L$ is tangent to L, since a local smooth function f on M is constant along each leaf if and only if $\check P(df) = -df \circ \check P : T^*M \to \mathbb{R}$ vanishes. Therefore, $\check P|L : T^*L \to TL$ is a surjective homomorphism of vector bundles of the same fiber dimension, and is thus an isomorphism. Then $\check\omega_L := (\check P|L)^{-1} : TL \to T^*L$ defines a 2-form $\omega_L \in \Omega^2(L)$ which is non-degenerate. It remains to check that ω_L is closed. For each $x \in L$ there exists an open neighborhood $U \subset M$ and functions $f, g, h \in C^\infty(U)$ such that the vector fields $H_f = \check P(df)|L$, H_g, and H_h on L take arbitrary prescribed values in T_xL at $x\in L$. Thus $d\omega_L=0\in\Omega^3(L)$ results from the following computation:

$$\begin{aligned}
\omega_L(H_f,H_g)&=(i_{H_f}\omega_L)(H_g)=\check\omega_L(H_f)(H_g)=df(H_g)=\{g,f\},\\
d\omega_L(H_f,H_g,H_h)&=H_f(\omega_L(H_g,H_h))+H_g(\omega_L(H_h,H_f))+H_h(\omega_L(H_f,H_g))-\\
&\quad-\omega_L([H_f,H_g],H_h)-\omega_L([H_g,H_h],H_f)-\omega_L([H_h,H_f],H_g)\\
&=\{\{h,g\},f\}+\{\{f,h\},g\}+\{\{g,f\},h\}\\
&\quad-\{h,\{f,g\}\}-\{f,\{g,h\}\}-\{g,\{h,f\}\}=0.\quad\square
\end{aligned}$$

28.5. Proposition. Poisson morphisms. *Let (M_1,P_1) and (M_2,P_2) be two Poisson manifolds. A smooth mapping $\varphi:M_1\to M_2$ is called a Poisson morphism if any of the following equivalent conditions is satisfied:*

(1) *For all $f,g\in C^\infty(M_2)$ we have $\varphi^*\{f,g\}_2=\{\varphi^*f,\varphi^*g\}_1$.*
(2) *For all $f\in C^\infty(M_2)$ the Hamiltonian vector fields $H^1_{\varphi^*f}\in\mathfrak{X}(M_1,P_1)$ and $H^2_f\in\mathfrak{X}(M_2,P_2)$ are φ-related.*
(3) *We have $\bigwedge^2 T\varphi\circ P_1=P_2\circ\varphi:M_1\to\bigwedge^2 TM_2$.*
(4) *For each $x\in M_1$ we have*

$$T_x\varphi\circ(\check P_1)_x\circ(T_x\varphi)^*=(\check P_2)_{\varphi(x)}:T^*_{\varphi(x)}M_2\to T_{\varphi(x)}M_2.$$

Proof. For $x\in M_1$ we have

$$\begin{aligned}
\{\varphi^*f,\varphi^*g\}_1(x)&=(P_1)_x(d(f\circ\varphi)|_x,d(g\circ\varphi)|_x)\\
&=(P_1)_x(df|_{\varphi(x)}.T_x\varphi,dg|_{\varphi(x)}.T_x\varphi)\\
&=(P_1)_x.\Lambda^2(T_x\varphi)^*.(df|_{\varphi(x)},dg|_{\varphi(x)})\\
&=\Lambda^2T_x\varphi.(P_1)_x.(df|_{\varphi(x)},dg|_{\varphi(x)}),\\
\varphi^*\{f,g\}_2(x)&=\{f,g\}_2(\varphi(x))=(P_2)_{\varphi(x)}(df|_{\varphi(x)},dg|_{\varphi(x)}).
\end{aligned}$$

This shows that (1) and (3) are equivalent since $df(y)$ meets each point of T^*M_2. (3) and (4) are obviously equivalent.

(2) and (4) are equivalent since we have

$$\begin{aligned}
T_x\varphi.H^1_{\varphi^*f}(x)&=T_x\varphi.(\check P_1)_x.d(f\circ\varphi)|_x=T_x\varphi.(\check P_1)_x.(T_x\varphi)^*.df|_{\varphi(x)}\\
H^2_f(\varphi(x))&=(\check P_2)_{\varphi(x)}.df|_{\varphi(x)}.\quad\square
\end{aligned}$$

28.6. Proposition. *Let (M_1,P_1), (M_2,P_2), and (M_3,P_3) be Poisson manifolds and let $\varphi:M_1\to M_2$ and $\psi:M_2\to M_3$ be smooth mappings.*

(1) *If φ and ψ are Poisson morphisms then also $\psi\circ\varphi$ is a Poisson morphism.*
(2) *If φ and $\psi\circ\varphi$ are Poisson morphisms and if φ is surjective, then also ψ is a Poisson morphism. In particular, if φ is Poisson and a diffeomorphism, then also φ^{-1} is Poisson.*

Proof. (1) follows from (28.5.1), say. For (2) we use (28.5.3) as follows:

$$\Lambda^2 T\varphi \circ P_1 = P_2 \circ \varphi \quad \text{and} \quad \Lambda^2 T(\psi \circ \varphi) \circ P_1 = P_3 \circ \psi \circ \varphi \quad \text{imply}$$

$$\Lambda^2 T\psi \circ P_2 \circ \varphi = \Lambda^2 T\psi \circ \Lambda^T \varphi \circ P_1 = \Lambda^2 T(\psi \circ \varphi) \circ P_1 = P_3 \circ \psi \circ \varphi,$$

which implies the result since φ is surjective. □

28.7. Example and Theorem. *For a Lie algebra $\mathfrak{g}$ there is a canonical Poisson structure P on the dual $\mathfrak{g}^*$, given by the dual of the Lie bracket:*

$$[\quad,\quad] : \Lambda^2\mathfrak{g} \to \mathfrak{g}, \qquad P = -[\quad,\quad]^* : \mathfrak{g}^* \to \Lambda^2\mathfrak{g}^*,$$

$$\{f, g\}(\alpha) = \langle \alpha, [dg(\alpha), df(\alpha)]\rangle \quad \textit{for } f, g \in C^\infty(\mathfrak{g}^*), \alpha \in \mathfrak{g}^*$$

The symplectic leaves are exactly the coadjoint orbits with their symplectic structures from (25.14).

Proof. We check directly the properties (28.1) of a Poisson structure. Skew symmetry is clear. The derivation property (28.1.1) is:

$$\begin{aligned}
\{f, gh\}(\alpha) &= \langle \alpha, [h(\alpha)dg(\alpha) + g(\alpha)dh(\alpha), df(\alpha)]\rangle \\
&= \langle \alpha, [dg(\alpha), df(\alpha)]\rangle h(\alpha) + g(\alpha)\langle \alpha, [dh(\alpha), df(\alpha)]\rangle \\
&= (\{f, g\}h + g\{f, h\})(\alpha).
\end{aligned}$$

For the Jacobi identity (28.1.1) we compute

$$\begin{aligned}
&\langle \beta, d\{g, h\}|_\alpha\rangle = \\
&= \langle \beta, [dh(\alpha), dg(\alpha)]\rangle + \langle \alpha, [d^2h(\alpha)(\beta,\quad), dg(\alpha)]\rangle + \langle \alpha, [dh(\alpha), d^2g(\alpha)(\beta,\quad)]\rangle \\
&= \langle \beta, [dh(\alpha), dg(\alpha)]\rangle - \langle (\mathrm{ad}_{dg(\alpha)})^*\alpha, d^2h(\alpha)(\beta,\quad)\rangle + \langle (\mathrm{ad}_{dh(\alpha)})^*\alpha, d^2g(\alpha)(\beta,\quad)\rangle \\
&= \langle \beta, [dh(\alpha), dg(\alpha)]\rangle - d^2h(\alpha)(\beta, (\mathrm{ad}_{dg(\alpha)})^*\alpha) + d^2g(\alpha)(\beta, (\mathrm{ad}_{dh(\alpha)})^*\alpha)
\end{aligned}$$

and use this to obtain

$$\begin{aligned}
&\{f,\{g, h\}\}(\alpha) = \langle \alpha, [d\{g, h\}(\alpha), df(\alpha)]\rangle = \\
&\quad = \langle \alpha, [[dh(\alpha), dg(\alpha)], df(\alpha)]\rangle - \\
&\quad\quad - \langle \alpha, [d^2h(\alpha)(\quad, (\mathrm{ad}_{dg(\alpha)})^*\alpha), df(\alpha)]\rangle + \langle \alpha, [d^2g(\alpha)(\quad, (\mathrm{ad}_{dh(\alpha)})^*\alpha), df(\alpha)]\rangle \\
&\quad = \langle \alpha, [[dh(\alpha), dg(\alpha)], df(\alpha)]\rangle - \\
&\quad\quad - d^2h(\alpha)((\mathrm{ad}_{df(\alpha)})^*\alpha, (\mathrm{ad}_{dg(\alpha)})^*\alpha) + d^2g(\alpha)((\mathrm{ad}_{df(\alpha)})^*\alpha, (\mathrm{ad}_{dh(\alpha)})^*\alpha).
\end{aligned}$$

The cyclic sum over the last expression vanishes. Comparing with (25.14) and (25.22.2) we see that the symplectic leaves are exactly the coadjoint orbits, since

$$\begin{aligned}
\langle H_f(\alpha), dg(\alpha)\rangle = H_f(g)|_\alpha &= \{f, g\}(\alpha) = \langle \alpha, [dg(\alpha), df(\alpha)]\rangle \\
&= -\langle (\mathrm{ad}_{df(\alpha)})^*\alpha, dg(\alpha)\rangle \\
H_f(\alpha) &= -(\mathrm{ad}_{df(\alpha)})^*\alpha.
\end{aligned}$$

The symplectic structure on an orbit $O = \mathrm{Ad}(G)^*\alpha$ is the same as in (25.14) which was given by $\omega_O(\zeta_X, \zeta_Y) = \mathrm{ev}_{[X,Y]}$ where $\zeta_X = -\,\mathrm{ad}(X)^*$ is the fundamental vector field of the (left) adjoint action. But then $d\,\mathrm{ev}_Y(\zeta_X(\alpha)) = -\langle \mathrm{ad}(X)^*\alpha, Y\rangle = \langle \alpha, [Y, X]\rangle = \omega_O(\zeta_Y, \zeta_X)$ so that on the orbit the Hamiltonian vector field is given by $H_{\mathrm{ev}_Y} = \zeta_Y = -\,\mathrm{ad}(Y)^* = -\,\mathrm{ad}(d\,\mathrm{ev}_Y(\alpha))^*$, as for the Poisson structure above. □

28.8. Theorem. Poisson reduction. *Let (M,P) be a Poisson manifold and let $r : M \times G \to M$ be the right action of a Lie group on M such that each $r^g : M \to M$ is a Poisson morphism. Let us suppose that the orbit space M/G is a smooth manifold such that the projection $p : M \to M/G$ is a submersion.*

Then there exists a unique Poisson structure $\bar P$ on M/G such that $p : (M,P) \to (M/G,\bar P)$ is a Poisson morphism.

The quotient M/G is a smooth manifold if all orbits of G are of the same type: all isotropy groups G_x are conjugated in G. See ???.

Proof. We work with Poisson brackets. A function $f \in C^\infty(M)$ is of the form $f = \bar f \circ p$ for $\bar f \in C^\infty(M/G)$ if and only if f is G-invariant. Thus $p^* : C^\infty(M/G) \to C^\infty(M)$ is an algebra isomorphism onto the subalgebra $C^\infty(M)^G$ of G-invariant functions. If $f,h \in C^\infty(M)$ are G-invariant then so is $\{f,h\}$ since $(r^g)^*\{f,h\} = \{(r^g)^f,(r^g)^*h\} = \{f,h\}$ by (28.5), for all $g \in G$. So $C^\infty(M)^G$ is a subalgebra for the Poisson bracket which we may regard as a Poisson bracket on $C^\infty(M/G)$. □

28.9. Poisson cohomology. Let (M,P) be a Poisson manifold. We consider the mapping

$$\delta_P := [P,\quad] : \Gamma(\Lambda^{k-1}TM) \to \Gamma(\Lambda^k TM)$$

which satisfies $\delta_P \circ \delta_P = 0$ since $[P,[P,U]] = [[P,P],U] + (-1)^{1.1}[P,[P,U]]$ by the graded Jacobi identity. Thus we can define the *Poisson cohomology* by

$$H^k_{\text{Poisson}}(M) := \frac{\ker(\delta_P : \Gamma(\Lambda^k TM) \to \Gamma(\Lambda^{k+1}TM))}{\operatorname{im}(\delta_P : \Gamma(\Lambda^{k-1}TM) \to \Gamma(\Lambda^k TM))}.$$

(1) $$H^*_{\text{Poisson}}(M) = \bigoplus_{k=0}^{\dim(M)} H^k_{\text{Poisson}}(M)$$

is a graded commutative algebra via $U \wedge V$ since $\operatorname{im}(\delta_P)$ is an ideal in $\ker(\delta_P)$ by (28.2.5). The degree 0 part of Poisson cohomology is given by

(2) $$H^0_{\text{Poisson}}(M) = \{f \in C^\infty(M) : H_f = \{f,\quad\} = 0\},$$

i.e. the vector space of all functions which are constant along each symplectic leaf of the Poisson structure, since $[P,f] = [f,P] = -\bar\imath(df)P = -\check P(df) = -H_f = -\{f,\quad\}$ by (28.2.2), (28.2.8), and (28.1.2). The degree 1 part of Poisson cohomology is given by

(3) $$H^1_{\text{Poisson}}(M) = \frac{\{X \in \mathfrak X(M) : [P,X] = -\mathcal L_X P = 0\}}{\{[P,f] : f \in C^\infty(M)\}} = \frac{\mathfrak X(M,P)}{\{H_f : f \in C^\infty(M)\}}.$$

Thus we get the following refinement of lemma (28.3). *There exists an exact sequence of homomorphisms of Lie algebras:*

(4) $$\begin{array}{ccccccccc} 0 \to H^0_{\text{Poisson}}(M) & \xrightarrow{\alpha} & C^\infty(M) & \xrightarrow{H = \operatorname{grad}^P} & \mathfrak X(M,P) & \xrightarrow{\gamma} & H^1_{\text{Poisson}}(M) \to 0, \\ 0 & & \{\ ,\ \} & & [\ ,\ ] & & [\ ,\ ] \end{array}$$

where the brackets are written under the spaces, where α is the embedding of the space of all functions which are constant on all symplectic leaves, and where γ is the quotient mapping from (3). The bracket on $H^1_{\text{Poisson}}(M)$ is induced by the Lie bracket on $\mathfrak{X}(M,P)$ since $\{H_f : f \in C^\infty(M)\}$ is an ideal: $[H_f, X] = [-[f,P], X] = -[f,[P,X]] - [P,[f,X]] = 0 + [X(f), P] = -H_{X(f)}$.

