

MATH 518 Notes

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Definition 1.1. Let M be a topological space. An *atlas* on M is a collection $\{\varphi_\alpha : U_\alpha \rightarrow W_\alpha\}_{\alpha \in A}$ of homeomorphisms called *coordinate charts*, so that

1. $\{U_\alpha\}_{\alpha \in A}$ is an open cover of M ,
2. for all $\alpha \in A$, W_α is an open subset of some \mathbb{R}^{n_α} ,
3. for all $\alpha, \beta \in A$, the induced map $\varphi_\beta \circ \varphi_\alpha^{-1}|_{U_\alpha \cap U_\beta}$ is C^∞ , i.e., smooth.

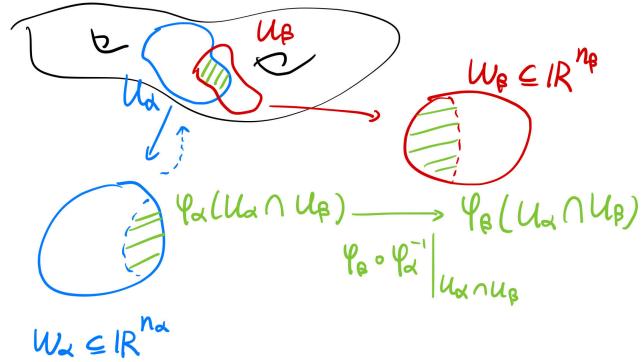


Figure 1: Atlas and Coordinate Chart

Example 1.2. Let $M = \mathbb{R}^n$ be equipped with standard topology, and let $A = \{*\}$, so $U_* = \mathbb{R}^n$ is the open cover of itself. Now the identity map

$$\begin{aligned}\varphi_* : U_* &\rightarrow \mathbb{R}^n \\ u &\mapsto u\end{aligned}$$

is an atlas on \mathbb{R}^n .

Example 1.3. Let $M = S^1 = \{(x, y) \in \mathbb{R}^2 \mid x^2 + y^2 = 1\}$ be equipped with subspace topology. Let $U_\alpha = S^1 \setminus \{(1, 0)\}$ and $U_\beta = S^1 \setminus \{(-1, 0)\}$, and let $A = \{\alpha, \beta\}$. Let $W_\alpha = (0, 2\pi)$ and $W_\beta = (-\pi, \pi)$. We define $\varphi_\alpha^{-1}(\theta) = (\cos(\theta), \sin(\theta))$ and $\varphi_\beta^{-1}(\theta) = (\cos(\theta), \sin(\theta))$, then

$$(\varphi_\beta \circ \varphi_\alpha^{-1})(\theta) = \begin{cases} \theta, & 0 < \theta < \pi \\ \theta - 2\pi, & \pi < \theta < 2\pi \end{cases}$$

is smooth.

Example 1.4. Let X be a topological space with discrete topology, and let $A = X$, then $\{\varphi_x : \{x\} \rightarrow \mathbb{R}^0\}_{x \in X}$ gives an atlas.

Example 1.5. Let V be a finite-dimensional real vector space of dimension n . Pick a basis $\{v_1, \dots, v_n\}$ of V , then there is a linear bijection φ with inverse

$$\begin{aligned}\varphi^{-1} : \mathbb{R}^n &\rightarrow V \\ (x_1, \dots, x_n) &\mapsto \sum_{i=1}^n x_i v_i.\end{aligned}$$

The topology on V needs to make φ^{-1} a homeomorphism, and the obvious choice is just the collection of preimages, namely

$$\mathcal{T} = \{\varphi^{-1}(W) \mid W \subseteq \mathbb{R}^n \text{ open}\},$$

then $\varphi : V \rightarrow \mathbb{R}^n$ becomes an atlas.

Definition 1.6. Two atlases $\{\varphi_\alpha : U_\alpha \rightarrow W_\alpha\}_{\alpha \in A}$ and $\{\psi_\beta : V_\beta \rightarrow O_\beta\}_{\beta \in B}$ on a topological space M are *equivalent* if for all $\alpha \in A$ and $\beta \in B$,

$$\psi_\beta \circ \varphi_\alpha^{-1} : \varphi_\alpha(U_\alpha \cap V_\beta) \subseteq \mathbb{R}^{n_\alpha} \rightarrow \psi_\beta(U_\alpha \cap V_\beta) \subseteq \mathbb{R}^{n_\beta}$$

is always C^∞ , with C^∞ -inverses. Such continuous maps are called *diffeomorphisms*. Alternatively, the two atlases are equivalent if their union $\{\varphi_\alpha\}_{\alpha \in A} \cup \{\psi_\beta\}_{\beta \in B}$ is always an atlas.

Exercise 1.7. Equivalence of atlases is an equivalence condition.

Definition 1.8. A (smooth) *manifold* is a topological space together with an equivalence class of atlases.

Convention. All manifolds are assumed to be smooth of C^∞ , but not necessarily *Hausdorff* and/or *second countable*.

Example 1.9. Continuing from [Example 1.5](#), now suppose $\{w_1, \dots, w_n\}$ gives another basis of V , with

$$\begin{aligned}\psi^{-1} : \mathbb{R}^n &\rightarrow V \\ (y_1, \dots, y_n) &\mapsto \sum_{i=1}^n y_i w_i.\end{aligned}$$

This gives a change-of-basis matrix, so it is automatically C^∞ as a multiplication of invertible matrices. Therefore, the topology here does not depend on the chosen basis.

Recall. A topological space X is *Hausdorff* if for all distinct points $x, y \in X$, there exists open neighborhoods $U \ni x$ and $V \ni y$ such that $U \cap V = \emptyset$.

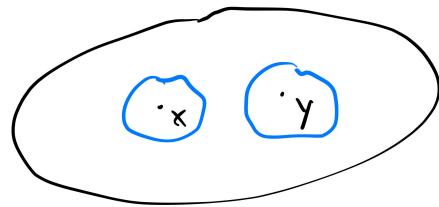


Figure 2: Hausdorff Condition

Convention. Via our definition ([Definition 1.8](#)), not all manifolds are Hausdorff.

Example 1.10. Let $Y = \mathbb{R} \times \{0, 1\}$, i.e., a space with two parallel lines, with a fixed topology. Define \sim to be the smallest equivalence relation on Y such that $(x, 0) \sim (x, 1)$ for $x \neq 0$, and define $X = Y / \sim$. X is called the *line with two origins*, and it is second countable but not Hausdorff.

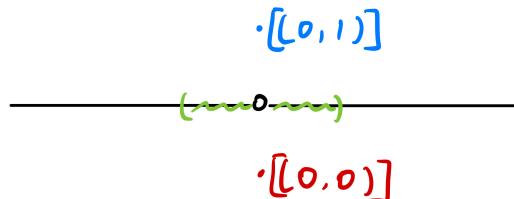


Figure 3: Line with Two Origins

Example 1.11. Take charts

$$\begin{aligned} \{\varphi : M = \mathbb{R} \rightarrow \mathbb{R}\} \\ x \mapsto x \end{aligned}$$

and

$$\begin{aligned} \{\psi : M = \mathbb{R} \rightarrow \mathbb{R}\} \\ x \mapsto x^3 \end{aligned}$$

on $M = \mathbb{R}$, then

$$\begin{aligned} \varphi \circ \psi^{-1} : \mathbb{R} \rightarrow \mathbb{R} \\ x \mapsto x^{\frac{1}{3}} \end{aligned}$$

is not C^∞ , so φ and ψ are two different charts, hence give two different manifolds.

Definition 1.12. A map $F : M \rightarrow N$ between two manifolds is *smooth* if

1. F is continuous, and
2. for all charts $\varphi : U \rightarrow \mathbb{R}^m$ on M and charts $\psi : V \rightarrow \mathbb{R}^n$ on N , $\psi^{-1} \circ F \circ \varphi|_{\varphi(U \cap F^{-1}(V))}$ is C^∞ .

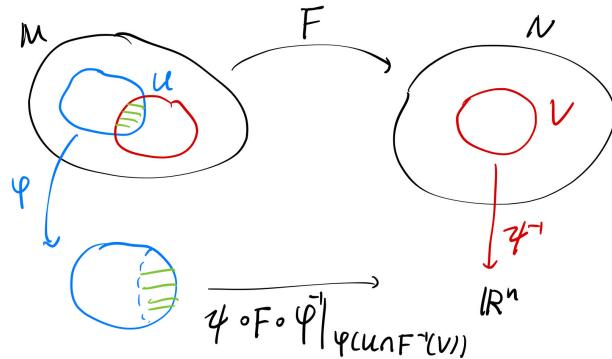


Figure 4: Smooth Map between Manifolds

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Exercise 2.1. 1. $\text{id} : M \rightarrow M$ is smooth.

2. If $f : M \rightarrow N$ and $g : N \rightarrow Q$ are smooth maps between manifolds, then so is $gf : M \rightarrow Q$.

Punchline. The manifolds and the smooth maps between manifolds form a category.

Recall. A smooth map $f : M \rightarrow N$ is called a *diffeomorphism*, as seen in [Definition 1.6](#), if it has a smooth inverse. This is the notion of an isomorphism in the category of manifolds.

Warning. 1. Following [Example 1.11](#),

$$\begin{aligned} f : \mathbb{R} &\rightarrow \mathbb{R} \\ x &\mapsto x^3 \end{aligned}$$

has an inverse

$$\begin{aligned} f^{-1} : \mathbb{R} &\rightarrow \mathbb{R} \\ x &\mapsto x^{\frac{1}{3}}, \end{aligned}$$

but f^{-1} is not differentiable at $x = 0$. Hence, f is not a diffeomorphism.

2. Take \mathbb{R} with discrete topology, then all singletons are open sets, then the map

$$\begin{aligned} f : \mathbb{R}_{\text{dis}} &\rightarrow \mathbb{R}_{\text{std}} \\ x &\mapsto x \end{aligned}$$

is a smooth bijection, but f^{-1} is not continuous.

Example 2.2. Consider $M = (\mathbb{R}, \{\psi = \text{id} : \mathbb{R} \rightarrow \mathbb{R}\})$ and $N = (\mathbb{R}, \{\psi : \mathbb{R} \rightarrow \mathbb{R}, x \mapsto x^3\})$ as two manifolds on \mathbb{R} with standard topology. To see that they are equivalent, consider the homeomorphism

$$\begin{aligned} f : \mathbb{R} &\rightarrow \mathbb{R} \\ x &\mapsto x^{\frac{1}{3}}, \end{aligned}$$

then $(\psi \circ f \circ \varphi^{-1})(x) = \psi(f(x)) = (x^{\frac{1}{3}})^3 = x$, so f is smooth, and $(\psi \circ f \circ \varphi^{-1})^{-1} = \varphi \circ f^{-1} \circ \psi^{-1} = \text{id}$, therefore f^{-1} is also smooth. Hence, f is a diffeomorphism.

We will now consider the real projective space $\mathbb{R}P^{n-1}$ and the quotient map $\pi : \mathbb{R}^n \setminus \{0\} \rightarrow \mathbb{R}P^{n-1}$.

Definition 2.3. Define a binary relation on $\mathbb{R}^n \setminus \{0\}$ by $v_1 \sim v_2$ if and only if there exists $\lambda \neq 0$ such that $v_1 = \lambda v_2$. This is an equivalence relation, and we identify the equivalence class $[v]$ of $v \in \mathbb{R}^n \setminus \{0\}$ as a line $\mathbb{R}v = \text{span}_{\mathbb{R}}\{v\}$ through v . Then we define the *real projective space* $\mathbb{R}P^{n-1} = (\mathbb{R}^n \setminus \{0\}) / \sim$.

The natural topology on $\mathbb{R}P^{n-1}$ is the quotient topology, where $\pi : \mathbb{R}^n \setminus \{0\} \rightarrow \mathbb{R}P^{n-1}$ is surjective and continuous, so we define $U \subseteq \mathbb{R}P^{n-1}$ to be open if and only if $\pi^{-1}(U)$ is open in $\mathbb{R}^n \setminus \{0\}$.

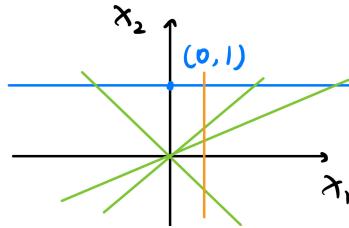


Figure 5: Stereographical Projection

Claim 2.4. $\mathbb{R}P^{n-1}$ is a manifold.

Proof. Define

$$\begin{aligned} \varphi_i : U_i &\rightarrow \mathbb{R}^{n-1} \\ [v_1, \dots, v_n] &\mapsto \left(\frac{v_1}{v_i}, \dots, \frac{v_{i-1}}{v_i}, \frac{v_{i+1}}{v_i}, \dots, \frac{v_n}{v_i} \right), \end{aligned}$$

then

$$\begin{aligned}\varphi_i^{-1} : \mathbb{R}^{n-1} &\mapsto U_i \\ (x_1, \dots, x_{n-1}) &\mapsto [(x_1, \dots, x_{i-1}, 1, x_i, \dots, x_{n-1})],\end{aligned}$$

therefore

$$\begin{aligned}\varphi_j \circ \varphi_i^{-1} : \varphi_i(U_i \cap U_j) &\rightarrow \varphi_j(U_i \cap U_j) \\ (x_1, \dots, x_{n-1}) &\mapsto \varphi_j([(x_1, \dots, x_{i-1}, 1, x_i, \dots, x_{n-1})]) \\ &= \begin{cases} \left(\frac{x_1}{x_j}, \dots, \frac{x_{j-1}}{x_j}, \frac{x_{j+1}}{x_j}, \dots, \frac{x_{n-1}}{x_j} \right), & j < i \\ (x_1, \dots, x_{n-1}), & j = i \\ \left(\frac{x_1}{x_{j-1}}, \dots, \frac{1}{x_{j-1}}, \dots, \frac{x_{j-2}}{x_{j-1}}, \frac{x_j}{x_{j-1}}, \dots, \frac{x_{n-1}}{x_{j-1}} \right), & j > i \end{cases}\end{aligned}$$

Therefore, this is C^∞ as a rational map on $\varphi_i(U_i \cap U_j)$, and so this gives an atlas, hence $\mathbb{R}P^{n-1}$ is a manifold. \square

Claim 2.5. $\pi : \mathbb{R}^n \setminus \{0\} \rightarrow \mathbb{R}P^{n-1}$ is smooth.

Proof. Note that

$$\begin{aligned}\psi : \mathbb{R}^n \setminus \{0\} &\hookrightarrow \mathbb{R}^n \\ x &\mapsto x\end{aligned}$$

is an atlas on $\mathbb{R}^n \setminus \{0\}$, and

$$\begin{aligned}\varphi_i \circ \pi \circ \varphi_i^{-1} : \mathbb{R}^n \setminus \{0\} &\rightarrow \mathbb{R}^{n-1} \\ (v_1, \dots, v_n) &\mapsto \varphi_i([(v_1, \dots, v_n)]) \\ &= \left(\frac{v_1}{v_i}, \dots, \frac{v_{i-1}}{v_i}, \frac{v_{i+1}}{v_i}, \dots, \frac{v_n}{v_i} \right).\end{aligned}$$

This is C^∞ on $\pi^{-1}(U_i) = \{(v_1, \dots, v_n) \mid v_i \neq 0\}$, so π is smooth. \square

Definition 2.6. A *smooth function* on a manifold M is a function $f : M \rightarrow \mathbb{R}$ so that for any coordinate chart $\varphi : U \rightarrow \varphi(U)$ open in \mathbb{R}^m , the function $f \circ \varphi^{-1} : \varphi(U) \rightarrow \mathbb{R}$ is smooth.

Remark 2.7. $f : M \rightarrow \mathbb{R}$ is smooth if and only if $f : M \rightarrow (\mathbb{R}, \{\text{id} : \mathbb{R} \rightarrow \mathbb{R}\})$, usually called the *standard manifold structure on \mathbb{R}* , is smooth.

Notation. We denote $C^\infty(M)$ to be the set of all smooth functions $f : M \rightarrow \mathbb{R}$.

Remark 2.8. $C^\infty(M)$ is a smooth \mathbb{R} -vector space, that is, for all $\lambda, \mu \in \mathbb{R}$ and $f, g \in C^\infty(M)$,

- $(\lambda f + \mu g)(x) = \lambda f(x) + \mu g(x)$ for all $x \in M$,
- $(f \cdot g)(x) = f(x)g(x)$ for all $x \in M$.

Therefore, $C^\infty(M)$ becomes a (commutative, associative) \mathbb{R} -algebra.

Fact. Connecting manifolds have the notion of dimension. That is, the dimensions of open subsets induced by coordinate charts are the same.

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Definition 3.1. Let M be a manifold, then for every point $q \in M$, there exists a well-defined non-negative integer $\dim_M(q)$, so that for any coordinate chart $\varphi : U \rightarrow \mathbb{R}^m$ for $U \ni q$, we have $\dim_M(q) = m$ for some non-negative integer m that only depend on M . Consequently, $\dim_M : M \rightarrow \mathbb{Z}^{\geq 0}$ is a locally constant function. This integer m is called the *dimension* of M .