28.10. Lemma. [Gelfand, Dorfman, 1982], [Magri, Morosi, 1984], *Let (M,P) be a Poisson manifold.*

Then there exists a Lie bracket $\{\ \ ,\ \ \}^1 : \Omega^1(M)\times\Omega^1(M) \to \Omega^1(M)$ which is given by

$$(1)\qquad \begin{aligned}\{\varphi,\psi\}^1 &= \mathcal{L}_{\check P(\varphi)}\psi - \mathcal{L}_{\check P(\psi)}\varphi - d(P(\varphi,\psi))\\ &= \mathcal{L}_{\check P(\varphi)}\psi - \mathcal{L}_{\check P(\psi)}\varphi - d i_{\check P(\varphi)}\psi.\end{aligned}$$

It is the unique $\mathbb{R}$-bilinear skew symmetric bracket satifying

$$(2)\qquad \{df, dg\}^1 = d\{f,g\} \quad \text{for } f,g \in C^\infty(M)$$

$$(3)\qquad \{\varphi, f\psi\}^1 = f\{\varphi,\psi\}^1 + \mathcal{L}_{\check P(\varphi)}(f)\,\psi \quad \text{for } \varphi,\psi \in \Omega^1(M).$$

Furthermore $\check P_* : \Omega^1(M) \to \mathfrak{X}(M)$ is a homomorphism of Lie algebras:

$$(4)\qquad \check P(\{\varphi,\psi\}^1) = [\check P(\varphi), \check P(\psi)] \text{ for } \varphi,\psi \in \Omega^1(M).$$

The coboundary operator of Poisson cohomology has a similar form in terms of the bracket $\{\ \ ,\ \ \}^1$ as the exterior derivative has in terms of the usual Lie bracket. Namely, for $U \in \Gamma(\Lambda^k TM)$ and $\varphi_0,\dots,\varphi_k \in \Omega^1(M)$ we have

$$(5)\quad \begin{aligned}(-1)^k(\delta_P U)(\varphi_0,\dots,\varphi_k) := &\sum_{i=0}^k (-1)^i \mathcal{L}_{P(\varphi_i)}(U(\varphi_0,\dots,\widehat{\varphi_i},\dots,\varphi_k)) +\\ &+ \sum_{i<j}(-1)^{i+j} U(\{\varphi_i,\varphi_j\}^1, \varphi_0,\dots,\widehat{\varphi_i},\dots,\widehat{\varphi_j},\dots,\varphi_k).\end{aligned}$$

Proof. (1) is skew symmetric $\mathbb{R}$-bilinear and satisfies (2) and (3) since by (28.3) we have

$$\begin{aligned}\{df,dg\}^1 &= \mathcal{L}_{\check P(df)}dg - \mathcal{L}_{\check P(dg)}df - d(P(df,dg)) = d\mathcal{L}_{H_f}g - d\mathcal{L}_{H_g}f - d\{f,g\}\\ &= d\{f,g\},\\ \{\varphi, f\psi\}^1 &= \mathcal{L}_{\check P(\varphi)}(f\psi) - \mathcal{L}_{f\check P(\psi)}\varphi - d(fP(\varphi,\psi))\\ &= \mathcal{L}_{\check P(\varphi)}(f)\psi + f\mathcal{L}_{\check P(\varphi)}(\psi) - f\mathcal{L}_{\check P(\psi)}\varphi - \varphi(\check P(\psi))\,df -\\ &\quad - P(\varphi,\psi)\,df - f\,d(P(\varphi,\psi))\\ &= f\{\varphi,\psi\}^1 + \mathcal{L}_{\check P(\varphi)}(f)\,\psi.\end{aligned}$$

So an $\mathbb{R}$-bilinear and skew symmetric operation satisfying (2) and (3) exists. It is uniquely determined since from (3) we see that is local in ψ, i.e. if $\psi|U = 0$ for some open U then also $\{\varphi,\psi\}^1|U=0$ by using a appropriate bump functions. By skew symmetry it also local in φ. But locally each 1-form is a linear combination of expressions $f\,df'$. Thus (2) and (3) determine the bracket $\{\quad,\quad\}^1$ uniquely. By locality it suffices to check the condition (4) for 1-forms $f\,df'$ only:

$$\begin{aligned}
\check P(\{f\,df',g\,dg'\}^1) &= \check P\big(fg\,\{df',dg'\}^1 + f\,H_{f'}(g)\,dg' - g\,H_{g'}(f)\,df'\big)\\
&= fg\,\check P(d\{f',g'\}) + f\,H_{f'}(g)\,\check P(dg') - g\,H_{g'}(f)\,\check P(df')\\
&= fg\,H_{\{f',g'\}} + f\,H_{f'}(g)\,\check P(dg') - g\,H_{g'}(f)\,\check P(df')\\
&= fg\,[H_{f'},H_{g'}] + f\,H_{f'}(g)\,H_{g'} - g\,H_{g'}(f)\,H_{f'}\\
&= [f\,H_{f'},g\,H_{g'}] = [\check P(f\,df'),\check P(g\,dg')].
\end{aligned}$$

Now we can check the Jacobi identity. Again it suffices to do this for 1-forms $f\,df'$. We shall use:

$$\begin{aligned}
\{f\,df',g\,dg'\}^1 &= fg\,\{df',dg'\}^1 + f\,H_{f'}(g)\,dg' - g\,H_{g'}(f)\,df'\\
&= fg\,d\{f',g'\} + f\,\{f',g\}\,dg' - g\,\{g',f\}\,df'
\end{aligned}$$

in order to compute

$$\begin{aligned}
&\{\{f\,df',g\,dg'\}^1,h\,dh'\}^1 = \{\{fg\,d\{f',g'\} + f\{f',g\}\,dg' - g\{g',f\}\,df',h\,dh'\}^1\\
&= \{\{fg\,d\{f',g'\},h\,dh'\}^1 + \{f\{f',g\}\,dg',h\,dh'\}^1 - \{g\{g',f\}\,df',h\,dh'\}^1\\
&= fgh\,d\{\{f',g'\},h'\} + fg\{\{f',g'\},h\}\,dh' - h\{h',fg\}\,d\{f',g'\}\\
&\quad + f\{f',g\}h\,d\{g',h'\} + f\{f',g\}\{g',h\}\,dh' - h\{h',f\{f',g\}\}\,dg'\\
&\quad - g\{g',f\}h\,d\{f',h'\} - g\{g',f\}\{f',h\}\,dh' + h\{h',g\{g',f\}\}\,df'\\
&= fgh\,d\{\{f',g'\},h'\} + (fg\{f',\{g',h\}\}\,dh' - fg\{g'\{f',h\}\}\,dh')\\
&\qquad + (-gh\{h',f\}\,d\{f',g'\} - fh\{h',g\}\,d\{f',g'\})\\
&\quad + hf\{f',g\}\,d\{g',h'\} + f\{f',g\}\{g',h\}\,dh'\\
&\qquad + (-h\{h',f\}\{f',g\}\,dg' - hf\{h',\{f',g\}\}\,dg')\\
&\quad - hg\{g',f\}\,d\{f',h'\} - g\{g',f\}\{f',h\}\,dh'\\
&\qquad + (h\{h',g\}\{g',f\}\,df' + gh\{h',\{g',f\}\}\,df').
\end{aligned}$$

The cyclic sum over these expression vanishes by once the Jacobi identity for the Poisson bracket and many pairwise cancellations.

It remains to check formula (5) for the coboundary operator of Poisson cohomology. we use induction on k. For $k=0$ we have

$$(\delta_P f)(dg) = \mathcal{L}_{H_g} f = \{g,f\} = -\mathcal{L}_{H_f} g = -H_f(dg) = [P,f](dg).$$

For $k=1$ we have

$$\begin{aligned}
(\delta_P X)(df,dg) &= \mathcal{L}_{H_f}(X(dg)) - \mathcal{L}_{H_g}(X(df)) - X(\{df,dg\}^1)\\
&= \mathcal{L}_{H_f}(X(dg)) - \mathcal{L}_{H_g}(X(df)) - X(d\{f,g\})\\
[P,X](df,dg) &= -(\mathcal{L}_X P)(df,dg) = -\mathcal{L}_X(P(df,dg)) + P(\mathcal{L}_X df,dg) + P(df,\mathcal{L}_X dg)\\
&= -X(d\{g,f\}) + \{g,X(df)\} + \{X(dg),f\}\\
&= -(X(d\{f,g\}) - \mathcal{L}_{H_g}(X(df)) - \mathcal{L}_{H_f}(X(dg))) = -(\delta_P)(df,dg).
\end{aligned}$$

Finally we note that the algebraic consequences of the definition of δ_P are the same as for the exterior derivative d; in particular, we have $\delta_P(U \wedge V) = (\delta_P U) \wedge V + (-1)^u U \wedge (\delta_P V)$. So formula (5) now follows since both sides are graded derivations and agree on the generators of $\Gamma(\Lambda^* TM)$, namely on $C^\infty(M)$ and on $\mathfrak{X}(M)$. □

28.11. Dirac structures — a common generalization of symplectic and Poisson structures. [T. Courant, 1990], [Bursztyn, Radko, 2003], [Bursztyn, Crainic, Weinstein, Zhu, 2004]. Let M be a smooth manifold of dimension m. A *Dirac structure* on M is a vector subbundle $D \subset TM \times_M T^*M$ with the following two properties:

(1) Each fiber D_x is maximally isotropic with respect to the metric of signature (m, m) on $TM \times_M T^*M$ given by $\langle (X, \alpha), (X', \alpha') \rangle_+ = \alpha(X') + \alpha'(X)$. So D is of fiber dimension m.

(2) The space of sections of D is closed under the non-skew-symmetric version of the Courant-bracket $[(X, \alpha), (X', \alpha')] = ([X, X'], \mathcal{L}_X \alpha' - i_{X'} d\alpha)$.

If (X, α) and (X', α') are sections of D then $i_X \alpha' = -i_{X'} \alpha$ by isotropy, thus $\mathcal{L}_X \alpha' - i_{X'} d\alpha = i_X d\alpha' + \frac{1}{2} d(i_X \alpha' - i_{X'} \alpha) - i_{X'} d\alpha$ so the Courant bracket is skew symmetric on $\Gamma(D)$.

Natural examples of Dirac structures are the following:

(3) Symplectic structures ω on M, where $D = D^\omega = \{(X, \check{\omega}(X)) : X \in TM\}$ is just the graph of $\check{\omega} : TM \to T^*M$. More generally, for a 2-form ω on M the graph D^ω of $\check{\omega} : TM \to T^*M$ is a Dirac structure if and only if $d\omega = 0$ (a presymplectic structure); these are precisely the Dirac structures D with $TM \cap D = \{0\}$. Namely,

$$\begin{aligned}
\langle (X, \check{\omega}(X)), (Y, \check{\omega}(Y)) \rangle_+ &= \omega(X, Y) + \omega(Y, X) = 0 \\
[(X, i_X \omega), (Y, i_Y \omega)] &= ([X, Y], \mathcal{L}_X i_Y \omega - i_Y d i_X \omega) \\
\mathcal{L}_X i_Y \omega - i_Y d i_X \omega &= i_{[X,Y]} \omega + i_Y \mathcal{L}_X \omega - i_Y d i_X \omega = i_{[X,Y]} \omega + i_Y i_X d\omega.
\end{aligned}$$

(4) Poisson structures P on M where $D = D^P = \{(P(\alpha), \alpha) : \alpha \in T^*M\}$ is the graph of $P : T^*M \to TM$; these are precisely the Dirac structures D which are transversal to T^*M. Namely,

$$\begin{aligned}
\langle (\check{P}(\alpha), \alpha), (\check{P}(\beta), \beta) \rangle_+ &= P(\alpha, \beta) + P(\beta, \alpha) = 0, \\
[(\check{P}(\alpha), \alpha), (\check{P}(\beta), \beta)] &= ([\check{P}(\alpha), \check{P}(\beta)], \mathcal{L}_{\check{P}(\alpha)} \beta - i_{\check{P}(\beta)} d\alpha) \\
&= (\check{P}(\{\alpha, \beta\}^1), \{\alpha, \beta\}^1)
\end{aligned}$$

using (28.10) and since Given a Dirac structure D on M we consider its range $R(D) = \mathrm{pr}_{TM}(D) = \{X \in TM : (X, \alpha) \in D \text{ for some } \alpha \in T^*M\}$. There is a skew symmetric 2-form Θ_D on $R(D)$ which is given by $\Theta_D(X, X') = \alpha(X')$ where $\alpha \in T^*M$ is such that $(X, \alpha) \in D$. The range $R(D)$ is an integrable distribution of non-constant rank in the sense of (3.28), so M is foliated into maximal integral submanifolds L of $R(D)$ of varying dimensions, which are all initial submanifolds. The form Θ_D induces a closed 2-form on each leaf L and (L, Θ_D) is thus a presymplectic manifold (Θ_D might be degenerate on some L). If the Dirac structure corresponds to a Poisson structure then the (L, Θ_D) are exactly the symplectic leaves of the Poisson structure.

The main advantage of Dirac structures is that one can apply arbitrary push forwards and pull backs to them. So if $f : N \to M$ is a smooth mapping and D_M is a Dirac structure on M then the pull back is defined by $f^*D_M = \{(X, f^*\alpha) \in TN \times_N T^*N : (Tf.X, \alpha) \in D_M\}$. Likewise the push forward of a Dirac structure D_N on N is given by $f_*D_N = \{(Tf.X, \alpha) \in TM \times_M T^*M : (X, f^*\alpha) \in D_N\}$. If $D = D^\omega$ for a closed 2-form ω on M then $f^*(D^\omega) = D^{f^*\omega}$. If P_N and P_M are Poisson structures on N and M, respectively, which are f-related, then $f_*D^{P_n} = D^{f_*P_N} = D^{P_M}$.

29. Hamiltonian group actions and momentum mappings

29.1. Symplectic group actions. Let us suppose that a Lie group G acts from the right on a symplectic manifold (M, ω) by $r : M \times G \to M$ in a way which respects ω, so that each transformation r^g is a symplectomorphism. This is called a *symplectic group action.* Let us list some immediate consequences:

(1) *The space $C^\infty(M)^G$ of G-invariant smooth functions is a Lie subalgebra for the Poisson bracket,* since $(r^g)^*\{f, h\} = \{(r^g)^*f, (r^g)^*h\} = \{f, h\}$ holds for each $g \in G$ and $f, h \in C^\infty(M)^G$.

(2) *For $x \in M$ the pullback of ω to the orbit $x.G$ is a 2-form of constant rank and is invariant under the action of G on the orbit.* Note first that the orbit is an initial submanifold by (5.14). If $i : x.G \to M$ is the embedding of the orbit then $r^g \circ i = i \circ r^g$, so that $i^*\omega = i^*(r^g)^*\omega = (r^g)^*i^*\omega$ holds for each $g \in G$ and thus $i^*\omega$ is invariant. Since G acts transitively on the orbit, $i^*\omega$ has constant rank (as a mapping $T(x.G) \to T^*(x.G)$).

(3) By (5.13) the fundamental vector field mapping $\zeta : \mathfrak{g} \to \mathfrak{X}(M, \omega)$, given by $\zeta_X(x) = T_e(r(x, \quad))X$ for $X \in \mathfrak{g}$ and $x \in M$, is a homomorphism of Lie algebras, where $\mathfrak{g}$ is the Lie algebra of G. (For a left action we get an anti homomorphism of Lie algebras, see (5.12)). Moreover, ζ takes values in $\mathfrak{X}(M, \omega)$. Let us consider again the exact sequence of Lie algebra homomorphisms from (25.22):

$$\begin{array}{ccccccccc} 0 \to H^0(M) & \xrightarrow{\alpha} & C^\infty(M) & \xrightarrow{H} & \mathfrak{X}(M,\omega) & \xrightarrow{\gamma} & H^1(M) \to 0 \\ & & & {\nwarrow}^{j} & \uparrow{\zeta} & & \\ & & & & \mathfrak{g} & & \end{array}$$

One can lift ζ to a linear mapping $j : \mathfrak{g} \to C^\infty(M)$ if and only if $\gamma \circ \zeta = 0$. In this case the action of G is called a *Hamiltonian group action*, and the linear mapping $j : \mathfrak{g} \to C^\infty(M)$ is called a *generalized Hamiltonian function* for the group action. It is unique up to addition of a mapping $\alpha \circ \tau$ for $\tau : \mathfrak{g} \to H^0(M)$.

(4) *If $H^1(M) = 0$ then any symplectic action on (M, ω) is a Hamiltonian action. If not we may lift ω and the action to the universal cover of M. But if $\gamma \circ \zeta \neq 0$*

we can replace $\mathfrak{g}$ *by its Lie subalgebra* $\ker(\gamma\circ\zeta)\subset\mathfrak{g}$ *and consider the corresponding Lie subgroup G which then admits a Hamiltonian action.*

(5) *If the Lie algebra* $\mathfrak{g}$ *is equal to its commutator subalgebra algebra* $[\mathfrak{g},\mathfrak{g}]$*, the linear span of all* $[X,Y]$ *for* $X,Y\in\mathfrak{g}$*, then any infinitesimal symplectic action* $\zeta:\mathfrak{g}\to\mathfrak{X}(M,\omega)$ *is a Hamiltonian action,* since then any $Z\in\mathfrak{g}$ can be written as $Z=\sum_i[X_i,Y_i]$ so that $\zeta_Z=\sum[\zeta_{X_i},\zeta_{Y_i}]\in\operatorname{im}(\operatorname{grad}^\omega)$ since $\gamma:\mathfrak{X}(M,\omega)\to H^1(M)$ is a homomorphism into the zero Lie bracket.

29.2. Lemma. Momentum mappings. *For an infinitesimal symplectic action, i.e. a homomorphism* $\zeta:\mathfrak{g}\to\mathfrak{X}(M,\omega)$ *of Lie algebras, we can find a linear lift* $j:\mathfrak{g}\to C^\infty(M)$ *if and only if there exists a mapping* $J:M\to\mathfrak{g}^*$ *such that*

$$H_{\langle J,X\rangle}=\zeta_X \quad \text{for all } X\in\mathfrak{g}.$$

Proof. Namely, for $y\in M$ we have

$$J:M\to\mathfrak{g}^*,\quad \langle J(y),X\rangle=j(X)(y)\in\mathbb{R},\quad j:\mathfrak{g}\to C^\infty(M).\quad\square$$

The mapping $J:M\to\mathfrak{g}^*$ is called the *momentum mapping* for the infinitesimal action $\zeta:\mathfrak{g}\to\mathfrak{X}(M,\omega)$. This holds even for a Poisson manifold (M,P) (see section (28)) and an infinitesimal action of a Lie algebra $\zeta:\mathfrak{g}\to\mathfrak{X}(M,P)$ by Poisson morphisms. Let us note again the relations between the generalized Hamiltonian j and the momentum mapping J:

$$\begin{gathered}J:M\to\mathfrak{g}^*,\quad j:\mathfrak{g}\to C^\infty(M),\quad \zeta:\mathfrak{g}\to\mathfrak{X}(M,P),\\ \langle J,X\rangle=j(X)\in C^\infty(M),\quad H_{j(X)}=\zeta(X),\quad X\in\mathfrak{g},\end{gathered}\tag{1}$$

where $\langle\ ,\ \rangle$ is the duality pairing.