Proof. Indeed, say $\psi : V \rightarrow \mathbb{R}^n$ is another chart with $U \cap V \ni q$, then $\psi \circ \varphi^{-1}|_{\varphi(U \cap V)} : \varphi(U \cap V) \subseteq \mathbb{R}^m \rightarrow \psi(U \cap V) \subseteq \mathbb{R}^n$ is a diffeomorphism, therefore the Jacobian $D(\psi \circ \varphi^{-1})(\varphi(a)) : \mathbb{R}^m \rightarrow \mathbb{R}^n$ is a linear isomorphism, thus $m = n$. \square

Definition 3.2. Suppose $(M, \{\varphi_\alpha : U_\alpha \rightarrow \mathbb{R}^m\}_{\alpha \in A})$ and $(N, \{\psi_\beta : V_\beta \rightarrow \mathbb{R}^n\}_{\beta \in B})$ are two manifolds. One can give a manifold structure to the product set $M \times N$, called the *product manifold*, as follows:

- give $M \times N$ the product topology,
- let $\{\varphi_\alpha \times \psi_\beta : U_\alpha \times V_\beta \rightarrow \mathbb{R}^m \times \mathbb{R}^n\}_{(\alpha, \beta) \in A \times B}$ to be the atlas on $M \times N$. This is well-defined since the transition maps of $\alpha, \alpha' \in A$ and $\beta, \beta' \in B$ are over $(U_\alpha \times V_\beta) \cap U_{\alpha'} \times V_{\beta'} = (U_\alpha \cap U_{\alpha'}) \times (V_\beta \cap V_{\beta'})$ with $(\varphi_{\alpha'} \times \psi_{\beta'}) \circ (\varphi_\alpha \times \psi_\beta)^{-1} = (\varphi_{\alpha'} \circ \varphi_\alpha^{-1}, \psi_{\beta'} \circ \psi_\beta^{-1})$. This is smooth since products of smooth maps are smooth.

Punchline. The product construction of manifolds gives the categorical product in the category of manifolds.

Property. 1. The projection maps

$$\begin{aligned} p_M : M \times N &\rightarrow M \\ (m, n) &\mapsto m \end{aligned}$$

and

$$\begin{aligned} p_N : M \times N &\rightarrow N \\ (m, n) &\mapsto n \end{aligned}$$

are C^∞ .

2. *Universal Property of Product:* for any manifold Q and smooth maps $f_M : Q \rightarrow M$ and $f_N : Q \rightarrow N$, there exists a unique map

$$\begin{aligned} g : Q &\rightarrow M \times N \\ q &\mapsto (f(q), g(q)) \end{aligned}$$

such that $p_M \circ g = f_M$, and $p_N \circ g = f_N$.

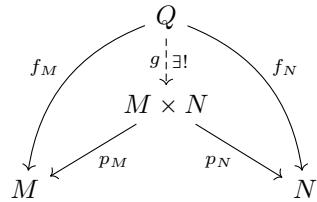


Figure 6: Universal Property of Product

Recall. • A topological space X is *second countable* if the topology has a countable basis: there exists a collection $\mathcal{B} = \{B_i\}_{i \in \mathbb{N}}$ of open sets so that any open set of X is a union of some B_i 's.

- A cover $\{U_\alpha\}_{\alpha \in A}$ of a topological space is *locally finite* if for all $x \in X$, there exists a neighborhood N of x such that $N \cap U_\alpha = \emptyset$ for all but finitely many α 's.

Example 3.3. Let $X = \mathbb{R}$, then

- $\{U_n = (-n, n)\}_{n \geq 0}$ is an open cover, but is not locally finite,
- $\{U_n = (n, n+2)\}_{n \in \mathbb{Z}}$ is a locally finite open cover of \mathbb{R} ,
- $\{U_n = (n, n+2]\}_{n \in \mathbb{Z}}$ is a locally finite cover of \mathbb{R} , but is not an open cover.

Recall. An (open) cover $\{V_\beta\}_{\beta \in B}$ is a *refinement* of a cover $\{U_\alpha\}_{\alpha \in A}$ if for all β , there exists $\alpha = \alpha(\beta)$ such that $V_\beta \subseteq U_{\alpha(\beta)}$.

Definition 3.4. A Hausdorff topological space is *paracompact* if every open cover has a locally finite open refinement.

Fact. A connected Hausdorff manifold is paracompact if and only if it is second countable.

Corollary 3.5. A Hausdorff manifold is paracompact if and only if its connected components are second countable.

Example 3.6. \mathbb{R} with discrete topology is paracompact but not second countable.

Convention. Usually, we assume manifolds are paracompact, except when we need a non-Hausdorff manifold. This condition is required for the existence of *partition of unity* (i.e., constant function id).

Recall. If X is a space, and $Y \subseteq X$ is a subset, then the *closure* \bar{Y} of Y is the smallest closed set containing Y .

Definition 3.7. Given a topological space X and a function $f : X \rightarrow \mathbb{R}$, the *support* of f over X is

$$\text{supp}(f) = \overline{\{x \in X \mid f(x) \neq 0\}}.$$

Example 3.8. The function

$$f(x) = \begin{cases} e^{-\frac{1}{x}}, & x > 0 \\ 0, & x \leq 0 \end{cases}$$

is C^∞ , with support $\overline{(0, \infty)} = [0, \infty)$.

Definition 3.9. Let M be a topological space and let $\{U_\alpha\}_{\alpha \in A}$ be an open cover. A *partition of unity* subordinate to the cover is a collection of continuous functions $\{\psi_\alpha : M \rightarrow [0, 1]\}_{\alpha \in A}$ such that

1. $\text{supp}(\psi_\alpha) \subseteq U_\alpha$ for all $\alpha \in A$,
2. $\{\text{supp}(\psi_\alpha)\}_{\alpha \in A}$ is a locally finite closed cover of M ,
3. $\sum_{\alpha \in A} \psi_\alpha(x) = 1$ for all $x \in M$.

Remark 3.10. For all $x \in M$, there exists $\alpha_1, \dots, \alpha_n$ such that $x \in \text{supp}(\psi_{\alpha_i})$. Hence, for $\alpha \neq \alpha_1, \dots, \alpha_n$, $\psi_\alpha(x) = 0$. Therefore, the summation in [Definition 3.9](#) is finite.

Theorem 3.11. Let M be a paracompact manifold with open cover $\{U_\alpha\}_{\alpha \in A}$, then there exists a partition of unity $\{\psi_\alpha : U_\alpha \rightarrow [0, 1]\}_{\alpha \in A} \subseteq C^\infty(M)$ subordinate to the cover.

Example 3.12. Let $M = \mathbb{R}$ and consider for $n > 0$ the open sets $\{U_n = (-n, n)\}_{n \in \mathbb{N}}$. This is not locally finite at one point.

Example 3.13. Let $M = \mathbb{R}^n$, then for all $x \in \mathbb{R}^n$ and for $r > 0$, we have $B_r(x) = \{x' \in \mathbb{R}^n \mid \|x - x'\| < r\}$ and so $\{B_r(x)\}_{r > 0, x \in \mathbb{R}^n}$ is an open cover, but this is not locally finite everywhere.

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We will start to talk about tangent vectors.

Recall. For any point $q \in \mathbb{R}^n$ and any vector $v \in \mathbb{R}^n$, and any $f \in C^\infty(\mathbb{R}^n)$, the *directional derivative* of f at q in direction v with respect to f is

$$D_v f(q) = \frac{d}{dt}|_{t=0} f(q + tv).$$

This gives a map $D_v(-)(q) : C^\infty(\mathbb{R}^n) \rightarrow \mathbb{R}$ which is

- linear, and

- Leibniz rule holds, i.e.,

$$D_v(fg)(q) = D_v(f)(q) \cdot g(q) + f(q)D_v(g)(q).$$

In other words, $D_v(-)(q) : C^\infty(\mathbb{R}^n) \rightarrow \mathbb{R}$ is a derivation.

Definition 4.1. Let q be a point of a manifold M . A *tangent vector* to M at q is an \mathbb{R} -linear map $v : C^\infty(M) \rightarrow \mathbb{R}$ such that for all $f, g \in C^\infty(M)$,

$$v(fg) = v(f)g(q) + f(q)v(g).$$

Remark 4.2. v gives smooth vector fields over M an $C^\infty(M)$ -module structure via evaluation.

Lemma 4.3. The set $T_q M$ of all tangent vectors to M at q is an \mathbb{R} -vector space.

Lemma 4.4. Suppose $c \in C^\infty(M)$ is a constant function, then for all q and all $v \in T_q M$, $v(c) = 0$.

Proof. We have $v(1) = v(1 \cdot 1) = 1(q)v(1) + v(1)1(q) = 2v(1)$, so $v(1) = 0$. For a constant function c , we have

$$v(c) = v(c \cdot 1) = cv(1) = c(0) = 0.$$

□

Lemma 4.5 (Hadamard). For any $f \in C^\infty(\mathbb{R}^n)$, there exists $g_1, \dots, g_n \in C^\infty(\mathbb{R}^n)$ such that

- $f(x) = f(0) + \sum_{i=1}^n x_i g_i(x)$, and
- $g_i(0) = \left(\frac{\partial}{\partial x_i} f \right)(0)$.

Proof. We have

$$\begin{aligned} f(x) - f(0) &= \int_0^1 \frac{d}{dt}(f(tx))dt \\ &= \int_0^1 \sum_{i=1}^n \frac{\partial f}{\partial x_i}(tx) \cdot x_i dt \\ &= \sum_{i=1}^n x_i \int_0^1 \frac{\partial f}{\partial x_i}(tx) dt \\ &= \sum_{i=1}^n x_i g_i(x). \end{aligned}$$

Therefore, $g_i(0) = \int_0^1 \frac{\partial f}{\partial x_i}(t \cdot 0) dt = \frac{\partial f}{\partial x_i}(0)$. □

Remark 4.6. For $1 \leq i \leq n$, we have canonical tangent vectors to \mathbb{R}^n at 0 given by

$$\begin{aligned} \frac{\partial}{\partial x_i}|_0 : C^\infty(\mathbb{R}^n) &\rightarrow \mathbb{R} \\ f &\mapsto \frac{\partial f}{\partial x_i}(0). \end{aligned}$$

Lemma 4.7. $\left\{ \frac{\partial}{\partial x_1}|_0, \dots, \frac{\partial}{\partial x_n}|_0 \right\}$ is a basis of $T_0 \mathbb{R}^n$.

Proof. Suppose $\sum c_i \frac{\partial}{\partial x_i}|_0 = 0$, then

$$0 = \left(\sum_i c_i \frac{\partial}{\partial x_i}|_0 \right) (x_j) = \sum_i c_i \delta_{ij} = c_j.$$

Therefore, $c_j = 0$ for all j , thus we have linear independence. For all $v \in T_0 \mathbb{R}^n$, i.e., $v : C^\infty(\mathbb{R}^n) \rightarrow \mathbb{R}$ is a derivation, then $v = \sum_i v(x_i) \frac{\partial}{\partial x_i}|_0$. Let $f \in C^\infty(\mathbb{R}^n)$, then $f(X) = f(0) + \sum x_i g_i(x)$, thus

$$\begin{aligned} v(f) &= v(f(0)) + \sum_{i=1}^n v(x_i g_i(x)) \\ &= \sum_{i=1}^n v(x_i g_i(x)) \\ &= \sum_{i=1}^n (v(x_i) g_i(0) + x_i(0) v(g_i)) \\ &= \sum_{i=1}^n v(x_i) g_i(0) \\ &= \sum_{i=1}^n v(x_i) \frac{\partial f}{\partial x_i}(0). \end{aligned}$$

□

Remark 4.8. This shows $\dim(T_0 \mathbb{R}^n) = n$ with the basis above.

Now let V be a finite-dimensional vector space with a basis e_1, \dots, e_n , then

$$\begin{aligned} \varphi : \mathbb{R}^n &\rightarrow V \\ (t_1, \dots, t_n) &\mapsto \sum_{i=1}^n t_i e_i \end{aligned}$$

is a linear bijection, with linear inverse

$$\begin{aligned} \psi : V &\rightarrow \mathbb{R}^n \\ v &\mapsto (\psi_1(v), \dots, \psi_n(v)) \end{aligned}$$

where $\psi_i(v)$'s are linear maps. To describe this with a basis, we have $\psi(\sum_i a_i e_i) = (a_1, \dots, a_n)$, i.e., $\psi_i(e_j) = \delta_{ij}$.

Claim 4.9. $\{\psi_1, \dots, \psi_n\}$ is a basis of $V^* = \text{Hom}(V, \mathbb{R})$, called the *dual basis* of $\{e_1, \dots, e_n\}$, denoted $e_j^* = \psi_j$.

Proof. Linear independence follows from $e_j^*(e_i) = \delta_{ij}$. Given $\ell : V \rightarrow \mathbb{R}$ to be a linear map, then $\ell = \sum \ell(e_i) e_i^*$ since $\left(\sum_i \ell(e_i) e_i^*\right)(e_j) = \ell(e_j)$. Given $v \in T_0 \mathbb{R}^n$, $v(f) = \sum a_i \left(\frac{\partial}{\partial x_i}|_0\right)$ for all $f \in C^\infty(\mathbb{R}^n)$. Note that $\frac{\partial}{\partial x_i}|_0(x_j) = \delta_{ij}$, so $v(x_j) = \sum a_i \frac{\partial}{\partial x_i}|_0(x_j) = \sum_i a_i \delta_{ij} = a_j$. Therefore, we have $a_i = v(x_i)$ for all i , thus $v(f) = \sum v(x_i) \left(\frac{\partial}{\partial x_i}|_0\right)$. Thus, the dual basis to $\frac{\partial}{\partial x_1}|_0, \dots, \frac{\partial}{\partial x_n}|_0$ is $\{d(x_i)_0\}_{i=1}^n$ where $(dx_i)_0(v) = v(x_i)$ for all i . Hence, we have $v = \sum (dx_i)_0(v) \frac{\partial}{\partial x_i}|_0$. □

Remark 4.10. Via a change of basis, this works at every point q on the local chart, so we can describe the tangent space on any point on a local chart.

5 AUG 30, 2023

Let M be a manifold and $x \in M$. Recall that a tangent vector $v : C^\infty(M) \rightarrow \mathbb{R}$ is a derivation, i.e., linear map, and the set of tangent vectors at q gives the tangent space.

Example 5.1. Let $M = \mathbb{R}^n$, and $q = 0$, then $\left\{\frac{\partial}{\partial x_1}|_0, \dots, \frac{\partial}{\partial x_n}|_0\right\}$ is a basis of $T_0 \mathbb{R}^n$. Moreover, for all $v \in T_0 \mathbb{R}^n$, $v = \sum v(x_i) \frac{\partial}{\partial x_i}|_0$, thus $\{v \mapsto v(x_i)\}_{i=1}^n$ is the dual basis, with $v(x_i) = (dx_i)_0(v)$ for all $1 \leq i \leq n$.

Remark 5.2. The proof used Hadamard's lemma ([Lemma 4.5](#)) and the fact that for all $x \in \mathbb{R}^n$ and all $t \in [0, 1]$, $f(tx)$ is defined. Thus, the same argument should work for a version of Hadamard's lemma for star-shaped open subsets $U \subseteq \mathbb{R}^n$.

Definition 5.3. We say an open subset $U \subseteq \mathbb{R}^n$ is a *star-shaped domain* if for all $t \in [0, 1]$ and all $x \in U$, $tx \in U$.

Definition 5.4. Let $F : M \rightarrow N$ be a smooth map between two manifolds, and $q \in M$ is a point, then

$$\begin{aligned} T_q F : T_q M &\rightarrow T_q N \\ v(f) &\mapsto v(f \circ F) \end{aligned}$$

via the pullback.

Exercise 5.5. Check that the definition makes sense, in particular:

- (i) $(T_q F)(v)$ is a tangent vector to N of $F(q)$, and
- (ii) $T_q F$ is a derivation.

Remark 5.6. (a) It is easy to deduce the *chain rule*. That is, given $M \xrightarrow{F} N \xrightarrow{G} Q$ with $q \in M$, then $T_q(G \circ F) = T_{F(q)}G \circ T_q F$ because for all $f \in C^\infty(Q)$ and all $v \in T_q M$, we have

$$(T_q(G \circ F)(v))(f) = v(f \circ (G \circ F))$$

and

$$(T_{F(q)}G(T_q F(v))) = (T_q F)(v)(f \circ G) = v((f \circ G) \circ F).$$

- (b) $T_q(\text{id}_M) = \text{id}_{T_q M}$.

As a result, we know T is a functor from the category of pointed manifolds to the category of \mathbb{R} -vector spaces.

Corollary 5.7. If $F : M \rightarrow N$ is a diffeomorphism, then for all $q \in M$, $T_q F : T_q M \rightarrow T_{F(q)}N$ is an isomorphism.