29.3. Basic properties of the momentum mapping. Let $r:M\times G\to M$ be a Hamiltonian right action of a Lie group G on a symplectic manifold M, let $j:\mathfrak{g}\to C^\infty(M)$ be a generalized Hamiltonian and let $J:M\to\mathfrak{g}^*$ be the associated momentum mapping.

(1) *For* $x\in M$*, the transposed mapping of the linear mapping* $dJ(x):T_xM\to\mathfrak{g}^*$ *is*

$$dJ(x)^\top:\mathfrak{g}\to T_x^*M,\qquad dJ(x)^\top=\check\omega_x\circ\zeta,$$

since for $\xi\in T_xM$ and $X\in\mathfrak{g}$ we have

$$\langle dJ(\xi),X\rangle=\langle i_\xi dJ,X\rangle=i_\xi d\langle J,X\rangle=i_\xi i_{\zeta_X}\omega=\langle\check\omega_x(\zeta_X(x)),\xi\rangle.$$

(2) *The image* $dJ(T_xM)$ *of* $dJ(x):T_xM\to\mathfrak{g}*$ *is the annihilator* $\mathfrak{g}_x^\circ$ *of the isotropy Lie algeba* $\mathfrak{g}_x:=\{X\in\mathfrak{g}:\zeta_X(x)=0\}$ *in* $\mathfrak{g}^*$*,* since the annihilator of the image is the kernel of the transposed mapping,

$$\operatorname{im}(dJ(x))^\circ=\ker(dJ(x)^\top)=\ker(\check\omega_x\circ\zeta)=\ker(\operatorname{ev}_x\circ\zeta)=\mathfrak{g}_x.$$

(3) *The kernel of $dJ(x)$ is the symplectic orthogonal $(T_x(x.G))^\perp \in T_xM$,* since for the annihilator of the kernel we have

$$\ker(dJ(x))^\circ = \operatorname{im}(dJ(x)^\top) = \operatorname{im}(\check\omega_x \circ \zeta) = \{\check\omega_x(\zeta_X(x)) : X \in \mathfrak{g}\} = \check\omega_x(T_x(x.G)).$$

(4) *For each $x \in M$ the rank of $dJ(x) : T_xM \to \mathfrak{g}^*$ equals the dimension of the orbit $x.G$, i.e. to the codimension in $\mathfrak{g}$ of the isotropy Lie algebra $\mathfrak{g}_x$.* This follows from (3) since

$$\operatorname{rank}(dJ(x)) = \operatorname{codim}_{T_xM}(\ker dJ(x)) = \dim(\ker(dJ(x))^\circ) = \dim(T_x(x.G)).$$

(5) *The momentum mapping $J : M \to \mathfrak{g}^*$ is a submersion at $x \in M$ if and only if the isotropy group G_x is discrete.*

(6) *If G is connected, $x \in M$ is a fixed point for the G-action if and only if x is a critical point of J, i.e. $dJ(x) = 0$.*

(7) *Suppose that all orbits of the G-action on M have the same dimension. Then $J : M \to \mathfrak{g}^*$ is of constant rank. Moreover, the distribution $\mathcal{F}$ of all symplectic orthogonals to the tangent spaces to all orbits is then an integrable distribution of constant rank and its leaves are exactly the connected components of the fibers of J.* Namely, the rank of J is constant by (3). For each in $x \in M$ the subset $J^{-1}(J(x))$ is then a submanifold by (1.13), and by (1) $J^{-1}(J(x))$ is a maximal integral submanifold of $\mathcal{F}$ through x.

A direct proof that the distribution $\mathcal{F}$ is integrable is as follows: it has constant rank, and is involutive, since for $\xi \in \mathfrak{X}(M)$ we have $\xi \in \mathfrak{X}(\mathcal{F})$ if and only if $i_\xi i_{\zeta_X}\omega = -\omega(\xi, \zeta_X) = 0$ for all $X \in \mathfrak{g}$. For $\xi, \eta \in \mathfrak{X}(\mathcal{F})$ and $X \in \mathfrak{g}$ we have

$$i_{[\xi,\eta]} i_{\zeta_X}\omega = [\mathcal{L}_\xi, i_\eta] i_{\zeta_X}\omega = \mathcal{L}_\xi i_\eta i_{\zeta_X}\omega - i_\eta \mathcal{L}_\xi i_{\zeta_X}\omega = 0 - i_\eta i_\xi d i_{\zeta_X}\omega - i_\eta d i_\xi i_{\zeta_X}\omega = 0.$$

(8) *(E. Noether's theorem) Let $h \in C^\infty(M)$ be a Hamiltonian function which is invariant under the Hamiltonian G action. Then the momentum mapping $J : M \to \mathfrak{g}^*$ is constant on each trajectory of the Hamiltonian vector field H_h.* Namely,

$$\begin{aligned} \tfrac{d}{dt}\langle J \circ \operatorname{Fl}^{H_h}_t, X\rangle &= \langle dJ \circ \tfrac{d}{dt}\operatorname{Fl}^{H_h}_t, X\rangle = \langle dJ(H_h \circ \operatorname{Fl}^{H_h}_t, X\rangle = (i_{H_h} d\langle J, X\rangle) \circ \operatorname{Fl}^{H_h}_t \\ &= \{h, \langle J, X\rangle\} \circ \operatorname{Fl}^{H_h}_t = -\{\langle J, X\rangle, h\} \circ \operatorname{Fl}^{H_h}_t = -(\mathcal{L}_{\zeta_X} h) \circ \operatorname{Fl}^{H_h}_t = 0. \end{aligned}$$

E. Noether's theorem admits the following generalization.

29.4. Theorem. *(Marsden and Weinstein) Let G_1 and G_2 be two Lie groups which act by Hamiltonian actions r_1 and r_2 on the symplectic manifold (M, ω), with momentum mappings J_1 and J_2, respectively. We assume that J_2 is G_1-invariant, i.e. J_2 is constant along all G_1-orbits, and that G_2 is connected.*

Then J_1 is constant on the G_2-orbits and the two actions commute.

Proof. Let $\zeta^i : \mathfrak{g}_i \to \mathfrak{X}(M,\omega)$ be the two infinitesimal actions. Then for $X_1 \in \mathfrak{g}_1$ and $X_2 \in \mathfrak{g}_2$ we have

$$\begin{aligned}\mathcal{L}_{\zeta^2_{X_2}} \langle J_1, X_1\rangle &= i_{\zeta^2_{X_2}} d\langle J_1, X_1\rangle = i_{\zeta^2_{X_2}} i_{\zeta^1_{X_1}} \omega = \{\langle J_2, X_2\rangle, \langle J_1, X_1\rangle\}\\ &= -\{\langle J_1, X_1\rangle, \langle J_2, X_2\rangle\} = -i_{\zeta^1_{X_1}} d\langle J_2, X_2\rangle = -\mathcal{L}_{\zeta^1_{X_1}} \langle J_2, X_2\rangle = 0\end{aligned}$$

since J_2 is constant along each G_1-orbit. Since G_2 is assumed to be connected, J_1 is also constant along each G_2-orbit. We also saw that each Poisson bracket $\{\langle J_2, X_2\rangle, \langle J_1, X_1\rangle\}$ vanishes; by $H_{\langle J_i, X_i\rangle} = \zeta^i_{X_i}$ we conclude that $[\zeta^1_{X_1}, \zeta^2_{X_2}] = 0$ for all $X_i \in \mathfrak{g}_i$ which implies the result if also G_1 is connected. In the general case we can argue as follows:

$$\begin{aligned}(r_1^{g_1})^* \zeta^2_{X_2} &= (r_1^{g_1})^* H_{\langle J_2, X_2\rangle} = (r_1^{g_1})^* (\check\omega^{-1} d\langle J_2, X_2\rangle)\\ &= (((r_1^{g_1})^*\omega)^\vee)^{-1} d\langle (r_1^{g_1})^* J_2, X_2\rangle = (\check\omega^{-1} d\langle J_2, X_2\rangle = H_{\langle J_2, X_2\rangle} = \zeta^2_{X_2}.\end{aligned}$$

Thus $r_1^{g_1}$ commutes with each $r_2^{\exp(tX_2)}$ and thus with each $r_2^{g_2}$, since G_2 is connected. □

29.5. Remark. The classical first integrals of mechanical systems can be derived by Noether's theorem, where the group G is the group of isometries of Euclidean 3-space $\mathbb{R}^3$, the semidirect product $\mathbb{R}^3 \rtimes SO(3)$. Let (M, ω, h) be a Hamiltonian mechanical system consisting of several rigid bodies moving in physical 3-pace. This system is said to be free if the Hamiltonian function h describing the movement of the system is invariant under the group of isometries acting on $\mathbb{R}^3$ and its induced action on phase space $M \subseteq T^*(\mathbb{R}^{3k})$. This action is Hamiltonian since for the motion group G we have $[\mathfrak{g}, \mathfrak{g}] = \mathfrak{g}$, by (29.1.5). Thus there exists a momentum mapping $J = (J_l, J_a) : M \to (\mathbb{R}^3 \rtimes \mathfrak{so}(3))^* = (\mathbb{R}^3)^* \times \mathfrak{so}(3)^*$. Its component J_l is the momentum mapping for the action of the translation group and is called the *linear momentum*, the component J_a is the momentum mapping for the action of the rotation group and is called the *angular momentum*.

The momentum map is essentially due to Lie, [Lie, 1890], pp. 300–343. The modern notion is due to [Kostant, 1966], [Souriau, 1966], and Kirillov [Kirillov, 1986]. [Marmo, Saletan, Simoni, 1985], [Libermann, Marle, 1987] and [Marsden, Ratiu, 1999] are convenient references, [Marsden, Ratiu, 1999] has a large and updated bibliography. The momentum map has a strong tendency to have *convex image*, and is important for *representation theory*, see [Kirillov, 1986] and [Neeb, 1999]. Recently, there is also a proposal for a group-valued momentum mapping, see [Alekseev, Malkin, Meinrenken, 1998].

29.6. Strongly Hamiltonian group actions. Suppose that we have a Hamiltonian action $M \times G \to M$ on the symplectic manifold (M, ω), and consider a generalized Hamiltonian $j : \mathfrak{g} \to C^\infty(M)$, which is unique up to addition of $\alpha \circ \tau$ for some $\tau : \mathfrak{g} \to H^0(M)$.

$$\begin{array}{ccccccccc} 0 \to H^0(M) & \xrightarrow{\alpha} & C^\infty(M) & \xrightarrow{H} & \mathfrak{X}(M,\omega) & \xrightarrow{\gamma} & H^1(M) \to 0 \\ & & & {\scriptstyle j}\nwarrow & \uparrow{\scriptstyle \zeta} & & \\ & & & & \mathfrak{g} & & \end{array}$$

We want to investigate whether we can change j into a homomorphism of Lie algebras.

(1) The map $\mathfrak{g} \ni X, Y \mapsto \{jX, jY\} - j([X,Y]) =: \bar{j}(X,Y)$ takes values in $\ker(H) = \operatorname{im}(\alpha)$ since

$$H(\{jX, jY\}) - H(j([X,Y])) = [H_{jX}, H_{jY}] - \zeta_{[X,Y]} = [\zeta_X, \zeta_Y] - \zeta_{[X,Y]} = 0.$$

Moreover, $\bar{j} : \Lambda^2\mathfrak{g} \to H^0(M)$ is a cocycle for the Chevalley cohomology of the Lie algebra $\mathfrak{g}$, as explained in (12.14):

$$\begin{aligned} d\bar{j}(X,Y,Z) &= -\sum_{\text{cyclic}} \bar{j}([X,Y],Z) = -\sum_{\text{cyclic}} (\{j([X,Y]), jZ\} - j([[X,Y],Z])) \\ &= -\sum_{\text{cyclic}} \{\{jX,jY\} - \bar{j}(X,Y), jZ\} - 0 \\ &= -\sum_{\text{cyclic}} (\{\{jX,jY\},jZ\} - \{\bar{j}(X,Y),jZ\}) = 0, \end{aligned}$$

by the Jacobi identity and since $\bar{j}(X,Y) \in H^0(M)$ which equals the center of the Poisson algebra. Recall that the linear mapping $j : \mathfrak{g} \to C^\infty(M)$ was unique only up to addition of a mapping $\alpha \circ \tau$ for $\tau : \mathfrak{g} \to H^0(M)$. But

$$\begin{aligned} \overline{j+\tau}(X,Y) &= \{(j+\tau)X, (j+\tau)Y\} - (j+\tau)([X,Y]) \\ &= \{jX, jY\} + 0 - j([X,Y]) - \tau([X,Y]) = (\bar{j} + d\tau)(X,Y). \end{aligned}$$

Thus, if $\gamma \circ \zeta = 0$, there is a unique Chevalley cohomology class $\tilde{\zeta} := [\bar{j}] \in H^2(\mathfrak{g}, H^0(M))$.

(2) The cohomology class $\tilde{\zeta} = [\bar{j}]$ is automatically zero if $H^2(\mathfrak{g}, H^0(M)) = H^2(\mathfrak{g}) \otimes H^0(M) = 0$. This is the case for semisimple $\mathfrak{g}$, by the Whitehead lemmas, see [Hilton, Stammbach, 1970], p. 249.

(3) The cohomology class $\tilde{\zeta} = [\bar{j}]$ is automatically zero if the symplectic structure ω on M is exact, $\omega = -d\theta$ for $\theta \in \Omega^1(M)$, and $\mathcal{L}_{\zeta_X}\theta = 0$ for each $X \in \mathfrak{g}$: Then we may use $j(X) = i_{\zeta_X}\theta = \theta(\zeta_X)$, since $i(H_{jX})\omega = d(jX) = di_{\zeta_X}\theta = \mathcal{L}_{\zeta_X}\theta - i_{\zeta_X}d\theta = 0 + i_{\zeta_X}\omega$ implies $H_{jX} = \zeta_X$. For this choice of j we have

$$\begin{aligned} \bar{j}(X,Y) &= \{jX, jY\} - j([X,Y]) = \mathcal{L}_{H_{jX}}(jY) - i_{\zeta([X,Y])}\theta = \mathcal{L}_{\zeta_X} i_{\zeta_Y}\theta - i_{[\zeta_X,\zeta_Y]}\theta \\ &= \mathcal{L}_{\zeta_X} i_{\zeta_Y}\theta - [\mathcal{L}_{\zeta_X}, i_{\zeta_Y}]\theta = -i_{\zeta_Y}\mathcal{L}_{\zeta_X}\theta = 0. \end{aligned}$$

This is the case if $M = T^*Q$ is a cotantent bundle and if $\zeta : \mathfrak{g} \to \mathfrak{X}(T^*Q, \omega_Q)$ is induced by $\sigma : \mathfrak{g} \to \mathfrak{X}(Q)$. Namely, by (25.10) we have:

$$\mathcal{L}_{\zeta_X}\theta_Q = \tfrac{\partial}{\partial t}\big|_0 (\mathrm{Fl}_t^{\zeta_X})^*\theta_Q = \tfrac{\partial}{\partial t}\big|_0 (T^*(\mathrm{Fl}_t^{\sigma_X}))^*\theta_Q = 0.$$

(4) An example, where the cohomology class $\tilde{\zeta} = [\bar{j}] \in H^2(\mathfrak{g}, H^0(M))$ does not vanish: Let $\mathfrak{g} = (\mathbb{R}^2, [\quad,\quad] = 0)$ with coordinates a, b. Let $M = T^*\mathbb{R}$ with

coordinates q,p, and $\omega = dq\wedge dp$. Let $\zeta_{(a,b)} = a\partial_q + b\partial_p$. A lift is given by $j(a,b)(q,p) = ap - bq$. Then

$$\begin{aligned}\bar{\jmath}((a_1,b_1),(a_2,b_2)) &= \{j(a_1,b_1), j(a_2,b_2)\} - j(0) = \{a_1p - b_1q, a_2p - b_2q\}\\ &= -a_1b_2 + a_2b_1.\end{aligned}$$

(5) For a symplectic group action $r: M\times G\to M$ of a Lie group G on a symplectic manifold M, let us suppose that the cohomology class $\tilde{\zeta} = [\bar{\jmath}] \in H^2(\mathfrak{g}, H^0(M))$ from (29.1.1) vanishes. Then there exists $\tau\in L(\mathfrak{g}, H^0(M))$ with $d\tau = \bar{\jmath}$, i.e.