Proof. Since F is a diffeomorphism, then it has a smooth inverse $G : N \rightarrow M$, so

$$\text{id}_{T_q M} = T_q(\text{id}_M) = T_q(G \circ F) = T_{F(q)}G \circ T_q F$$

and

$$\text{id}_{T_{F(q)}N} = T_{F(q)}(\text{id}_N) = T_{F(q)}(F \circ G) = T_{F(q)}F \circ T_{F(q)}G.$$

□

We also need to show that $\dim(T_q M) = \dim_q(M)$, which is a result of [Lemma 5.8](#), whose proof will be postponed till next time.

Lemma 5.8. Let M be a manifold and $q \in M$, and let U be an open neighborhood of q in M , and let $i : U \hookrightarrow M$ be an inclusion, then

$$\begin{aligned} I = T_q i : T_q U &\rightarrow T_q M \\ v(f) &\mapsto v(f|_U) \end{aligned}$$

is an isomorphism for all $v \in T_q M$ and all $U \subseteq M$.

Notation. We denote $r_1, \dots, r_n : \mathbb{R}^m \rightarrow \mathbb{R}$ to be the standard coordinates on \mathbb{R}^m .

Let M be a manifold, $q_0 \in M$, and $\varphi : U \rightarrow \mathbb{R}^m$ is a coordinate chart with $q_0 \in U$. Now let $x_i = r_i \circ \varphi$, then $\varphi(q) = (x_1(q), \dots, x_m(q))$.

We may now assume that

- $\varphi(q_0) = 0$, otherwise, we replace $\varphi(q)$ by $\varphi(q) := \varphi(q) - \varphi(q_0)$, and
- $\varphi(U)$ is an open ball $B_R(0) = \{r \in \mathbb{R}^m \mid \|r\| < R\}$ because there exists $R > 0$ such that $B_R(0) \subseteq \varphi(U)$, and we can then replace U with $\varphi^{-1}(B_R(0))$ and restrict the charts φ to $\varphi|_{\varphi^{-1}(B_R(0))}$.

We now define

$$\begin{aligned}\frac{\partial}{\partial x_j}|_{q_0} : C^\infty(U) &\rightarrow \mathbb{R} \\ f &\mapsto \frac{\partial}{\partial r_j}|_0(f \circ \varphi^{-1})\end{aligned}$$

Claim 5.9. $\left\{ \frac{\partial}{\partial x_j}|_{q_0} \right\}_{j=1}^m$ is a basis of $T_q M$ and for all $v \in T_{q_0} M$, $v = \sum v(x_j) \frac{\partial}{\partial x_j}|_{q_0}$.

Proof. By Hadamard's lemma [Lemma 4.5](#) on $B_R(0)$, for all $f \in C^\infty(U)$, we have $f \circ \varphi^{-1} \in C^\infty(B_R(0))$, so there exists $g_1, \dots, g_m \in C^\infty(B_R(0))$ such that $(f \circ \varphi^{-1})(r) = f(\varphi^{-1}(0)) + \sum r_i g_i(r)$. Therefore, $f(q) = f(q_0) + \sum (r_i \circ \varphi)(q)(g_i \circ \varphi)(q)$, hence $f = f(q_0) + \sum x_i (g_i \circ \varphi)$, and $(g_i \circ \varphi)(q_0) = g_i(0) = \frac{\partial}{\partial r_i}|_0(f \circ \varphi^{-1}) = \frac{\partial}{\partial x_i}|_0(f)$.

Hence, for all $v \in T_{q_0}(U)$, we know

$$\begin{aligned}v(f) &= v(f(q_0)) + v\left(\sum x_i \cdot (g_i \circ \varphi)\right) \\ &= \sum_i v(x_i)(g_i \circ \varphi)(q_0) \\ &= \sum v(x_i) \frac{\partial}{\partial x_i}|_{q_0}(f).\end{aligned}$$

□

Remark 5.10. 1. The linear functionals

$$\begin{aligned}(dx_i)_{q_0} : T_{q_0} U &\rightarrow \mathbb{R} \\ v &\mapsto v(x_i)\end{aligned}$$

is the basis of $(T_{q_0} U)^*$ dual to $\left\{ \frac{\partial}{\partial x_i}|_{q_0} \right\}$.

2. $(T_0 \varphi^{-1})\left(\frac{\partial}{\partial r_i}|_0\right) = \frac{\partial}{\partial x_i}|_{q_0}$ by definition. Since $\left\{ \frac{\partial}{\partial x_i}|_0 \right\}_{i=1}^n$ is a basis of $T_0(B_R(0))$, then $\left\{ \frac{\partial}{\partial x_i}|_{q_0} \right\}$ has to be a basis.

Lemma 5.11. Let M be a manifold and $q \in M$ a point. Let $U \ni q$ be an open neighborhood, and $f \in C^\infty(M)$ such that $f|_U = 0$, then for all $v \in T_q M$, we have $v(f) = 0$.

Proof. We have shown the existence of a bump function $\rho \in C^\infty(M)$ in homework 1, that is, $0 \leq \rho(x) \leq 1$, $\text{supp}(\rho) \subseteq U$ and $\rho \equiv 1$ near q .

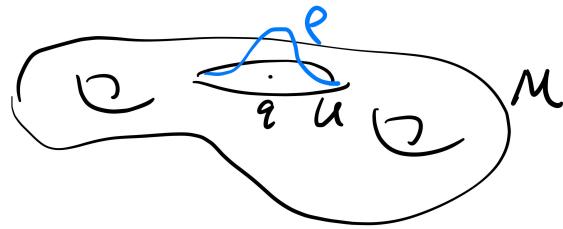


Figure 7: Bump Function

Therefore, $\rho f \equiv 0$, so $v(f) = v(\rho f)(q) + \rho(q)v(f) = v(\rho f) = 0$. □

6 SEPT 1, 2023

Recall. Given a coordinate chart $\varphi = (x_1, \dots, x_m) : U \rightarrow \mathbb{R}^m$, and $q \in U$ with $f(q) = 0$, we defined $\left\{ \frac{\partial}{\partial x_i}|_q \right\}_{i=1}^m \subseteq T_q U$ by $\frac{\partial}{\partial x_i}|_q f = \frac{\partial}{\partial r_i}(f \circ \varphi^{-1})|_{\varphi(q)}$ where $\frac{\partial}{\partial r_i}$'s are the standard partials on $C^\infty(\mathbb{R}^m)$. We know this is a basis with dual basis

$$(dx_i)_q : T_q M \rightarrow \mathbb{R}$$

$$v \mapsto v(x_i)$$

therefore $v = \sum v(x_i) \frac{\partial}{\partial x_i}|_q$ for all v . Note that

$$C^\infty(M) \rightarrow C^\infty(U)$$

$$f \mapsto f|_U$$

is not surjective.

Also, we know $v \in T_q M$ is local, if $f, g \in C^\infty(M)$ agree on a neighborhood of q , then $v(f) = v(g)$.

Finally, given $F : M \rightarrow N$, this induces

$$T_q F : T_q M \rightarrow T_{F(q)} N$$

$$v \mapsto v(f \circ F).$$

Lemma 6.1. Given a manifold M and $q \in M$, open neighborhood $q \in U \subseteq M$ and $i : U \hookrightarrow M$ inclusion, then

$$I \equiv T_q i : T_q U \rightarrow T_q M$$

is an isomorphism with $(I(v))(f) = v(f|_U)$ for all $f \in C^\infty(M)$.

Proof. Suppose $v \in \ker(I)$, then $v(f|_U) = 0$ for all $f \in C^\infty(M)$. We want $v(h) = 0$ for all $h \in C^\infty(U)$. We first choose bump function $\rho : M \rightarrow [0, 1]$ that is C^∞ , and $\rho \equiv 1$ near q , and suppose $\text{supp}(\rho) \subseteq U$, hence $\rho|_{M \setminus U} \equiv 0$. Then define $\rho h \in C^\infty(M)$ via

$$\rho h(x) = \begin{cases} \rho(x)h(x), & x \in U \\ 0, & x \notin U \end{cases}$$

Now $\rho h|_U \equiv h$ near q , i.e., identically 1. Therefore, $v(h) = v(\rho h|_U) = 0$, so $v \equiv 0$.

It remains to show that for all $w \in T_q M$, there exists $v \in T_q U$ such that $I(v) = w$, i.e., for all $f \in C^\infty(M)$, $w(f) = v(f|_U)$. Take the same $\rho \in C^\infty(M, [0, 1])$ as above, define $v(h) = w(\rho h)$ for all $h \in C^\infty(M)$, and we can check that

- $v \in T_q M$, and
- for all $f \in C^\infty(M)$, $v(f|_U) = w(f)$.

Note that v is \mathbb{R} -linear, and for all $f, g \in C^\infty(W)$ we have $v(fg) = w(\rho fg) = w(\rho^2 fg)$ since $\rho fg = \rho^2 fg$ near q , then we have

$$\begin{aligned} v(fg) &= w(\rho^2 fg) \\ &= w((\rho f)(\rho g)) \\ &= v(\rho f) \cdot (\rho g)(g) + \rho(f)(q) \cdot v(\rho g) \\ &= v(f)g(q) + f(q)v(g). \end{aligned}$$

Finally, for all $f \in C^\infty(M)$, we have $v(f|_U) = w(\rho f) = w(f)$ since $\rho f = f$ near q . \square

Notation. We now suppress the isomorphisms $I : T_q U \rightarrow T_q M$. In particular, given a chart $\varphi = (x_1, \dots, x_m) : U \rightarrow \mathbb{R}^m$, we view $\left\{ \frac{\partial}{\partial x_i}|_q \right\}_{i=1}^m$ as a basis of $T_q M$.

Lemma 6.2. Let V be a finite-dimensional vector space with $q \in V$, then

$$\begin{aligned}\varphi : V &\rightarrow T_q V \\ v(f) &\mapsto \frac{d}{dt}|_0 f(q + tv)\end{aligned}$$

for all $f \in C^\infty(V)$, is an isomorphism.

Proof. One can see this is linear, so it suffices to show injectivity. We have

$$\ker(\varphi) = \{v \in V \mid \frac{d}{dt}|_0(q + tv) = 0 \ \forall f \in C^\infty(V)\}.$$

If $0 \neq v \in \ker(\varphi)$, then there exists $\ell : V \rightarrow \mathbb{R}$ such that $\ell(V) \neq 0$, so

$$0 \neq \frac{d}{dt}|_0(\ell(q + tv)) = \frac{d}{dt}|_0(\ell(q) + t\ell(v)) = \ell(v).$$

□

Definition 6.3. A curve through a point $q \in M$ on a manifold M is a C^∞ -map $\gamma : (a, b) \rightarrow M$ with $0 \in (a, b)$ such that $\gamma(0) = q$.

Definition 6.4. Given $\gamma : (a, b) \rightarrow M$ with $\gamma(0) = q$, we define $\dot{\gamma}(0) \in T_q M$ by $\dot{\gamma}(0)f = \frac{d}{dt}|_0 f(\gamma(t)) = \frac{d}{dt}|_0(f \circ \gamma)$ for all $f \in C^\infty(M)$.

Remark 6.5.

$$\begin{aligned}t : (a, b) &\rightarrow \mathbb{R} \\ x &\mapsto x\end{aligned}$$

is a coordinate chart on (a, b) , where $\frac{d}{dt}|_0 \in T_0(a, b)$ is a basis vector. Since γ is C^∞ ,

$$\begin{aligned}T_0\gamma : T_0(a, b) &\rightarrow T_{\gamma(0)}M \equiv T_q M \\ ((T_0\gamma)(\frac{d}{dt}|_0))f &= \frac{d}{dt}|_0(f \circ \gamma) = \dot{\gamma}(0),\end{aligned}$$

so $\dot{\gamma}(0) = (T_0\gamma)(\frac{d}{dt}|_0)$.

Let $\mathcal{C} = \{\gamma : I \rightarrow M \mid \gamma(0) = q, I \text{ interval depending on } \gamma\}$, then we have a map

$$\begin{aligned}\Phi : \mathcal{C} &\rightarrow T_q M \\ \gamma &\mapsto \dot{\gamma}(0)\end{aligned}$$

Note that Φ is not injective. However, there is an equivalence relation \sim on \mathcal{C} defined by $\gamma \sim \sigma$ if and only if $\Phi(\gamma) = \Phi(\sigma)$, so this gives an injection

$$\begin{aligned}\tilde{\Phi} : \mathcal{C}/\sim &\rightarrow T_q M \\ [\gamma] &\mapsto \dot{\gamma}(0).\end{aligned}$$

Claim 6.6. $\tilde{\Phi}$ is onto.

Proof. Choose coordinates $\varphi = (x_1, \dots, x_m) : U \rightarrow \mathbb{R}^m$ near q such that $(x_1, \dots, x_m)(q) = 0$. Now, for all $v \in T_q M$, we have $v = \sum v(x_i) \frac{\partial}{\partial x_i}|_q$. Consider $\gamma(t) = \varphi^{-1}(tv(x_1), \dots, tv(x_m))$, then $\gamma(0) = \varphi^{-1}(0) = q$ and for any $f \in C^\infty(M)$, we have

$$\begin{aligned}\dot{\gamma}(0)f &= \frac{d}{dt}|_0(f \circ \varphi^{-1})(tv(x_1), \dots, tv(x_m)) \\ &= \sum \frac{\partial}{\partial r_i}(f \circ \varphi^{-1})|_0 \cdot v(x_i) \\ &= \sum v(x_i) \frac{\partial}{\partial x_i}|_q f \\ &= v(f).\end{aligned}$$

□

Lemma 6.7. For any smooth map $F : M \rightarrow N$ between manifolds, for all $q \in M$, we have

$$T_q F(\dot{\gamma}(0)) = (F \circ \gamma)'(0).$$

Proof.

$$\begin{aligned} T_q F(\dot{\gamma}(0)) &= T_q F(T_0 \gamma \left(\frac{d}{dt}|_0 \right)) \\ &= T_0(F \circ \gamma) \left(\frac{d}{dt}|_0 \right) \\ &= (F \circ \gamma)'(0). \end{aligned}$$

□

Example 6.8. Let $M = N = \mathbb{C}$ and $F(z) = e^z$. We claim that $(T_z F)(v) = e^z v$, which uses $\mathbb{C} \cong T_w \mathbb{C}$ for all $w \in \mathbb{C}$. Indeed, since $\frac{d}{dt}|_0 e^{tv} = v$, then

$$\begin{aligned} (T_z F)(v) &= \frac{d}{dt}|_0 F(z + tv) \\ &= \frac{d}{dt}|_0 e^{z+tv} \\ &= \frac{d}{dt}|_0 (e^z e^{tv}) \\ &= e^z v. \end{aligned}$$

Note that $T_z F$ is an isomorphism for all z , given by

$$\begin{array}{ccc} T_z \mathbb{C} & \xrightarrow{T_z F} & T_{F(z)} \mathbb{C} \\ \downarrow \cong & & \downarrow \cong \\ \mathbb{C} & \xrightarrow[e^z \cdot -]{} & \mathbb{C} \end{array}$$

Also note that this is not a diffeomorphism, since the inverse is the complex logarithm function, which is only well-behaved on the principal branches.

7 SEPT 6, 2023

Definition 7.1. Given a manifold M , $q \in M$, and $f \in C^\infty(M)$, we define the *exact differential* to be a linear map

$$\begin{aligned} df_q : T_q M &\rightarrow \mathbb{R} \\ v &\mapsto v(f) \end{aligned}$$

in $\text{Hom}(T_q M, \mathbb{R}) =: T_q^* M$, the cotangent space.

Exercise 7.2. • df_q is linear,

- $f \equiv g$ near q , then $df_q = dg_q$.

We have seen differentials before: given a coordinate chart $\varphi = (x_1, \dots, x_m) : U \rightarrow \mathbb{R}^m$ is a coordinate chart, then $\{(dx_i)_q\}_{i=1}^m$ is a basis of $T_q^* M$ dual to $\{\frac{\partial}{\partial x_i}|_q\}_{i=1}^m$. Note that for all $\eta \in T_q^* M \equiv (T_q M)^*$, then $\eta = \sum \eta \left(\frac{\partial}{\partial x_i}|_q \right) (dx_i)_q$.