$$\begin{aligned}d\tau(X,Y) &= -\tau([X,Y]) = \bar{\jmath}(X,Y) = \{jX, jY\} - j([X,Y])\\ \overline{j-\tau}(X,Y) &= \{(j-\tau)X, (j-\tau)Y\} - (j-\tau)([X,Y])\\ &= \{jX,jY\} + 0 - j([X,Y]) + \tau([X,Y]) = 0,\end{aligned}$$

so that $j-\tau:\mathfrak{g}\to C^\infty(M)$ is a homomorphism of Lie algebras. Then the action of G is called a *strongly Hamiltonian group action* and the homomorphism $j-\tau: \mathfrak{g}\to C^\infty(M)$ is called the associated *infinitesimal strongly Hamiltonian action.*

29.7. Theorem. *The momentum mapping $J: M\to\mathfrak{g}^*$ for an infinitesimal strongly Hamiltonian action $j:\mathfrak{g}\to C^\infty(M)$ on a Poisson manifold (M, P^M) has the following properties:*

1. *J is infinitesimally equivariant: For each $X\in\mathfrak{g}$ the Hamiltonian vector fields $H_{j(X)} = \zeta_X \in \mathfrak{X}(M,P)$ and $\operatorname{ad}(X)^*:\mathfrak{g}^*\to\mathfrak{g}^*$ are J-related.*
2. *J is a Poisson morphism $J:(M,P^M)\to(\mathfrak{g}^*, P^{\mathfrak{g}^*})$ into the canonical Poisson structure on $\mathfrak{g}^*$ from (28.7).*
3. *The momentum mapping for a strongly Hamiltonian right action of a connected Lie group G on a Poisson manifold is G-equivariant: $J(x.g) = \operatorname{Ad}(g)^*.J(x)$.*

Proof. (1) By definition (29.2.1) we have $\langle J(x), X\rangle = j(X)(x)$; differentiating this we get $\langle dJ(x)(\xi_x), X\rangle = d(j(X))(\xi_x)$ or $d\langle J,X\rangle = dj(X)\in\Omega^1(M)$. Then we have

$$\begin{aligned}\langle dJ(\zeta_X), Y\rangle &= dj(Y)(\zeta_X) = H_{j(X)}(j(Y)) = \{j(X), j(Y)\} = j[X,Y],\\ \langle \operatorname{ad}(X)^*\circ J, Y\rangle &= \langle J, \operatorname{ad}(X)Y\rangle = \langle J, [X,Y]\rangle,\\ dJ.\zeta_X &= \operatorname{ad}(X)^*\circ J.\end{aligned}$$

(2) We have to show that $\Lambda^2 dJ(x).P^M = P^{\mathfrak{g}^*}(J(x))$, by (28.5.3).

$$\begin{aligned}\langle P^{\mathfrak{g}^*}\circ J, X\wedge Y\rangle &= \langle J, [X,Y]\rangle \qquad\text{by (28.7)}\\ &= j[X,Y] = \{j(X), j(Y)\},\\ \langle \Lambda^2 dJ(x).P^M, X\wedge Y\rangle &= \langle \Lambda^2 dJ(x)^*.(X\wedge Y), P^M\rangle = \langle dJ(x)^*X\wedge dJ(x)^*Y, P^M\rangle\\ &= \langle P^M, d\langle J,X\rangle\wedge d\langle J,Y\rangle\rangle(x) = \langle P^M, dj(X)\wedge dj(Y)\rangle(x)\\ &= \{j(X), j(Y)\}(x).\end{aligned}$$

(3) is an immediate consequence of (1). □

29.8. Equivariance of momentum mappings. Let $J : M \to \mathfrak{g}^*$ be a momentum mapping for a Hamiltonian right group action $r : M \times G \to M$ on a symplectic manifold (M, ω). We do not assume here that the lift $j : \mathfrak{g} \to C^\infty(M)$ given by $j(X) = \langle J, X\rangle$ is a Lie algebra homomorphism. Recall that for the fundamental vector field mapping $\zeta : \mathfrak{g} \to \mathfrak{X}(M, \omega)$ we have $\zeta_X = H_{j(X)} = H_{\langle J,X\rangle}$. We also assume that M is connected; otherwise one has to treat each connected component separately.

For $X \in \mathfrak{g}$ and $g \in G$ we have (compare with the proof of (29.4))

$$\begin{aligned}
(r^g)^*\zeta_X &= (r^g)^* H_{\langle J,X\rangle} = (r^g)^*(\check\omega^{-1} d\langle J, X\rangle) \\
&= (((r^g)^*\omega)^\vee)^{-1} d\langle (r^g)^* J, X\rangle = (\check\omega^{-1} d\langle J \circ r^g, X\rangle) = H_{\langle J\circ r^g, X\rangle}, \\
(r^g)^*\zeta_X &= T(r^{g^{-1}}) \circ \zeta_X \circ r^g = \zeta_{\mathrm{Ad}(g)X} \qquad \text{by (5.13.2)} \\
&= H_{\langle J, \mathrm{Ad}(g)X\rangle} = H_{\langle \mathrm{Ad}(g)^* J, X\rangle}.
\end{aligned}$$

So we conclude that $\langle J \circ r^g - \mathrm{Ad}(g)^* J, X\rangle \in H^0(M)$ is a constant function on M (which we assumed to be connected) for every $X \in \mathfrak{g}$ and we get a smooth mapping

$$\begin{aligned}
(1) \qquad & \bar J : G \to \mathfrak{g}^*, \\
& \bar J(g) := J \circ r^g - \mathrm{Ad}(g)^* \circ J = J(x.g) - \mathrm{Ad}(g)^* J(x) \in \mathfrak{g}^* \quad \text{for each } x \in M,
\end{aligned}$$

which satifies for $g_1, g_2 \in G$ and each $x \in M$

$$\begin{aligned}
(2) \qquad \bar J(g_0 g_1) &= J(x.g_0 g_1) - \mathrm{Ad}(g_0 g_1)^* J(x) \\
&= J((x.g_0).g_1) - \mathrm{Ad}(g_1)^* \mathrm{Ad}(g_0)^* J(x) \\
&= J((x.g_0).g_1) - \mathrm{Ad}(g_1)^* J(x.g_0) + \mathrm{Ad}(g_1)^*(J(x.g_0) - \mathrm{Ad}(g_0)^* J(x)) \\
&= \bar J(g_1) + \mathrm{Ad}(g_1)^* \bar J(g_0) = \bar J(g_1) + \bar J(g_0).\mathrm{Ad}(g_1)
\end{aligned}$$

This equation says that $\bar J : G \to \mathfrak{g}^*$ is a smooth 1-cocycle with values in the right G-module $\mathfrak{g}^*$ for the smooth group cohomomology which is given by the following coboundary operator, which for completeness sake we write for a G-bimodule V, i.e. a vector space V with a linear left action $\lambda : G \times V \to V$ and a linear right action $\rho : V \times G \to V$ which commute:

$$\begin{aligned}
(3) \qquad & C^k(G, V) := C^\infty(G^k = G \times \ldots \times G, V), \quad C^0(G, V) = V, \quad k \geq 0 \\
& \delta : C^k(G, V) \to C^{k+1}(G, V) \\
& \delta\Phi(g_0, \ldots, g_k) = g_0.\Phi(g_1, \ldots, g_k) + \sum_{i=1}^{k} (-1)^i \Phi(g_0, \ldots, g_{i-1}g_i, \ldots, g_k) \\
& \qquad\qquad + (-1)^{k+1} \Phi(g_0, \ldots, g_{k-1}).g_k.
\end{aligned}$$

It is easy to check that $\delta \circ \delta = 0$. The *group cohomology* is defined by

$$H^k(G; V) := \frac{\ker(\delta : C^k(G, V) \to C^{k+1}(G, V))}{\mathrm{im}(\delta : C^{k-1}(G, V) \to C^k(G, V))}.$$

Since for $v \in V = C^0(G,V)$ we have $\delta v(g_0) = g_0.v - v.g_0$ we have $H^0(G,V) = \{v \in V : g.v = v.g\} = Z_V(G)$. A smooth mapping $\Phi : G \to V$ is a cocycle $\delta\Phi = 0$ if and only if $\Phi(g_0g_1) = g_0.\Phi(g_1) + \Phi(g_0).g_1$, i.e. Φ is a 'derivation'.

In our case $V = \mathfrak{g}^*$ with trivial left G-action (each $g \in G$ acts by the identity) and right action $\mathrm{Ad}(\ )^*$. Any other moment mapping $J' : M \to \mathfrak{g}^*$ is of the form $J' = J + \alpha$ for constant $\alpha \in \mathfrak{g}^*$ since M is connected. The associated group cocycle is then

$$\begin{aligned}\overline{J+\alpha}(g) &= J(x.g) + \alpha - \mathrm{Ad}(g)^*(J(x)+\alpha) = \bar J(g) + \alpha - \alpha.\mathrm{Ad}(g)\\ &= (\bar J + \delta\alpha)(g),\end{aligned}\tag{4}$$

so that the group cohomology class $\tilde r = [\bar J] \in H^1(G,\mathfrak{g}^*)$ of the Hamiltonian G-action does not depend on the choice of the momentum mapping.

(5) *The differential $d\bar J(e) : \mathfrak{g} \to \mathfrak{g}^*$ at $e \in G$ of the group cocycle $\bar J : G \to \mathfrak{g}*$ satifies*

$$\langle d\bar J(e)X, Y\rangle = \bar j(X,Y),$$

where $\bar j$ is the Lie algebra cocycle from (29.6.1)*, given by* $\bar j(X,Y) = \{j(X), j(Y)\} - j([X,Y])$*,* since

$$\begin{aligned}\{j(X),j(Y)\}(x) &= H_{j(X)}(j(Y))(x) = i(H_{\langle J,X\rangle}(x))d\langle J,Y\rangle = \langle dJ(\zeta_X(x)),Y\rangle\\ &= \tfrac{\partial}{\partial t}\big|_0 \langle J(x.\exp(tX)),Y\rangle = \tfrac{\partial}{\partial t}\big|_0 \langle \mathrm{Ad}(\exp(tX))^*J(x) + \bar J(\exp(tX)),Y\rangle\\ &= \langle \mathrm{ad}(X)^*J(x) + d\bar J(e)(X),Y\rangle = \langle J(x),\mathrm{ad}(X)Y\rangle + \langle d\bar J(e)(X),Y\rangle\\ &= j[X,Y] + \langle d\bar J(e)(X),Y\rangle.\end{aligned}$$

(6) *If the group cohomology class $\tilde r$ of the Hamiltonian group action vanishes then there exists a G-equivariant momentum mapping $J : M \to \mathfrak{g}^*$, i.e.*

$$J(x.g) = \mathrm{Ad}(g)^*J(x).$$

Namely, let the group cohomology class be given by $\tilde r = [\bar J] \in H^1(G,\mathfrak{g}^*)$. Then $\bar J = \delta\alpha$ for some constant $\alpha \in \mathfrak{g}^*$. Then $J_1 = J - \alpha$ is a G-equivariant momentum mapping since $J_1(x.g) = J(x.g) - \alpha = \mathrm{Ad}(g)^*J(x) + \bar J(g) - \alpha = \mathrm{Ad}(g)^*J(x) + \delta\alpha(g) - \alpha = \mathrm{Ad}(g)^*J(x) - \mathrm{Ad}(g)^*\alpha = \mathrm{Ad}(g)^*J_1(x)$.

For $X, Y \in \mathfrak{g}$ and $g \in G$ we have

$$\langle \bar J(g), [X,Y]\rangle = -\bar\jmath(X,Y) + \bar\jmath(\mathrm{Ad}(g)X, \mathrm{Ad}(g)Y).\tag{7}$$

To see this we use the cocycle property $\bar J(g_1g_2) = \bar J(g_2) + \mathrm{Ad}(g_2)^*\bar J(g_1)$ from (2) to get

$$\begin{aligned}d\bar J(g)(T(\mu^g)X) &= \tfrac{\partial}{\partial t}\big|_0 \bar J(\exp(tX)g) = \tfrac{\partial}{\partial t}\big|_0 \big(\bar J(g) + \mathrm{Ad}(g)^*\bar J(\exp(tX))\big)\\ &= \mathrm{Ad}(g)^*d\bar J(e)X\\ \langle \bar J(g),[X,Y]\rangle &= \tfrac{\partial}{\partial t}\big|_0 \langle \bar J(g), \mathrm{Ad}(\exp(tX))Y\rangle = \tfrac{\partial}{\partial t}\big|_0 \langle \mathrm{Ad}(\exp(tX))^*\bar J(g),Y\rangle\\ &= \tfrac{\partial}{\partial t}\big|_0 \langle \bar J(g\exp(tX)) - \bar J(\exp(tX)),Y\rangle\\ &= \langle \tfrac{\partial}{\partial t}\big|_0 \bar J(g\exp(tX)g^{-1}g) - \tfrac{\partial}{\partial t}\big|_0 \bar J(\exp(tX)),Y\rangle\\ &= \langle \mathrm{Ad}(g)^*d\bar J(e)\,\mathrm{Ad}(g)X - d\bar J(e)X, Y\rangle\\ &= \bar\jmath(\mathrm{Ad}(g)X,\mathrm{Ad}(g)Y) - \bar\jmath(X,Y)\end{aligned}$$

29.9. Theorem. *Let $J : M \to \mathfrak{g}^*$ be a momentum mapping for a Hamiltonian right group action $r : M \times G \to M$ on a connected symplectic manifold (M, ω) with group 1-cocycle $\bar{J} : G \to \mathfrak{g}^*$ and Lie algebra 2-cocycle $\bar{\jmath} : \Lambda^2\mathfrak{g} \to \mathbb{R}$. Then we have:*

(1) *There is a unique affine right action $a^g = a^g_{\bar{J}} : \alpha \mapsto \operatorname{Ad}(g)^*\alpha + \bar{J}(g)$ of G on $\mathfrak{g}^*$ whose linear part is the coadjoint action such that $J : M \to \mathfrak{g}^*$ is G-equivariant.*

(2) *There is a Poisson structure on $\mathfrak{g}^*$, given by*

$$\{f, h\}_{\bar{\jmath}}(\alpha) = \langle \alpha, [df(\alpha), dh(\alpha)]_{\mathfrak{g}} \rangle + \bar{\jmath}(df(\alpha), dh(\alpha)),$$

which is invariant under the affine G-action a from (1) and has the property that the momentum mapping $J : (M, \omega) \to (\mathfrak{g}^*, \{\ \ ,\ \ \}_{\bar{\jmath}})$ is a Poisson morphism. The symplectic leaves of this Poisson structure are exactly the orbits under the connected component G_0 of e for the affine action in (1)

Proof. (1) By (29.8.1) J is G-equivariant. It remains to check that we have a right action:

$$\begin{aligned} a^{g_2}a^{g_1}(\alpha) &= a^{g_2}(\operatorname{Ad}(g_1)^*\alpha + \bar{J}(g_1)) = \operatorname{Ad}(g_2)^* \operatorname{Ad}(g_1)^*\alpha + \operatorname{Ad}(g_2)^*\bar{J}(g_1)) + \bar{J}(g_2) \\ &= \operatorname{Ad}(g_1g_2)^*\alpha + \bar{J}(g_1g_2) = a^{g_1g_2}\alpha, \qquad \text{by (29.8.2).} \end{aligned}$$

(2) Let $X_1, \dots, X_n$ be a basis of $\mathfrak{g}$ with dual basis $\xi^1, \dots, \xi^n$ of $\mathfrak{g}^*$. Then we have in terms of the structure constants of the Lie algebra $\mathfrak{g}$

$$\begin{aligned} [X_i, X_j] &= \sum_k c^k_{ij} X_k, \\ [\ \ ,\ \ ] &= \tfrac{1}{2}\sum_{ijk} c^k_{ij} X_k \otimes (\xi^i \wedge \xi^j) \\ P^{\mathfrak{g}^*} &= -[\ \ ,\ \ ]^* = -\tfrac{1}{2}\sum_{ijk} c^k_{ij} (\xi^i \otimes X_k) \wedge \xi^j \\ \bar{\jmath} &= \tfrac{1}{2}\sum_{ij} \bar{\jmath}_{ij} \xi^i \wedge \xi^j \\ P^{\mathfrak{g}^*}_{\bar{\jmath}} &= -\tfrac{1}{2}\sum_{ijk} c^k_{ij} (\xi^i \otimes X_k) \wedge \xi^j + \tfrac{1}{2}\sum_{ij} \bar{\jmath}_{ij} \xi^i \wedge \xi^j : \mathfrak{g}^* \to \Lambda^2\mathfrak{g}^*. \end{aligned}$$