Lemma 7.3. Let M be a manifold, $q \in M$, and $f \in C^\infty(M)$, then the derivative

$$(T_q f)(v) = df_q(v) \frac{d}{dt}|_{f(q)}.$$

Proof. Note that $\{dt_{f(q)}\}$ is a basis of $T_{f(q)}^*\mathbb{R}$, then

$$dt_{f(q)}(T_q f(v)) = (T_q f(v))t = v(t \circ f) = v(f) = df_q(v),$$

so $(T_q f)(v) = df_q(v) \frac{d}{dt}|_{f(q)}$. \square

Recall. Let $T : V \rightarrow W$ be a linear map, and let $\{e_1, \dots, e_n\}$ be a basis of V , and let $\{f_1, \dots, f_n\}$ be a basis of W , with dual basis $\{f_1^*, \dots, f_n^*\}$ in W^* . Then let $t_{ij} = f_i^*(Te_j)$, then

$$T(e_j) = \sum_i f_i^*(Te_j) f_i = \sum_i t_{ij} f_i.$$

For all $F : \mathbb{R}^m \rightarrow \mathbb{R}^n$, consider the coordinates $(x_1, \dots, x_m) : \mathbb{R}^m \rightarrow \mathbb{R}$ and $(y_1, \dots, y_n) : \mathbb{R}^n \rightarrow \mathbb{R}$, which gives coordinates $\{(\frac{\partial}{\partial x_i}|_q)\}$ and $\{(\frac{\partial}{\partial y_i}|_{F(q)})\}$, respectively. With $T = T_q F$, we have

$$t_{ij} = (dy_i)_{F(q)}(T_q F(\frac{\partial}{\partial x_j}|_q)) = (T_q F(\frac{\partial}{\partial x_j}|_q))y_i = \frac{\partial}{\partial x_j}|_q(y_i \circ F).$$

If we denote $F = (F_1, \dots, F_n)$ where $F_i = y_i \circ F$ then this is just $\frac{\partial F_i}{\partial x_j}(q)$, so $\left(\frac{\partial F_i}{\partial x_j}(q)\right)$ is the matrix of $T_q F$.

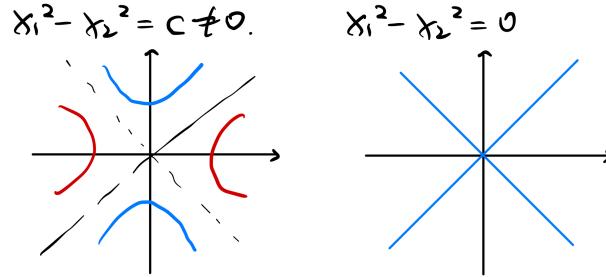
Definition 7.4. Let $F : M \rightarrow N$ be a smooth map, we say $c \in N$ is a *regular value* of F if either $F^{-1}(c) = \emptyset$, or for all $q \in F^{-1}(c)$, $T_q F : T_q M \rightarrow T_{F(q)}N = T_c N$ is onto.

We say $c \in N$ is a *singular value* if it is not a regular value.

Example 7.5. Consider

$$\begin{aligned} F : \mathbb{R}^2 &\rightarrow \mathbb{R} \\ (x_1, x_2) &\mapsto x_1 - x_2^2 \end{aligned}$$

for all $q = (x_1, x_2) \in \mathbb{R}^2$, then $T_q F$ is the matrix $\left(\frac{\partial F}{\partial x_1}(q), \frac{\partial F}{\partial x_2}(q)\right) = (2x_1, 2x_2)$. Hence, $c \neq 0$ is a regular value, and $c = 0$ is a singular value.



Definition 7.6. An *embedded submanifold* (of dimension k) of a manifold M is a subspace $Z \subseteq M$ such that for all $q \in Z$ there exists a coordinate chart $\varphi = (x_1, \dots, x_k, x_{k+1}, \dots, x_m) : U \rightarrow \mathbb{R}^m$ with $\varphi(U \cap Z) = \{(r_1, \dots, r_m) \in \varphi(U) \mid r_k = \dots = r_m = 0\}$.

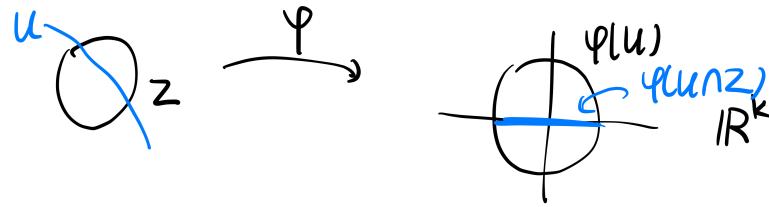


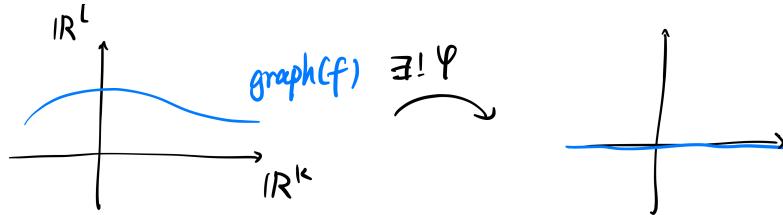
Figure 8: Embedded Submanifold

- Remark 7.7.**
- Any open subset $U \subseteq M$ is an embedded submanifold.
 - Any singleton in M is an embedded submanifold.

Example 7.8. Let $f : \mathbb{R}^k \rightarrow \mathbb{R}^l$ be C^∞ , then the graph of f is

$$\text{graph}(f) = \{(x, f(x)) \in \mathbb{R}^k \times \mathbb{R}^l \mid x \in \mathbb{R}^k\}$$

is an embedded submanifold of $\mathbb{R}^k \times \mathbb{R}^l$.



Here $\varphi(x, y) = (x, y - f(x))$ is a coordinate chart of $\mathbb{R}^k \times \mathbb{R}^l$ with inverse $\varphi^{-1}(x, y') = (x, y' + f(x))$.

Theorem 7.9 (Regular Value Theorem). Let $c \in N$ be a regular value of smooth function $F : M \rightarrow N$. If $F^{-1}(c) = \emptyset$, then for all $q \in F^{-1}(c)$, $T_q F : T_q M \rightarrow T_q N$ is onto, so $F^{-1}(c)$ is an embedded submanifold of M . Moreover, $T_q F^{-1}(c) = \ker(T_q F)$ and $\dim(F^{-1}(c)) = \dim(M) - \dim(N)$.

Example 7.10. Consider

$$\begin{aligned} F : \mathbb{R}^m &\rightarrow \mathbb{R} \\ x &\mapsto \sum x_i^2 = \|x\|^2 \end{aligned}$$

Now $T_q F$ gives a local chart with $(2x_1, \dots, 2x_m)$. Any $c \neq 0$ is a regular value. We have $F^{-1}(c) = \{x \mid \|x\|^2 = c\}$ is the sphere of radius \sqrt{c} for $c > 0$. Moreover, $F^{-1}(0) = \{0\}$, an embedded submanifold, but $\dim(\{0\}) \neq \dim(\mathbb{R}^m) - \dim(\mathbb{R})$.

8 SEPT 8, 2023

Recall. A subset Z of a manifold M is an embedded submanifold (of dimension k and codimension $m - k$ for $m = \dim(M)$) if for all $z \in Z$, there exists a coordinate chart $\varphi : U \rightarrow \mathbb{R}^m$ and $z \in U$ which is adapted to Z , i.e., $\varphi(U \cap Z) = \varphi(U) \cap (\mathbb{R}^k \times \{0\})$.

Remark 8.1.

- Submanifolds of codimension 0 are open subsets.

- Submanifolds of codimension $m = \dim(M)$ are discrete sets of points.

We will proceed to prove [Theorem 7.9](#).

Remark 8.2. Once we proved $F^{-1}(c)$ is embedded and $\dim(F^{-1}(c)) = \dim(M) - \dim(N)$, then the last statement follows. Indeed, given $v \in T_q(F^{-1}(c))$, there exists $\gamma : (a, b) \rightarrow F^{-1}(c)$ such that $\gamma(0) = q$, $\gamma'(0) = v$, and $F(\gamma(t)) = c$ for all t . Therefore,

$$0 = \frac{d}{dt}|_0 F(\gamma(t)) = T_q F(\gamma'(0)) = T_q F v,$$

so $v \in \ker(T_q F)$, and so $T_q F^{-1}(c) \subseteq \ker(T_q F)$. By dimension argument, we have equality.

We will introduce inverse function theorem and implicit function theorem.

Theorem 8.3 (Inverse Function Theorem). Let $U \subseteq \mathbb{R}^n$ be open, $f : U \rightarrow \mathbb{R}^n$ be C^∞ with $q \in U$ such that $T_q f = Df(q) : T_q U = \mathbb{R}^n \rightarrow \mathbb{R}^n = T_{F(q)} \mathbb{R}^n$ is an isomorphism. Then there exists an open neighborhood $q \in V \subseteq U$ and $f(q) \in W$ such that $f : V \rightarrow W$ is a diffeomorphism.

Notation. Given $F : \mathbb{R}^k \times \mathbb{R}^l \rightarrow \mathbb{R}^m$ for $(a, b) \in \mathbb{R}^k \times \mathbb{R}^l$, then we denote

- $\frac{\partial F}{\partial x}(a, b) = T_{(a,b)}F|_{\mathbb{R}^k \times \{0\}} = DF(a, b)|_{\mathbb{R}^k \times \{0\}}$,
- $\frac{\partial F}{\partial y}(a, b) = T_{(a,b)}F|_{\{0\} \times \mathbb{R}^l} = DF(a, b)|_{\{0\} \times \mathbb{R}^l}$.