Let us now compute the Schouten bracket. We note that $[P^{\mathfrak{g}^*}, P^{\mathfrak{g}^*}] = 0$ since this is a Poisson structure, and $[\bar{\jmath}, \bar{\jmath}] = 0$ since it is a constant 2-vector field on the vector space $\mathfrak{g}^*$.

$$\begin{aligned} [P^{\mathfrak{g}^*}_{\bar{\jmath}}, P^{\mathfrak{g}^*}_{\bar{\jmath}}] &= [P^{\mathfrak{g}^*} + \bar{\jmath}, P^{\mathfrak{g}^*} + \bar{\jmath}] = [P^{\mathfrak{g}^*}, P^{\mathfrak{g}^*}] + 2[P^{\mathfrak{g}^*}, \bar{\jmath}] + [\bar{\jmath}, \bar{\jmath}] = 0 + 2[P^{\mathfrak{g}^*}, \bar{\jmath}] + 0 \\ &= -\tfrac{1}{2}\sum_{ijklm} c^k_{ij}\, \bar{\jmath}_{lm} \Big([\xi^i \otimes X_k, \xi^l] \wedge \xi^j \wedge \xi^m - [\xi^i \otimes X_k, \xi^m] \wedge \xi^j \wedge \xi^l - \\ &\qquad - [\xi^j, \xi^l] \wedge (\xi^i \otimes X_k) \wedge \xi^m + [\xi^j, \xi^m] \wedge (\xi^i \otimes X_k) \wedge \xi^l \Big) \\ &= -\tfrac{1}{2}\sum_{ijklm} c^k_{ij}\, \bar{\jmath}_{lm} \Big(-\delta^l_k\, \xi^i \wedge \xi^j \wedge \xi^m + \delta^m_k\, \xi^i \wedge \xi^j \wedge \xi^l - 0 + 0 \Big) \\ &= \sum_{ijkm} c^k_{ij}\, \bar{\jmath}_{km}\, \xi^i \wedge \xi^j \wedge \xi^m = -2d\bar{\jmath} = 0 \end{aligned}$$

which is zero since $\bar{\jmath}$ is a Lie algebra cocycle. Thus $P^{\mathfrak{g}^*}_{\bar{\jmath}}$ is a Poisson structure. The Poisson structure $P^{\mathfrak{g}^*}_{\bar{\jmath}}$ is invariant under the affine action since

$$\begin{aligned}
\{f\circ a^g, h\circ a^g\}_{\bar{\jmath}}(\alpha) &= \langle \alpha, [df(a^g(\alpha)).T(a^g), dh(a^g(\alpha)).T(a^g)]\rangle + \\
&\quad + \bar{\jmath}(df(a^g(\alpha)).T(a^g), dh(a^g(\alpha)).T(a^g))\\
&= \langle \alpha, [df(a^g(\alpha)).\operatorname{Ad}(g)^*, dh(a^g(\alpha)).\operatorname{Ad}(g)^*]\rangle + \\
&\quad + \bar{\jmath}(df(a^g(\alpha)).\operatorname{Ad}(g)^*, dh(a^g(\alpha)).\operatorname{Ad}(g)^*)\\
&= \langle \alpha, \operatorname{Ad}(g)[df(a^g(\alpha)), dh(a^g(\alpha))]\rangle + \bar{\jmath}(\operatorname{Ad}(g)df(a^g(\alpha)), \operatorname{Ad}(g)dh(a^g(\alpha)))\\
&= \langle \operatorname{Ad}(g)^*\alpha, [df(a^g(\alpha)), dh(a^g(\alpha))]\rangle + \langle \bar{J}(g), [df(a^g(\alpha)), dh(a^g(\alpha))]\rangle + \\
&\quad + \bar{\jmath}(df(a^g(\alpha)), dh(a^g(\alpha))), \quad \text{by (29.8.7)}\\
&= \langle a^g(\alpha), [df(a^g(\alpha)), dh(a^g(\alpha))]\rangle + \bar{\jmath}(df(a^g(\alpha)), dh(a^g(\alpha)))\\
&= \{f,g\}_{\bar{\jmath}}(a^g(\alpha)).
\end{aligned}$$

To see that the momentum mapping $J:(M,\omega)\to(\mathfrak{g}^*, P^{\mathfrak{g}^*}_{\bar{\jmath}})$ is a Poisson morphism we have to show that $\Lambda^2 dJ(x).P^\omega(x) = P^{\mathfrak{g}^*}_{\bar{\jmath}}(J(x)) \in \Lambda^2\mathfrak{g}^*$ for $x\in M$, by (28.5.3). Recall from the definition (29.2.1) that $\langle J, X\rangle = j(X)$, thus also $\langle dJ(x), X\rangle = dj(X)(x) : T_xM \to \mathbb{R}$.

$$\begin{aligned}
\langle \Lambda^2 dJ(x).P^\omega(x), X\wedge Y\rangle &= \langle P^\omega(x), \Lambda^2 dJ(x)^*(X\wedge Y)\rangle\\
&= \langle P^\omega(x), dJ(x)^*X \wedge dJ(x)^*Y\rangle = \langle P^\omega(x), d\langle J,X\rangle\wedge d\langle J,Y\rangle\rangle\\
&= \langle P^\omega(x), dj(X)\wedge dj(Y)\rangle = \{j(X), j(Y)\}_\omega\\
&= \bar{\jmath}(X,Y) + j([X,Y])(x) \qquad \text{by (29.6.1)}\\
&= \langle J(x), [X,Y]\rangle + \bar{\jmath}(X,Y) = \langle P^{\mathfrak{g}^*}_{\bar{\jmath}}(J(x)), X\wedge Y\rangle.
\end{aligned}$$

It remains to investigate the symplectic leaves of the Poisson structure $P^{\mathfrak{g}^*}_{\bar{\jmath}}$. The fundamental vector fields for the twisted right action $a_{\bar{J}}$ is given by

$$\zeta^{a_{\bar{J}}}_X(\alpha) = \tfrac{\partial}{\partial t}\big|_0 (\operatorname{Ad}(\exp(tX))^*\alpha + \bar{J}(\exp(tX))) = \operatorname{ad}(X)^*\alpha + d\bar{J}(e)X.$$

This fundamental vector field is also the Hamiltonian vector field for the function $\operatorname{ev}_X : \mathfrak{g}^*\to\mathbb{R}$ since

(3) $$\begin{aligned}
H^{\bar{\jmath}}_{\operatorname{ev}_X}(f)(\alpha) &= \{\operatorname{ev}_X, f\}_{\bar{\jmath}}(\alpha) = \langle \alpha, [X, df(\alpha)]\rangle + \bar{\jmath}(X, df(\alpha))\\
&= \langle \operatorname{ad}(X)^*\alpha, df(\alpha)\rangle + \langle d\bar{J}(e)X, df(\alpha)\rangle = \zeta^{a_{\bar{J}}}_X(f)(\alpha).
\end{aligned}$$

Hamiltonian vector fields of linear functions suffice to span the integrable distribution with jumping dimension which generates the symplectic leaves. Thus the symplectic leaves are exactly the orbits of the G_0-action $a_{\bar{J}}$. □

29.10. Corollary. *(Kostant, Souriau) Let $J : M\to\mathfrak{g}^*$ be a momentum mapping for a transitive Hamiltonian right group action $r : M\times G\to M$ on a connected symplectic manifold (M,ω) with group 1-cocycle $\bar{J} : G\to\mathfrak{g}^*$ and Lie algebra 2-cocycle $\bar{\jmath}:\Lambda^2\mathfrak{g}\to\mathbb{R}$.*

Then the image $J(M)$ of the momentum mapping is an orbit O of the affine action $a_{\bar{J}}$ of G on $\mathfrak{g}^*$ for which J is equivariant, the corestriction $J : M \to O$ is locally a symplectomorphism and a covering mapping of O.

Proof. Since G acts transitively on M and J is G-equivariant, $J(M) = O$ is an orbit for the twisted action a_J of G on $\mathfrak{g}^*$. Since M is connected, O is connected and is thus a symplectic leaf of the twisted Poisson structure $P^{\mathfrak{g}^*}_{\bar{J}}$ for which $J : M \to \mathfrak{g}^*$ is a Poisson mapping. But along O the Poisson structure is symplectic, and its pullback via J equals ω, thus $T_xJ : T_xM \to T_{J(x)}O$ is invertible for each $x \in M$ and J is a local diffeomorphism. Since J is equivariant it is diffeomorphic to a mapping $M \cong G/G_x \to G/G_{J(x)}$ and is thus a covering mapping. $\square$

29.11. Let us suppose that for some symplectic infinitesimal action of a Lie algebra $\zeta : \mathfrak{g} \to \mathfrak{X}(M, \omega)$ the cohomology class $\tilde{\zeta} = [\bar{j}] \in H^2(\mathfrak{g}, H^0(M))$ does not vanish. Then we replace the Lie algebra $\mathfrak{g}$ by the *central extension*, see section (27),

$$0 \to H^0(M) \to \tilde{\mathfrak{g}} \to \mathfrak{g} \to 0$$

which is defined by $\tilde{\zeta} = [\bar{j}]$ in the following way: $\tilde{\mathfrak{g}} = H^0(M) \times \mathfrak{g}$ with bracket $[(a, X), (b, Y)] := (\bar{j}(X, Y), [X, Y])$. This satisfies the Jacobi identity since

$$[[(a, X), (b, Y)], (c, Z)] = [(\bar{j}(X, Y), [X, Y]), (c, Z)] = (\bar{j}([X, Y], Z), [[X, Y], Z])$$

and the cyclic sum of this expression vanishes. The mapping $j_1 : \tilde{g} \to C^\infty(M)$, given by $j_1(a, X) = j(X) + a$, fits into the diagram

$$\begin{array}{ccccccccc}
0 \to H^0(M) & \xrightarrow{\alpha} & C^\infty(M) & \xrightarrow{H} & \mathfrak{X}(M,\omega) & \xrightarrow{\gamma} & H^1(M) \to 0 \\
\| & & \uparrow{\scriptstyle j_1} & \nwarrow{\scriptstyle j} & \uparrow{\scriptstyle \zeta} & & \\
0 \to H^0(M) & \longrightarrow & \tilde{\mathfrak{g}} & \longrightarrow & \mathfrak{g} & \longrightarrow & 0
\end{array}$$

and is a homomorphism of Lie algebras since

$$\begin{aligned}
j_1([(a, X), (b, Y)]) &= j_1(\bar{j}(X, Y), [X, Y]) = j([X, Y]) + \bar{j}(X, Y) \\
&= j([X, Y]) + \{jX, jY\} - j([X, Y]) = \{jX, jY\} \\
&= \{jX + a, jY + b\} = \{j_1(a, X), j_1(b, Y)\}.
\end{aligned}$$

In this case we can consider the momentum mapping

$$\begin{gathered}
J_1 : M \to \tilde{\mathfrak{g}}^* = (H^0(M) \times \mathfrak{g})^*, \\
\langle J_1(x), (a, X)\rangle = j_1(a, X)(x) = j(X)(x) + a, \\
H_{j_1(a,X)} = \zeta_X, \quad x \in M, \quad X \in \mathfrak{g}, \quad a \in H^0(M)
\end{gathered}$$

which has all the properties of proposition (29.7).

Let us describe this in more detail. Property (29.7.1) says that for all $(a,X)\in H^0(M)\times\mathfrak{g}$ the vector fields $H_{j(X)+a}=\zeta_X\in\mathfrak{X}(M)$ and $\operatorname{ad}(a,X)^*\in\mathfrak{X}(\tilde g^*)$ are J_1-related. We have

$$\begin{aligned}\langle\operatorname{ad}(a,X)^*(\alpha,\xi),(b,Y)\rangle &= \langle(\alpha,\xi),[(a,X)(b,Y)]\rangle = \langle(\alpha,\xi),(\bar\jmath(X,Y),[X,Y])\rangle\\ &= \alpha\bar\jmath(X,Y)+\langle\xi,[X,Y]\rangle = \alpha\bar\jmath(X,Y)+\langle\operatorname{ad}(X)^*\xi,Y\rangle\\ &= \langle(0,\alpha\bar\jmath(X,\quad)+\operatorname{ad}(X)^*\xi),(b,Y)\rangle,\\ \operatorname{ad}(a,X)^*(\alpha,\xi) &= (0,\alpha\bar\jmath(X,\quad)+\operatorname{ad}(X)^*\xi).\end{aligned}$$

This is related to formula (29.9.3) which describes the infinitesimal twisted right action corresponding to the twisted group action of (29.9.1).

The Poisson bracket on $\tilde{\mathfrak{g}}^*=(H^0(M)\times\mathfrak{g})^*=H^0(M)^*\times\mathfrak{g}^*$ is given by

$$\begin{aligned}\{f,h\}^{\tilde{\mathfrak{g}}^*}(\alpha,\xi) &= \langle(\alpha,\xi),[(d_1f(\alpha,\xi),d_2f(\alpha,\xi)),(d_1h(\alpha,\xi),d_2h(\alpha,\xi))]\rangle\\ &= \langle(\alpha,\xi),(\bar\jmath(d_2f(\alpha,\xi),d_2h(\alpha,\xi)),[d_2f(\alpha,\xi),d_2h(\alpha,\xi)])\rangle\\ &= \alpha\bar\jmath(d_2f(\alpha,\xi),d_2h(\alpha,\xi))+\langle\xi,[d_2f(\alpha,\xi),d_2h(\alpha,\xi)]\rangle\end{aligned}$$

which for $\alpha=1$ and connected M is the twisted Poisson bracket in (29.9.2). We may continue and derive all properties of (29.9) for a connected Lie group from here, with some interpretation.

29.12. Symplectic reduction. Let $J:M\to\mathfrak{g}^*$ be a momentum mapping for a Hamiltonian right group action $r:M\times G\to M$ on a connected symplectic manifold (M,ω) with group 1-cocycle $\bar J:G\to\mathfrak{g}^*$ and Lie algebra 2-cocycle $\bar\jmath:\Lambda^2\mathfrak{g}\to\mathbb{R}$.

(1) [Bott, 1954] *A point $\alpha\in J(M)\subset\mathfrak{g}^*$ is called a weakly regular value for J if $J^{-1}(\alpha)\subset M$ is a submanifold such that for each $x\in J^{-1}(\alpha)$ we have $T_xJ^{-1}(\alpha)=\ker(T_xJ)$.* This is the case if α is a regular value for J, or if J is of constant rank in a neighborhood of $J^{-1}(\alpha)$, by (1.13). Let us fix a weakly regular value $\alpha\in\mathfrak{g}^*$ of J for the following. The submanifold $J^{-1}(\alpha)\subset M$ has then the following properties:

(2) *For a weakly regular value α of J, the submanifold $J^{-1}(\alpha)$ is invariant under the action of the isotropy group $G_\alpha=\{g\in G:a^g_{\bar J}(\alpha)=\alpha\}$. The dimension of the the isotropy group G_x of $x\in J^{-1}(\alpha)$ does not depend on $x\in J^{-1}(\alpha)$ and is given by*

$$\dim(G_x)=\dim(G)-\dim(M)+\dim(J^{-1}(\alpha)).$$

Namely, $J:M\to\mathfrak{g}^*$ is equivariant for these actions by (29.9.1). Thus $J^{-1}(\alpha)$ is invariant under G_α and $G_x\subseteq G_\alpha$. For each $x\in J^{-1}(\alpha)$, by (29.3.4) we have $\operatorname{im}(dJ(x))=\mathfrak{g}_x^\circ\subset\mathfrak{g}^*$. Since $T_x(J^{-1}(\alpha))=\ker(dJ(x))$ we get

$$\begin{aligned}\dim(T_xM) &= \dim(T_xJ^{-1}(\alpha))+\operatorname{rank}(dJ(x)),\\ \dim(G_x) &= \dim(G)-\dim(x.G)=\dim(G)-\dim(\mathfrak{g}_x^\circ)=\dim(G)-\operatorname{rank}(dJ(x))\\ &= \dim(G)-\dim(M)+\dim(J^{-1}(\alpha)).\end{aligned}$$

(3) *At any $x \in J^{-1}(\alpha)$ the kernel of the pullback $\omega^{J^{-1}(\alpha)}$ of the symplectic form ω equals $T_x(x.G_\alpha)$ and its rank is constant and is given by* by

$$\operatorname{rank}(\omega^{J^{-1}(\alpha)}) = 2\dim(J^{-1}(\alpha)) + \dim(a_{\bar J}^G(\alpha)) - \dim(M).$$

Namely, $T_x J^{-1}(\alpha) = \ker(dJ(x))$ implies

$$\begin{aligned}
\ker(\omega^{J^{-1}(\alpha)}) &= T_x(J^{-1}(\alpha)) \cap T_x(J^{-1}(\alpha))^\perp = T_x(J^{-1}(\alpha)) \cap \ker(dJ(x))^\perp\\
&= T_x(J^{-1}(\alpha)) \cap T_x(x.G), \qquad \text{by (29.3.3)}\\
&= T_x(x.G_\alpha),
\end{aligned}$$

$$\begin{aligned}
\operatorname{rank}(\omega_x^{J^{-1}(\alpha)}) &= \dim(J^{-1}(\alpha)) - \dim(x.G_\alpha) = \dim(J^{-1}(\alpha)) - \dim(G_\alpha) + \dim(G_x)\\
&= \dim(J^{-1}(\alpha)) - \dim(G_\alpha) + \dim(G) - \dim(M) + \dim(J^{-1}(\alpha)) \qquad \text{by (2)}\\
&= 2\dim(J^{-1}(\alpha)) + \dim(a_{\bar J}^G(\alpha)) - \dim(M).
\end{aligned}$$

(4) *If α is a regular value of $J : M \to \mathfrak{g}^*$ the action of G on M is locally free in a neighborhood of every point $x \in J^{-1}(\alpha)$, by* (29.3.5), *i.e. the isotropy group G_x is discrete,* since $\operatorname{codim}_M(J^{-1}(\alpha)) = \dim(\mathfrak{g}) - \dim(G)$.

29.13. Theorem. Weakly regular symplectic reduction. *Let $J : M \to \mathfrak{g}^*$ be a momentum mapping for a Hamiltonian right group action $r : M \times G \to M$ on a connected symplectic manifold (M, ω) with group 1-cocycle $\bar J : G \to \mathfrak{g}^*$ and Lie algebra 2-cocycle $\bar j : \Lambda^2\mathfrak{g} \to \mathbb{R}$. Let $\alpha \in J(M) \subset \mathfrak{g}^*$ be a weakly regular value of J.*

Then the pullback 2-form $\omega^{J^{-1}(\alpha)} \in \Omega^2(J^{-1}(\alpha))$ of ω is of constant rank, invariant under the action of G_α, and the leaves of the foliation described by its kernel are the orbits of the action of the connected component G_α^0 of the isotropy group $G_\alpha := \{g \in G : a_{\bar J}^g(\alpha) = \alpha\}$ in $J^{-1}(\alpha)$.

If moreover the orbit space $M_\alpha := J^{-1}(\alpha)/G_\alpha^0$ is a smooth manifold then there exists a unique symplectic form ω^α on it such that for the canonical projection $\pi : J^{-1}(\alpha) \to M_\alpha$ we have $\pi^*\omega^\alpha = \omega^{J^{-1}(\alpha)}$.

Let $h \in C^\infty(M)^G$ be a Hamiltonian function on M which is G-invariant, then $h|J^{-1}(\alpha)$ factors to $\bar h \in C^\infty(M_\alpha)$ with $\bar h \circ \pi = h|J^{-1}(\alpha)$. The Hamiltonian vector field $\operatorname{grad}^\omega(h) = H_h$ *is tangent to $J^{-1}(\alpha)$ and the vector fields $H_h|J^{-1}(\alpha)$ and $H_{\bar h}$ are π-related. Thus their trajectories are mapped onto each other:*

$$\pi(\mathrm{Fl}_t^{H_h}(x)) = \mathrm{Fl}_t^{H_{\bar h}}(\pi(x))$$

In this case we call $(M_\alpha = J^{-1}(\alpha)/G_\alpha, \omega^\alpha)$ the *reduced symplectic manifold*.

Proof. By (29.12.3) the 2-form $\omega^{J^{-1}(\alpha)} \in \Omega^2(J^{-1}(\alpha))$ is of constant rank and the foliation corresponding to its kernel is given by the orbits of the unit component G_α^0 of the isotropy group G_α. Let us now suppose that the orbit space $M_\alpha = J^{-1}(\alpha)/G_\alpha^0$ is a smooth manifold. Since the 2-form $\omega^{J^{-1}(\alpha)}$ is G_α^0-invariant and horizontal for the projection $\pi : J^{-1}(\alpha) \to J^{-1}(\alpha)/G_\alpha = M_\alpha$, it factors to a smooth 2-form $\omega^\alpha \in \Omega^2(M_\alpha)$ which is closed and non degenerate since we just factored out its kernel. Thus $(M_\alpha, \omega^\alpha)$ is a symplectic manifold and $\pi^*\omega^\alpha = \omega^{J^{-1}(\alpha)}$ by construction.

Now let $h \in C^\infty(M)$ be a Hamiltonian function which is invariant under G. By E. Noether's theorem (29.3.8) the momentum mapping J is constant along each trajectory of the Hamiltonian vector field H_h; thus H_h is tangent to $J^{-1}(\alpha)$ and G_α-invariant on $J^{-1}(\alpha)$. Let $\bar h \in C^\infty(M_\alpha)$ be the factored function with $\bar h \circ \pi = h$, and consider $H_{\bar h} \in \mathfrak{X}(M_\alpha, \omega^\alpha)$. Then for $x \in J^{-1}(\alpha)$ we have

$$(T_x\pi)^*(i_{T_x\pi.H_h(x)}\omega^\alpha) = i_{H_h(x)}\pi^*\omega^\alpha = dh(x) = (T_x\pi)^*(d\bar h(\pi(x))).$$

Since $(T_x\pi)^* : T^*_{\pi(x)}M_\alpha \to T_x(J^{-1}(\alpha))$ is injective we see that $i_{T_x\pi.H_h(x)}\omega^\alpha = d\bar h(\pi(x))$ and hence $T_x\pi.H_h(x) = H_{\bar h}(\pi(x))$. Thus $H_h|J^{-1}(\alpha)$ and $H_{\bar h}$ are π-related and the remaining assertions follow from (3.14) □

29.14. Proposition. Constant rank symplectic reduction. *Let $J : M \to \mathfrak{g}^*$ be a momentum mapping for a Hamiltonian right group action $r : M \times G \to M$ on a connected symplectic manifold (M, ω) with group 1-cocycle $\bar J : G \to \mathfrak{g}^*$ and Lie algebra 2-cocycle $\bar\jmath : \Lambda^2\mathfrak{g} \to \mathbb{R}$. Let $\alpha \in J(M) \subset \mathfrak{g}^*$ be such that J has constant rank in a neighborhood of $J^{-1}(\alpha)$. We consider the orbit $\alpha.G = a^G_{\bar J}(\alpha) \subset \mathfrak{g}^*$.*

Then $J^{-1}(\alpha.G)$ is an initial manifold in M, and there exists a natural diffeomorphism $\varphi : J^{-1}(\alpha) \times \alpha.G \to J^{-1}(\alpha).G$ which satisfies $\varphi(x, \alpha.g) = x.g$ and $\omega^{J^{-1}(\alpha)} \times \omega^{\alpha.G} = \varphi^*(\omega^{J^{-1}(\alpha.G)}$, where $\omega^{J^{-1}(\alpha.G)}$ is the pullback of ω, a 2-form of constant rank which is invariant under the action of G.

Moreover, the orbit spaces $J^{-1}(\alpha)/G^0_\alpha$ and $J^{-1}(\alpha.G)/G^0$ are homeomorphic, and diffeomorphic if one of the orbit spaces is a smooth manifold. Let us identify $M_\alpha = J^{-1}(\alpha)/G^0_\alpha = J^{-1}(\alpha.G)/G^0$.

If M_α is a manifold then $\omega^{J^{-1}(\alpha.G)}$ factors to symplectic form ω^{M_α}. Let $h \in C^\infty(M)^G$ be a Hamiltonian function on M which is G-invariant, then $h|J^{-1}(\alpha.G)$ factors to $\bar h \in C^\infty(M_\alpha)$ with $\bar h \circ \pi = h|J^{-1}(\alpha.G)$. The Hamiltonian vector field $\operatorname{grad}^\omega(f) = H_h$ is tangent to $J^{-1}(\alpha.G)$ and the vector fields $H_h|J^{-1}(\alpha.G)$ and $H_{\bar h}$ are π-related. Thus their trajectories are mapped onto each other:

$$\pi(\mathrm{Fl}^{H_h}_t(x)) = \mathrm{Fl}^{H_{\bar h}}_t(\pi(x))$$

Proof. Let $\alpha \in J(M) \subset \mathfrak{g}^*$ be such that J is of constant rank on a neighborhood of $J^{-1}(\alpha)$. Let $\alpha.G = a^G_{\bar J}(\alpha)$ be the orbit though α under the twisted coadjoint action. Then $J^{-1}(\alpha.G) = J^{-1}(\alpha).G$ by the G-equivariance of J. Thus the dimension of the isotropy group G_x of a point $x \in J^{-1}(\alpha.G)$ does not depend on x and is given by (29.12.2). It remains to show that the inverse image $J^{-1}(\alpha.G)$ is an initial submanifold which is invariant under G. If α is a regular value for J then J is a submersion on an open neighborhood of $J^{-1}(\alpha.G)$ and $J^{-1}(\alpha.G)$ is an initial submanifold by lemma (2.16). Under the weaker assumtion that J is of constant rank on a neighborhood of $J^{-1}(\alpha)$ we will construct an initial submanifold chart as in (2.13.1) centered at each $x \in J^{-1}(\alpha.G)$. Using a suitable transformation in G we may assume without loss that $x \in J^{-1}(\alpha)$. We shall use the method of the proof of theorem (3.25).

Let $m = \dim(M)$, $n = \dim(\mathfrak{g})$, $r = \operatorname{rank}(dJ(x))$, $p = m - r = \dim(J^{-1}(\alpha))$ and $k = \dim(\alpha.G) \le l = \dim(x.G)$. Using that $\mathfrak{g}_x \subseteq \mathfrak{g}_\alpha$, we choose a basis $X_1, \dots, X_n$ of $\mathfrak{g}$ such that

- $\zeta^{\mathfrak{g}^*}_{X_1}(\alpha), \dots, \zeta^{\mathfrak{g}^*}_{X_k}(\alpha)$ is a basis of $T_\alpha(\alpha.G)$ and $X_{k+1}, \dots, X_n$ is a basis of $\mathfrak{g}_\alpha$,
- $\zeta^M_{X_1}(x), \dots, \zeta^M_{X_l}(x)$ is a basis of $T_x(x.G)$ and $X_{l+1}, \dots, X_n$ is a basis of $\mathfrak{g}_x$,

By the constant rank theorem (1.13) there exists a chart (U, u) on M centered at x and a chart (V, v) on $\mathfrak{g}^*$ centered at α such that $v \circ J \circ u^{-1} : u(U) \to v(V)$ has the following form:

$$(x^1, \dots, x^m) \mapsto (x^1, \dots, x^k, x^{l+1}, \dots, x^{r+l-k}, 0, \dots, 0),$$

and we may also assume that

$$\begin{gathered}
\zeta^{\mathfrak{g}^*}_{X_1}(\alpha), \dots, \zeta^{\mathfrak{g}^*}_{X_k}(\alpha), \tfrac{\partial}{\partial v^{k+1}}|_\alpha, \dots, \tfrac{\partial}{\partial v^n}|_\alpha \text{ is a basis of } T_\alpha(\mathfrak{g}^*),\\
\zeta^M_{X_1}(x), \dots, \zeta^M_{X_l}(x), \tfrac{\partial}{\partial u^{l+1}}|_\alpha, \dots, \tfrac{\partial}{\partial u^m}|_\alpha \text{ is a basis of } T_x(M).
\end{gathered}$$

Then the mapping

$$f(y^1, \dots, y^n) = (\operatorname{Fl}^{\zeta^{\mathfrak{g}^*}_{X_1}}_{y^1} \circ \dots \circ \operatorname{Fl}^{\zeta^{\mathfrak{g}^*}_{X_k}}_{y^k} \circ v^{-1})(0, \dots, 0, y^{k+1}, \dots, y^n)$$

is a diffeomorphism from a neighborhood of 0 in $\mathbb{R}^n$ onto a neighborhood of α in $\mathfrak{g}^*$. Let $(\tilde V, \tilde v)$ be the chart f^{-1}, suitably restricted. We have

$$\beta \in \alpha.G \iff (\operatorname{Fl}^{\zeta^{\mathfrak{g}^*}_{X_1}}_{y^1} \circ \dots \circ \operatorname{Fl}^{\zeta^{\mathfrak{g}^*}_{X_k}}_{y^k})(\beta) \in \alpha.G$$

for all β and all $y^1, \dots, y^k$ for which both expressions make sense. So we have

$$f(y^1, \dots, y^n) \in \alpha.G \iff f(0, \dots, 0, y^{k+1}, \dots, y^n) \in \alpha.G,$$

and consequently $\alpha.G \cap \tilde V$ is the disjoint union of countably many connected sets of the form $\{\beta \in \tilde V : (\tilde v^{k+1}(\beta), \dots, \tilde v^n(\beta)) = \text{ constant}\}$, since $\alpha.G$ is second countable.

Now let us consider the situation on M. Since $J^{-1}(\alpha)$ is G_α-invariant exactly the vectors $\zeta^M_{X_{k+1}}(x), \dots, \zeta^M_{X_l}(x)$ are tangent to $x.G_\alpha \subseteq J^{-1}(\alpha)$. The mapping

$$g(x^1, \dots, x^m) = (\operatorname{Fl}^{\zeta^M_{X_1}}_{x^1} \circ \dots \circ \operatorname{Fl}^{\zeta^M_{X_k}}_{x^k} \circ u^{-1})(0, \dots, 0, x^{k+1}, \dots, x^m)$$

is a diffeomorphisms from a neighborhood of 0 in $\mathbb{R}^m$ onto a neighborhood of x in M. Let $(\tilde U, \tilde u)$ be the chart g^{-1}, suitably restricted. By G-invariance of J we have

$$\begin{aligned}
(J \circ g)(x^1, \dots, x^m) &= (J \circ \operatorname{Fl}^{\zeta^M_{X_1}}_{x^1} \circ \dots \circ \operatorname{Fl}^{\zeta^M_{X_k}}_{x^k} \circ u^{-1})(0, \dots, 0, x^{k+1}, \dots, x^m)\\
&= (\operatorname{Fl}^{\zeta^{\mathfrak{g}^*}_{X_1}}_{x^1} \circ \dots \circ \operatorname{Fl}^{\zeta^{\mathfrak{g}^*}_{X_k}}_{x^k} \circ v^{-1} \circ v \circ J \circ u^{-1})(0, \dots, 0, x^{k+1}, \dots, x^m)\\
&= (\operatorname{Fl}^{\zeta^{\mathfrak{g}^*}_{X_1}}_{x^1} \circ \dots \circ \operatorname{Fl}^{\zeta^{\mathfrak{g}^*}_{X_k}}_{x^k} \circ v^{-1})(0, \dots, 0, x^{k+1}, \dots, x^{r+l-k}, 0, \dots, 0)\\
&= f(x^1, \dots, x^k, x^{l+1}, \dots, x^{r+l-k}, 0, \dots, 0)
\end{aligned}$$

and thus

$$\begin{aligned}
&g(x^1,\dots,x^m)\in J^{-1}(\alpha.G)\iff\\
&\iff (J\circ g)(x^1,\dots,x^m)=f(x^1,\dots,x^k,x^{l+1},\dots,x^{r+l-k},0,\dots,0)\in\alpha.G\\
&\iff f(0_{\mathbb{R}^k},x^{l+1},\dots,x^{r+l-k},0_{\mathbb{R}^{n-r}})\in\alpha.G.
\end{aligned}$$

Consequently, $(J^{-1}(\alpha.G))\cap\tilde U$ is the disjoint union of countably many connected sets of the form $\{x\in\tilde U:(\tilde u^{l+1}(x),\dots,\tilde u^{r+l-k}(x))=\text{ constant}\}$, since $\alpha.G$ is second countable. We have proved now that $J^{-1}(\alpha.G)$ is an initial submanifold or M.

The mapping φ is defined by the following diagram which induces a bijective submersion, thus a diffeomorphism:

$$\begin{array}{ccccc}
 & & J^{-1}(\alpha)\times G & \xrightarrow{\;r:(x,g)\mapsto x.g\;} & \\
 & & \downarrow & & \searrow\\
J^{-1}(\alpha)\times\alpha.G & = & J^{-1}(\alpha)\times G/G_\alpha & \overset{\varphi}{\dashrightarrow} & J^{-1}(\alpha.G)
\end{array}$$

Now we need the symplectic structure on the orbit $\alpha.G=a^G_{\bar j}(\alpha)$. Recall from (29.9.3) that the Hamiltonian vector field for the linear function $\mathrm{ev}_X:\mathfrak g^*\to\mathbb R$ is given by $H_{\mathrm{ev}_X}=\zeta^{\mathfrak g^*}_X=\zeta^{a_{\bar j}}_X$. Thus the symplectic form is given by (we use again (29.9.3))

$$(1)\quad \omega^{\alpha.G}_\beta(\zeta^{\mathfrak g^*}_X,\zeta^{\mathfrak g^*}_Y)=\omega^{\alpha.G}_\beta(H_{\mathrm{ev}_X},H_{\mathrm{ev}_Y})=H_{\mathrm{ev}_Y}(\mathrm{ev}_X)(\beta)=\langle\beta,[Y,X]\rangle+\bar j(Y,X).$$

We compute the pullback. Let $\xi,\eta\in T_x(J^{-1}(\alpha))=\ker(dJ(x))=T_x(x.G)^\perp$ (see (29.3.3)), and let $X,Y\in\mathfrak g$.

$$\begin{aligned}
(\varphi^*\omega^{J^{-1}(\alpha.G)})_{(x,\beta=\alpha.g)}&((\xi,\zeta^{\mathfrak g^*}_X),(\eta,\zeta^{\mathfrak g^*}_Y))=\\
&=\omega_{x.g}(T_x(r^g)\xi+T_g(r_x)L_X,T_x(r^g)\eta+T_g(r_x)L_Y)\\
&=\omega_{x.g}(T_x(r^g)\xi+\zeta^M_X,T_x(r^g)\eta+\zeta^M_Y)\\
&=\omega_{x.g}(T_x(r^g)\xi,T_x(r^g)\eta)+\omega_{x.g}(\zeta^M_X,\zeta^M_Y)\quad\text{by (29.3.3)}\\
&=((r^g)^*\omega)_x(\xi,\eta)+\{j(Y),j(X)\}(x.g)\\
&=\omega_x(\xi,\eta)+j([Y,X])(x.g)+\bar j(Y,X)\\
&=\omega_x(\xi,\eta)+\langle J(x.g),[Y,X]\rangle+\bar j(Y,X)\\
&=\omega_x(\xi,\eta)+\langle\beta,[Y,X]\rangle+\bar j(Y,X)
\end{aligned}$$

□

29.15. Example of a symplectic reduction: The space of Hermitian matrices. Let $G = SU(n)$ act on the space $H(n)$ of complex Hermitian $(n \times n)$-matrices by conjugation, where the inner product is given by the (always real) trace $\operatorname{Tr}(AB)$. We also consider the linear subspace $\Sigma \subset H(n)$ of all diagonal matrices; they have real entries. For each hermitian matrix A there exists a unitary matrix g such that gAg^{-1} is diagonal with eigenvalues decreasing in size. Thus a fundamental domain (we will call it chamber) for the group action is here given by the quadrant $C \subset \Sigma$ consisting of all real diagonal matrices with eigenvalues $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_n$. There are no further identifications in the chamber, thus $H(n)/SU(n) \cong C$.

We are interested in the following problem: consider a straight line $t \mapsto A + tV$ of Hermitian matrices. We want to describe the corresponding curve of eigenvalues $t \mapsto \lambda(t) = (\lambda_1(t) \geq \cdots \geq \lambda_n(t))$ of the Hermitian matrix $A + tV$ as precisely as possible. In particular, we want to find an ordinary differential equation describing the evolution of eigenvalues. We follow here the development in [Alekseevsky, Losik, Kriegl, Michor, 2001] which was inspired by [Kazhdan, Kostant, Sternberg, 1978].

(1) *Hamiltonian description.* Let us describe the curves of eigenvalues as trajectories of a Hamiltonian system on a reduced phase space. Let $T^*H(n) = H(n) \times H(n)$ be the cotangent bundle where we identified $H(n)$ with its dual by the inner product, so the duality is given by $\langle \alpha, A\rangle = \operatorname{Tr}(A\alpha)$. Then the canonical 1-form is given by $\theta(A, \alpha, A', \alpha') = \operatorname{Tr}(\alpha A')$, the symplectic form is $\omega_{(A,\alpha)}((A', \alpha'), (A'', \alpha'')) = \operatorname{Tr}(A'\alpha'' - A''\alpha')$, and the Hamiltonian function for the straight lines $(A + t\alpha, \alpha)$ on $H(n)$ is $h(A, \alpha) = \frac{1}{2}\operatorname{Tr}(\alpha^2)$. The action $SU(n) \ni g \mapsto (A \mapsto gAg^{-1})$ lifts to the action $SU(n) \ni g \mapsto ((A, \alpha) \mapsto (gAg^{-1}, g\alpha g^{-1}))$ on $T^*H(n)$ with fundamental vector fields $\zeta_X(A, \alpha) = (A, \alpha, [X, A], [X, \alpha])$ for $X \in \mathfrak{su}(n)$, and with generating functions $j_X(A, \alpha) = \theta(\zeta_X(A, \alpha)) = \operatorname{Tr}(\alpha[X, A]) = \operatorname{Tr}([A, \alpha]X)$. Thus the momentum mapping $J : T^*H(n) \to \mathfrak{su}(n)^*$ is given by $\langle X, J(A, \alpha)\rangle = j_X(A, \alpha) = \operatorname{Tr}([A, \alpha]X)$. If we identify $\mathfrak{su}(n)$ with its dual via the inner product $\operatorname{Tr}(XY)$, the momentum mapping is $J(A, \alpha) = [A, \alpha]$. Along the line $t \mapsto A + t\alpha$ the momentum mapping is constant: $J(A + t\alpha, \alpha) = [A, \alpha] = Y \in \mathfrak{su}(n)$. Note that for $X \in \mathfrak{su}(n)$ the evaluation on X of $J(A + t\alpha, \alpha) \in \mathfrak{su}(n)^*$ equals the inner product:

$$\langle X, J(A + t\alpha, \alpha)\rangle = \operatorname{Tr}(\tfrac{d}{dt}(A + t\alpha), \zeta_X(A + t\alpha)),$$

which is obviously constant in t; compare with the general result of Riemannian transformation groups, e.g. [Michor, 1997], 8.1.

According to principles of symplectic reduction (29.12), ?? we have to consider for a regular value Y (and later for an arbitrary value) of the momentum mapping J the submanifold $J^{-1}(Y) \subset T^*H(n)$. The null distribution of $\omega|J^{-1}(Y)$ is integrable (with jumping dimensions) and its leaves (according to the Stefan-Sussmann theory of integrable distributions) are exactly the orbits in $J^{-1}(Y)$ of the isotropy group $SU(n)_Y$ for the coadjoint action. So we have to consider the orbit space $J^{-1}(Y)/SU(n)_Y$. If Y is not a regular value of J, the inverse image $J^{-1}(Y)$ is a subset which is described by polynomial equations since J is polynomial (in fact quadratic), so $J^{-1}(Y)$ is stratified into submanifolds; symplectic reduction works also for this case, see ??

(2) *The case of momentum $Y = 0$ gives billiard of straight lines in C.* If $Y = 0$ then $SU(n)_Y = SU(n)$ and $J^{-1}(0) = \{(A, \alpha) : [A, \alpha] = 0\}$, so A and α commute. If A is regular (i.e. all eigenvalues are distinct), using a uniquely determined transformation $g \in SU(n)$ we move the point A into the open chamber $C^o \subset H(n)$, so $A = \operatorname{diag}(a_1 > a_2 > \cdots > a_n)$ and since α commutes with A so it is also in diagonal form. The symplectic form ω restricts to the canonical symplectic form on $C^o \times \Sigma = C^o \times \Sigma^* = T^*(C^o)$. Thus symplectic reduction gives $(J^{-1}(0) \cap (T^*H(n))_{\text{reg}})/SU(n) = T^*(C^o) \subset T^*H(n)$. By [Sjamaar, Lerman, 1991] we also use symplectic reduction for non-regular A and we get (see in particular [Lerman, Montgomery, Sjamaar, 1993], 3.4) $J^{-1}(0)/SU(n) = T^*C$, the stratified cotangent cone bundle of the chamber C considered asstratified space. Namely, if one root $\varepsilon_i(A) = a_i - a_{i+1}$ vanishes on the diagonal matrix A then the isotropy group $SU(n)_A$ contains a subgroup $SU(2)$ corresponding to these coordinates. Any matrix α with $[A, \alpha] = 0$ contains an arbitrary hermitian submatrix corresponding to the coordinates i and $i + 1$, which may be brougth into diagonal form with the help of this $SU(2)$ so that $\varepsilon_i(\alpha) = \alpha_i - \alpha_{i+1} \geq 0$. Thus the tangent vector α with foot point in a wall is either tangent to the wall (if $\alpha_i = \alpha_{i+1}$) or points into the interior of the chamber C. The Hamiltonian h restricts to $C^o \times \Sigma \ni (A, \alpha) \mapsto \frac{1}{2} \sum_i \alpha_i^2$, so the trajectories of the Hamiltonian system here are again straight lines which are reflected at the walls.

(3) *The case of general momentum Y.* If $Y \neq 0 \in \mathfrak{su}(n)$ and if $SU(n)_Y$ is the isotropy group of Y for the adjoint representation, then it is well known (see references in (1) ???) that we may pass from Y to the coadjoint orbit $\mathcal{O}(Y) = \operatorname{Ad}^*(SU(n))(Y)$ and get

$$J^{-1}(Y)/SU(n)_Y = J^{-1}(\mathcal{O}(Y))/SU(n) = (J^{-1}(Y) \times \mathcal{O}(-Y))/SU(n),$$

where all (stratified) diffeomorphisms are symplectic ones.

(4) *The Calogero Moser system.* As the simplest case we assume that $Y' \in \mathfrak{su}(n)$ is not zero but has maximal isotropy group, and we follow [Kazhdan, Kostant, Sternberg, 1978]. So we assume that Y' has complex rank 1 plus an imaginary multiple of the identity, $Y' = \sqrt{-1}(c\mathbb{I}_n + v \otimes v^*)$ for $0 \neq v = (v^i)$ a column vector in $\mathbb{C}^n$. The coadjoint orbit is then $\mathcal{O}(Y') = \{\sqrt{-1}(c\mathbb{I}_n + w \otimes w^*) : w \in \mathbb{C}^n, |w| = |v|\}$, isomorphic to $S^{2n-1}/S^1 = \mathbb{C}P^n$, of real dimension $2n - 2$. Consider (A', α') with $J(A', \alpha') = Y'$, choose $g \in SU(n)$ such that $A = gA'g^{-1} = \operatorname{diag}(a_1 \geq a_2 \geq \cdots \geq a_n)$, and let $\alpha = g\alpha' g^{-1}$. Then the entry of the commutator is $[A, \alpha]_{ij} = \alpha_{ij}(a_i - a_j)$. So $[A, \alpha] = gY'g^{-1} =: Y = \sqrt{-1}(c\mathbb{I}_n + gv \otimes (gv)^*) = \sqrt{-1}(c\mathbb{I}_n + w \otimes w^*)$ has zero diagonal entries, thus $0 < w^i \bar{w}^i = -c$ and $w^i = \exp(\sqrt{-1}\theta_i)\sqrt{-c}$ for some θ_i But then all off-diagonal entries $Y_{ij} = \sqrt{-1} w^i \bar{w}^j = -\sqrt{-1}\, c \exp(\sqrt{-1}(\theta_i - \theta_j)) \neq 0$, and A has to be regular. We may use the remaining gauge freedom in the isotropy group $SU(n)_A = S(U(1)^n)$ to put $w^i = \exp(\sqrt{-1}\theta)\sqrt{-c}$ where $\theta = \sum \theta_i$. Then $Y_{ij} = -c\sqrt{-1}$ for $i \neq j$.

So the reduced space $(T^*H(n))_Y$ is diffeomorphic to the submanifold of $T^*H(n)$ consisting of all $(A, \alpha) \in H(n) \times H(n)$ where $A = \operatorname{diag}(a_1 > a_2 > \cdots > a_n)$, and where α has arbitrary diagonal entries $\alpha_i := \alpha_{ii}$ and off-diagonal entries $\alpha_{ij} = Y_{ij}/(a_i - a_j) = -c\sqrt{-1}/(a_i - a_j)$. We can thus use $a_1, \dots, a_n, \alpha_1, \dots, \alpha_n$ as coordinates. The invariant symplectic form pulls back to $\omega_{(A,\alpha)}((A'\alpha'), (A'', \alpha'')) = \operatorname{Tr}(A'\alpha'' - A''\alpha') = \sum(a_i'\alpha_i'' - a_i''\alpha_i')$. The invariant Hamiltonian h restricts to the Hamiltonian

$$h(A, \alpha) = \tfrac{1}{2}\operatorname{Tr}(\alpha^2) = \frac{1}{2}\sum_i \alpha_i^2 + \frac{1}{2}\sum_{i\neq j}\frac{c^2}{(a_i - a_j)^2}.$$

This is the famous Hamiltonian function of the Calogero-Moser completely integrable system, see [Moser, 1975], [Olshanetskii, Perelomov, 1977], [Kazhdan, Kostant, Sternberg, 1978], and [Perelomov, 1990], 3.1 and 3.3. The corresponding Hamiltonian vector field and the differential equation for the eigenvalue curve are then

$$H_h = \sum_i \alpha_i \frac{\partial}{\partial a_i} + 2\sum_i \sum_{j:j\neq i}\frac{c^2}{(a_i - a_j)^3}\frac{\partial}{\partial \alpha_i},$$

$$\ddot a_i = 2\sum_{j\neq i}\frac{c^2}{(a_i - a_j)^3},$$

$$(a_i - a_j)^{\cdot\cdot} = 2\sum_{k:k\neq i}\frac{c^2}{(a_i - a_k)^3} - 2\sum_{k:k\neq j}\frac{c^2}{(a_j - a_k)^3}.$$

Note that the curve of eigenvalues avoids the walls of the Weyl chamber C.

(5) *Degenerate cases of non-zero momenta of minimal rank.* Let us discuss now the case of non-regular diagonal A. Namely, if one root, say $\varepsilon_{12}(A) = a_1 - a_2$ vanishes on the diagonal matrix A then the isotropy group $SU(n)_A$ contains a subgroup $SU(2)$ corresponding to these coordinates. Consider α with $[A, \alpha] = Y$; then $0 = \alpha_{12}(a_1 - a_2) = Y_{12}$. Thus α contains an arbitrary hermitian submatrix corresponding to the first two coordinates, which may be brougth into diagonal form with the help of this $SU(2) \subset SU(n)_A$ so that $\varepsilon_{12}(\alpha) = \alpha_1 - \alpha_2 \geq 0$. Thus the tangent vector α with foot point A in a wall is either tangent to the wall (if $\alpha_1 = \alpha_2$) or points into the interior of the chamber C (if $\alpha_1 > \alpha_2$). Note that then $Y_{11} = Y_{22} = Y_{12} = 0$.

Let us now assume that the momentum Y is of the form $Y = \sqrt{-1}(c\mathbb{I}_{n-2} + v \otimes v^*)$ for some vector $0 \neq v \in \mathbb{C}^{n-2}$. We can repeat the analysis of (4) in the subspace $\mathbb{C}^{n-2}$, and get for the Hamiltonian (where $I_{1,2} = \{(i,j) : i \neq j\} \setminus \{(1,2),(2,1)\}$)

$$h(A, \alpha) = \tfrac{1}{2}\operatorname{Tr}(\alpha^2) = \frac{1}{2}\sum_{i=1}^n \alpha_i^2 + \frac{1}{2}\sum_{(i,j)\in I_{1,2}}\frac{c^2}{(a_i - a_j)^2},$$

$$H_h = \sum_{i=1}^n \alpha_i \frac{\partial}{\partial a_i} + 2\sum_{(i,j)\in I_{1,2}}\frac{c^2}{(a_i - a_j)^3}\frac{\partial}{\partial \alpha_i},$$

$$\ddot a_i = 2\sum_{\{j:(i,j)\in I_{1,2}\}}\frac{c^2}{(a_i - a_j)^3}.$$

(6) *The case of general momentum Y and regular A.* Starting again with some regular A' consider (A',α') with $J(A',\alpha')=Y'$, choose $g\in SU(n)$ such that $A=gA'g^{-1}=\operatorname{diag}(a_1>a_2>\dots>a_n)$, and let $\alpha=g\alpha'g^{-1}$ and $Y=gY'g^{-1}=[A,\alpha]$. Then the entry of the commutator is $Y_{ij}=[A,\alpha]_{ij}=\alpha_{ij}(a_i-a_j)$ thus $Y_{ii}=0$. We may pass to the coordinates a_i and $\alpha_i:=\alpha_{ii}$ for $1\le i\le n$ on the one hand, corresponding to $J^{-1}(Y)$ in (3), and Y_{ij} for $i\ne j$ on the other hand, corresponding to $\mathcal{O}(-Y)$ in (3), with the linear relation $Y_{ji}=-\overline{Y_{ij}}$ and with $n-1$ non-zero entries $Y_{ij}>0$ with $i>j$ (chosen in lexicographic order) by applying the remaining isotropy group $SU(n)_A=S(U(1)^n)=\{\operatorname{diag}(e^{\sqrt{-1}\theta_1},\dots,e^{\sqrt{-1}\theta_n}):\sum\theta_i\in 2\pi\mathbb{Z}\}$. We may use this canonical form as section

$$(J^{-1}(Y)\times\mathcal{O}(-Y))/SU(n)\to J^{-1}(Y)\times\mathcal{O}(-Y)\subset TH(n)\times\mathfrak{su}(n)$$

to pull back the symplectic or Poisson structures and the Hamiltonian function

$$\begin{aligned}
h(A,\alpha)&=\tfrac12\operatorname{Tr}(\alpha^2)=\frac12\sum_i\alpha_i^2-\frac12\sum_{i\ne j}\frac{Y_{ij}Y_{ji}}{(a_i-a_j)^2},\\
dh&=\sum_i\alpha_i\,d\alpha_i+\sum_{i\ne j}\frac{Y_{ij}Y_{ji}}{(a_i-a_j)^3}(da_i-da_j)-\frac12\sum_{i\ne j}\frac{dY_{ij}.Y_{ji}+Y_{ij}.dY_{ji}}{(a_i-a_j)^2},\\
&=\sum_i\alpha_i\,d\alpha_i+2\sum_{i\ne j}\frac{Y_{ij}Y_{ji}}{(a_i-a_j)^3}da_i-\sum_{i\ne j}\frac{Y_{ji}}{(a_i-a_j)^2}dY_{ij}. \qquad (7)
\end{aligned}$$

The invariant symplectic form on $TH(n)$ pulls back to $\omega_{(A,\alpha)}((A'\alpha'),(A'',\alpha''))=\operatorname{Tr}(A'\alpha''-A''\alpha')=\sum(a_i'\alpha_i''-a_i''\alpha_i')$ thus to $\sum_i da_i\wedge d\alpha_i$. The Poisson structure on $\mathfrak{su}(n)$ is given by

$$\begin{aligned}
\Lambda_Y(U,V)&=\operatorname{Tr}(Y[U,V])=\sum_{m,n,p}(Y_{mn}U_{np}V_{pm}-Y_{mn}V_{np}U_{pm})\\
\Lambda_Y&=\sum_{i\ne j,k\ne l}\Lambda_Y(dY_{ij},dY_{kl})\partial_{Y_{ij}}\otimes\partial_{Y_{kl}}\\
&=\sum_{i\ne j,k\ne l}\sum_{m,n}(Y_{mn}\delta_{ni}\delta_{jk}\delta_{lm}-Y_{mn}\delta_{nk}\delta_{li}\delta_{jm})\partial_{Y_{ij}}\otimes\partial_{Y_{kl}}\\
&=\sum_{i\ne j,k\ne l}(Y_{li}\delta_{jk}-Y_{jk}\delta_{li})\partial_{Y_{ij}}\otimes\partial_{Y_{kl}}
\end{aligned}$$

Since this Poisson 2-vector field is tangent to the orbit $\mathcal{O}(-Y)$ and is $SU(n)$-invariant, we can push it down to the orbit space. There it maps dY_{ij} to (remember that $Y_{ii}=0$)

$$\Lambda_{-Y}(dY_{ij})=-\sum_{k\ne l}(Y_{li}\delta_{jk}-Y_{jk}\delta_{li})\partial_{Y_{kl}}=-\sum_k(Y_{ki}\partial_{Y_{jk}}-Y_{jk}\partial_{Y_{ki}}).$$

So by (3) the Hamiltonian vector field is

$$\begin{aligned}
H_h&=\sum_i\alpha_i\,\partial_{a_i}-2\sum_{i\ne j}\frac{Y_{ij}Y_{ji}}{(a_i-a_j)^3}\,\partial_{\alpha_i}+\sum_{i\ne j}\frac{Y_{ji}}{(a_i-a_j)^2}\sum_k(Y_{ki}\,\partial_{Y_{jk}}-Y_{jk}\,\partial_{Y_{ki}})\\
&=\sum_i\alpha_i\,\partial_{a_i}-2\sum_{i\ne j}\frac{Y_{ij}Y_{ji}}{(a_i-a_j)^3}\,\partial_{\alpha_i}-\sum_{i,j,k}\left(\frac{Y_{ji}Y_{jk}}{(a_i-a_j)^2}-\frac{Y_{ij}Y_{kj}}{(a_j-a_k)^2}\right)\partial_{Y_{ki}}
\end{aligned}$$

The differential equation thus becomes (remember that $Y_{jj}=0$):

$$\begin{aligned}
\dot a_i &= \alpha_i\\
\dot\alpha_i &= -2\sum_j \frac{Y_{ij}Y_{ji}}{(a_i-a_j)^3} = 2\sum_j \frac{|Y_{ij}|^2}{(a_i-a_j)^3}\\
\dot Y_{ki} &= -\sum_j\left(\frac{Y_{ji}Y_{jk}}{(a_i-a_j)^2}-\frac{Y_{ij}Y_{kj}}{(a_j-a_k)^2}\right).
\end{aligned}$$

Consider the Matrix Z with $Z_{ii}=0$ and $Z_{ij}=Y_{ij}/(a_i-a_j)^2$. Then the differential equations become:

$$\ddot a_i = 2\sum_j \frac{|Y_{ij}|^2}{(a_i-a_j)^3},\qquad \dot Y=[Y^*,Z].$$

This is the Calogero-Moser integrable system with spin, see [Babelon, Talon, 1997] and [Babelon, Talon, 1999].

(8) *The case of general momentum Y and singular A.* Let us consider the situation of (6), when A is not regular. Let us assume again that one root, say $\varepsilon_{12}(A)=a_1-a_2$ vanishes on the diagonal matrix A. Consider α with $[A,\alpha]=Y$. From $Y_{ij}=[A,\alpha]_{ij}=\alpha_{ij}(a_i-a_j)$ we conclude that $Y_{ii}=0$ for all i and also $Y_{12}=0$. The isotropy group $SU(n)_A$ contains a subgroup $SU(2)$ corresponding to the first two coordinates and we may use this to move α into the form that $\alpha_{12}=0$ and $\varepsilon_{12}(\alpha)\geq 0$. Thus the tangent vector α with foot point A in the wall $\{\varepsilon_{12}=0\}$ is either tangent to the wall when $\alpha_1=\alpha_2$ or points into the interior of the chamber C when $\alpha_1>\alpha_2$. We can then use the same analysis as in (6) where we use now that $Y_{12}=0$.

In the general case, when some roots vanish, we get for the Hamiltonian function, vector field, and differential equation:

$$\begin{aligned}
h(A,\alpha) &= \tfrac12\operatorname{Tr}(\alpha^2)=\frac12\sum_i\alpha_i^2+\frac12\sum_{\{(i,j):a_i(0)\neq a_j(0)\}}\frac{|Y_{ij}|^2}{(a_i-a_j)^2},\\
H_h &= \sum_i\alpha_i\partial_{a_i}+2\sum_{(i,j):a_j(0)\neq a_i(0)}\frac{|Y_{ij}|^2}{(a_i-a_j)^3}\,\partial_{\alpha_i}+\\
&\quad-\sum_{(i,j):a_j(0)\neq a_i(0)}\sum_k\frac{Y_{ji}Y_{jk}}{(a_i-a_j)^2}\partial_{Y_{ki}}+\sum_{(j,k):a_j(0)\neq a_k(0)}\sum_i\frac{Y_{ij}Y_{kj}}{(a_j-a_k)^2}\partial_{Y_{ki}}\\
\ddot a_i &= 2\sum_{j:a_j(0)\neq a_i(0)}\frac{|Y_{ij}|^2}{(a_i-a_j)^3},\qquad \dot Y=[Y^*,Z]
\end{aligned}$$

where we use the same notation as above. It would be very interesting to investigate the reflection behavior of this curve at the walls.

29.16. Example: symmetric matrices. We finally treat the action of $SO(n)=SO(n,\mathbb{R})$ on the space $S(n)$ of symmetric matrices by conjugation. Following the method of (29.15.6) and (29.15.7) we get the following result. Let $t \mapsto A' + t\alpha'$ be a straight line in $S(n)$. Then the ordered set of eigenvalues $a_1(t), \dots, a_n(t)$ of $A' + t\alpha'$ is part of the integral curve of the following vector field:

$$H_h = \sum_i \alpha_i \partial_{a_i} + 2 \sum_{(i,j):a_j(0)\neq a_i(0)} \frac{Y_{ij}^2}{(a_i - a_j)^3} \partial_{\alpha_i} +$$
$$+ \sum_{(i,j):a_i(0)\neq a_j(0)} \sum_k \frac{Y_{ij}Y_{jk}}{(a_i - a_j)^2} \partial_{Y_{ki}} - \sum_{(j,k):a_j(0)\neq a_k(0)} \sum_i \frac{Y_{ij}Y_{jk}}{(a_j - a_k)^2} \partial_{Y_{ki}}$$
$$\ddot a_i = 2 \sum_{(i,j):a_j(0)\neq a_i(0)} \frac{Y_{ij}^2}{(a_i - a_j)^3}, \qquad \dot Y = [Y, Z], \qquad \text{where } Z_{ij} = -\frac{Y_{ij}}{(a_i - a_j)^2},$$

where we also note that $Y_{ij} = Z_{ij} = 0$ whenever $a_i(0) = a_j(0)$.

30. Lie Poisson groups

30.1. The Schouten Nijenhuis bracket on Lie groups. Let G be a Lie group with Lie algebra $\mathfrak{g}$. For $f \in C^\infty(G, \mathfrak{g})$ we get a smooth vector field $L_f \in \mathfrak{X}(G)$ by $L_f(x) := T_e(\mu_x).f(x)$. This describes an isomorphism $L : C^\infty(G, \mathfrak{g}) \to \mathfrak{X}(G)$. If $h \in C^\infty(G, V)$ then we have $L_f h(x) = dh(L_f(x)) = dh.T_e(\mu_x).f(x) = \delta h(x).f(x)$, for which we write shortly $L_f h = \delta h.f$.

For $g \in C^\infty(G, \bigwedge^k \mathfrak{g}^*)$ we get a k-form $L_g \in \Omega^k(G)$ by the prescription $(L_g)_x = g(x) \circ \bigwedge^k T_x(\mu_{x^{-1}})$. This gives an isomorphism $L : C^\infty(G, \bigwedge \mathfrak{g}) \to \Omega(G)$.

Result. [??]

(1) *For $f, g \in C^\infty(G, \mathfrak{g})$ we have*

$$[L_f, L_g]_{\mathfrak{X}(G)} = L_{K(f,g)},$$

where $K(f,g)(x) := [f(x), g(x)]_\mathfrak{g} + \delta g(x).f(x) - \delta f(x).g(x)$, or shorter $K(f,g) = [f,g]_\mathfrak{g} + \delta g.f - \delta f.g$.

(2) *For $g \in C^\infty(G, \bigwedge^k \mathfrak{g}^*)$ and $f_i \in C^\infty(G, \mathfrak{g})$ we have $L_g(L_{f_1}, \dots, L_{f_k}) = g.(f_1, \dots, f_k)$.*

(3) *For $g \in C^\infty(G, \bigwedge^k \mathfrak{g}^*)$ the exterior derivative is given by*

$$d(L_g) = L_{\delta^\wedge g + \partial^\mathfrak{g} \circ g},$$

where $\delta^\wedge g : G \to \bigwedge^{k+1} \mathfrak{g}^*$ is given by

$$\delta^\wedge g(x)(X_0, \dots, X_k) = \sum_{i=0}^k (-1)^i \delta g(x)(X_i)(X_0, \dots, \widehat{X_i}, \dots, X_k),$$

and where $\partial^\mathfrak{g}$ is the Chevalley differential on $\bigwedge \mathfrak{g}^*$.

(4) *For $g \in C^\infty(G, \bigwedge^k \mathfrak{g}^*)$ and $f \in C^\infty(G, \mathfrak{g})$ the Lie derivative is given by*

$$\mathcal{L}_{L_f} L_g = L_{\mathcal{L}_f^{\mathfrak{g}} \circ g + \mathcal{L}_f^\delta g},$$

where

$$\begin{aligned}(\mathcal{L}_f^{\mathfrak{g}} g)(x)(X_1, \dots, X_k) &= \sum_i (-1)^i g(x)([f(x), X_i], X_1, \dots, \widehat{X_i}, \dots, X_k),\\ (\mathcal{L}_f^\delta g)(x)(X_1, \dots, X_k) &= \delta g(x)(f(x))(X_1, \dots, X_k) +\\ &\quad + \sum_i (-1)^i g(x)(\delta f(x)(X_i), X_1, \dots, \widehat{X_i}, \dots, X_k).\end{aligned}$$

For a Lie group G we have an isomorphism $L : C^\infty(G, \bigwedge \mathfrak{g}) \to \Gamma(\bigwedge TG)$ which is given by $L(u)_x = \bigwedge T(\mu_x).u(x)$, via left trivialization. For $u \in C^\infty(G, \bigwedge^u \mathfrak{g})$ we have $\delta u : G \to L(\mathfrak{g}, \bigwedge^u \mathfrak{g}) = \mathfrak{g}^* \otimes \bigwedge^u \mathfrak{g}$, and with respect to the one component in $\mathfrak{g}^*$ we can consider the insertion operator $\bar\imath(\delta u(x)) : \bigwedge^k \mathfrak{g} \to \bigwedge^{k+u} \mathfrak{g}$. In more detail: if $u = f.U$ for $f \in C^\infty(G, \mathbb{R})$ and $U \in \bigwedge^u \mathfrak{g}$, then we put $\bar\imath(\delta f(x).U)V = U \wedge \bar\imath(\delta f(x))(V)$.

The algebraic Schouten-Nijenhuis bracket $[\ \ ,\ \ ]^{\mathfrak{g}} : \bigwedge^p \mathfrak{g} \times \bigwedge^q \mathfrak{g} \to \bigwedge^{p+q-1} \mathfrak{g}$ for the Lie algebra $\mathfrak{g}$ is given by formula (1), applied to this purely algebraic situation.

Proposition. *For $u \in C^\infty(G, \bigwedge^u \mathfrak{g})$ and $v \in C^\infty(G, \bigwedge^v \mathfrak{g})$ the Schouten-Nijenhuis bracket is given by*

$$[L(u), L(v)] = L([u, v]^{\mathfrak{g}} - \bar\imath(\delta u)(v) + (-1)^{(u-1)(v-1)} \bar\imath(\delta v)(u)). \tag{2}$$

Proof. This follows from formula (1) applied to

$$[L(f.X_1 \wedge \dots \wedge X_p), L(g.Y_1 \wedge \dots \wedge Y_q)],$$

where $f, g \in C^\infty(G, \mathbb{R})$ and $X_i, Y_j \in \mathfrak{g}$, and then by applying (3.3).(1). $\square$

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List of Symbols

(a, b) open interval or pair
$[a, b]$ closed interval
$\alpha : J^r(M, N) \to M$ the source mapping of jets
$\beta : J^r(M, N) \to N$ the target mapping of jets
$\Gamma(E)$, also $\Gamma(E \to M)$ the space of smooth sections of a fiber bundle
$\mathbb{C}$ field of complex numbers
$C : TM \times_M TM \to TTM$ connection or horizontal lift
$C^\infty(M, \mathbf{R})$ the space of smooth functions on M
d usually the exterior derivative
(E, p, M, S), also simply E usually a fiber bundle with total space E, base M, and standard fiber S
Fl^X_t, also $\mathrm{Fl}(t, X)$ the flow of a vector field X
$\mathbb{H}$ skew field of quaternions
$\mathbb{I}_k$, short for the $k \times k$-identity matrix $Id_{\mathbb{R}^k}$.

$K : TTM \to M$ the connector of a covariant derivative
$\mathcal{L}_X$ Lie derivative
G usually a general Lie group with multiplication $\mu : G \times G \to G$, we use $gh = \mu(g,h) = \mu_g(h) = \mu^h(g)$
$J^r(E)$ the bundle of r-jets of sections of a fiber bundle $E \to M$
$J^r(M,N)$ the bundle of r-jets of smooth functions from M to N
$j^r f(x)$, also $j^r_x f$ the r-jet of a mapping or function f
$\kappa_M : TTM \to TTM$ the canonical flip mapping
$\ell : G \times S \to S$ usually a left action
M usually a manifold
$\mathbb{N}$ natural numbers > 0
$\mathbb{N}_0$ nonnegative integers
∇_X, spoken 'Nabla', covariant derivative
$p : P \to M$ or (P, p, M, G) a principal bundle with structure group G
$\pi^r_l : J^r(M,N) \to J^l(M,N)$ projections of jets
$\mathbb{R}$ field of real numbers
$r : P \times G \to P$ usually a right action, in particular the principal right action of a principal bundle
TM the tangent bundle of a manifold M with projection $\pi_M : TM \to M$
$\mathbb{Z}$ integers

Index

Not yet final, the pagenumbers match.

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