Theorem 8.4 (Implicit Function Theorem). Let $F : \mathbb{R}^k \times \mathbb{R}^n \rightarrow \mathbb{R}^n$ be C^∞ , let $(a, b) \in \mathbb{R}^k \times \mathbb{R}^l$. Suppose $\frac{\partial F}{\partial y}(a, b) : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is an isomorphism, then there exists a neighborhood $W \ni (a, b)$ and $U \ni a$ in \mathbb{R}^k , as well as C^∞ -map $g : U \rightarrow \mathbb{R}^n$ such that $F^{-1}(c) \cap W = \text{graph}(g) \cap W$.

Remark 8.5. inverse function theorem and implicit function theorem are equivalent.

Proof. Consider

$$\begin{aligned} H : \mathbb{R}^k \times \mathbb{R}^n &\rightarrow \mathbb{R}^k \times \mathbb{R}^n \\ (x, y) &\mapsto (x, F(x, y)) \end{aligned}$$

then $H(a, b) = (a, F(a, b)) = (a, c)$. The partials give

$$DH(a, b) = \begin{pmatrix} I & 0 \\ \frac{\partial F}{\partial x}(a, b) & \frac{\partial F}{\partial y}(a, b) \end{pmatrix}$$

As $\frac{\partial F}{\partial y}(a, b)$ is invertible, so is $DH(a, b)$, so there exists neighborhoods $(a, b) \in W \subseteq \mathbb{R}^n \times \mathbb{R}^k$ and $a \in U \subseteq \mathbb{R}^k$, $c \in V \subseteq \mathbb{R}^n$, such that $H : W \rightarrow U \times V$ is a diffeomorphism. Consider

$$\begin{aligned} G = H^{-1} : U \times V &\rightarrow W \subseteq \mathbb{R}^n \times \mathbb{R}^l \\ (u, v) &\mapsto (G_1(u, v), G_2(u, v)) \end{aligned}$$

therefore

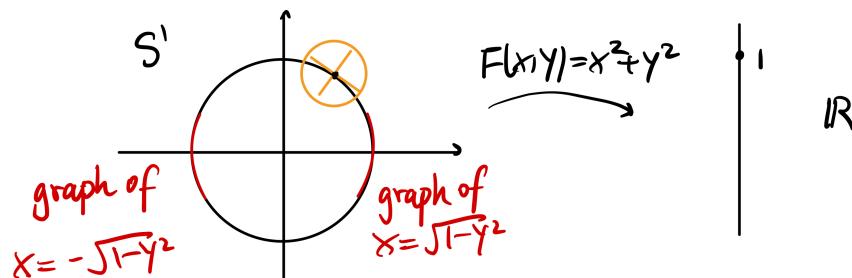
$$(u, v) = H(H^{-1}(u, v)) = H(G_1(u, v), G_2(u, v)) = (G_1(u, v), F(G_1(u, v), G_2(u, v)))$$

so $G_1(u, v) = u$, and $v = F(u, G_2(u, v))$ for all u, v , hence $c = F(u, G_2(u, c))$ for all u . Now let $g(u) = G_2(u, c)$, then $F(u, g(u)) = c$ for all u . Hence, $\text{graph}(g) \subseteq F^{-1}(c)$. \square

Proof of Regular Value Theorem. Let $F : M \rightarrow N$, $c \in N$, $F^{-1}(c) \neq \emptyset$. Now for all $q \in F^{-1}(c)$, then $T_q F : T_q M \rightarrow T_q N$ is onto. Given $q \in F^{-1}(c)$, we want a chart T from a neighborhood of q to \mathbb{R}^m , adapted to $F^{-1}(c)$. Let $\varphi : U \rightarrow \mathbb{R}^m$ and $\psi : V \rightarrow \mathbb{R}^m$ be charts such that $q \in U$, $c \in V$, then

$$\tilde{F} = \psi \circ F \circ \varphi^{-1}|_{\varphi(F^{-1}(V) \cap U)} : \varphi(F^{-1}(V) \cap U) \subseteq \mathbb{R}^m \rightarrow \mathbb{R}^n$$

is C^∞ . Now $\psi(c)$ is a regular value in \tilde{F} . Let $r = \varphi(q)$, then we have $D\tilde{F}(r) : \mathbb{R}^m \rightarrow \mathbb{R}^n$. Let $X = \ker(D\tilde{F}(r))$ and Y be a complement in \mathbb{R}^m . So $\mathbb{R}^m = X \otimes Y$ and $D\tilde{F}(r)|_Y : Y \rightarrow \mathbb{R}^n$ is an isomorphism. Apply inverse function theorem to \tilde{F} from the intersection of $X \times Y$ and the open subset to \mathbb{R}^n .



\square

Example 8.6. Let $\text{Sym}^2(\mathbb{R}^n)$ be the $n \times n$ symmetric real matrices, also known as $\mathbb{R}^{\frac{n^2-n}{2}+n}$. There is

$$\begin{aligned} F : \text{GL}(n, \mathbb{R}) &\rightarrow \text{Sym}^2(\mathbb{R}^n) \\ A &\mapsto A^T A \\ F^{-1}I &= \{A \in \text{GL}(n, \mathbb{R}) \mid A^T A = I\} \leftrightarrow I \end{aligned}$$

Remark 8.7. We have $F = F \circ L_A$ for all $A \in O(U)$, then for all A , we have $T_A F$ onto.

Claim 8.8. 1 is a regular value of F , so $O(n)$ is an embedded submanifold of $\text{GL}(n, \mathbb{R})$.

Proof.

$$\begin{aligned} (T_I F)(v) &= \frac{d}{dt}|_0 (I + tv)^T (I + tv) \\ &= \frac{d}{dt}|_0 (I^2 + tv^T + tv + t^2 v^T v) \\ &= v^T + v \end{aligned}$$

and this is surjective since for all $Y \in \text{Sym}^2(\mathbb{R})$, we have $Y = \frac{1}{2}(Y^T + Y)$, so $Y = (T_I F)(\frac{1}{2}Y)$. \square

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Recall. Let $F : M \rightarrow N$ be C^∞ , let $c \in N$ be a regular value such that $F^{-1}(c) \neq \emptyset$. (For all $q \in F^{-1}(c)$, $T_q F : T_q M \rightarrow T_q N$ is onto.) Then:

- i $F^{-1}(c)$ is an embedded submanifold of M .
- ii $\dim(M) = \dim(F^{-1}(c)) = \dim(N)$.
- iii for all $q \in F^{-1}(c)$, $T_q F^{-1}(c) = \ker(T_q F)$.

The proof uses inverse function theorem and/or implicit function theorem, and the key is to note that locally $f^{-1}(c)$ is a graph.

Also, $O(n) = \{A \in \text{GL}(n, \mathbb{R}) \mid A^T A = I\}$ is an embedded submanifold.

Definition 9.1. A *Lie group* G is a group and a manifold so that

- i the multiplication map

$$\begin{aligned} m : G \times G &\rightarrow G \\ (a, b) &\mapsto (a, b) \end{aligned}$$

is C^∞ .

- ii the inverse map

$$\begin{aligned} \text{inv} : G &\rightarrow G \\ g &\mapsto g^{-1} \end{aligned}$$

is C^∞ .

Notation. $e_G = 1_G$ is the identity element.

Example 9.2. $G = \mathbb{R}^n$ with $m(v, w) = v + w$, and $\text{inv}(v) = -v$ gives a Lie group.

Example 9.3. Let $G = \text{GL}(n, \mathbb{R})$ be with $e_G = \text{diag}(1, \dots, 1) = I$, with maps $m(A, B) = AB$ and $\text{inv}(A) = A^{-1}$.

Remark 9.4. One can think of a Lie group G as four pieces of data:

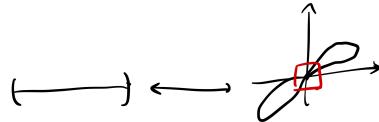
- manifold G ,
- map $m : G \times G \rightarrow G$,
- map $\text{inv} : G \rightarrow G$,
- $e_G \in G$.

Note that a subgroup H of a Lie group G is not necessarily a Lie group. The sufficient condition would be H is an embedded submanifold of G , i.e.,

- $m|_{H \times H} : H \times H \rightarrow H$ are C^∞ ,
- $\text{inv}|_H : H \rightarrow H$

are C^∞ . Note $m|_{H \times H} : H \times H \rightarrow G$ is C^∞ since $i : H \hookrightarrow G$ is C^∞ and $m|_{H \times H} = m(i \times i)$.

Example 9.5. For example, think of the embedding



but at the origin the preimage is split into three pieces, because the inverse is not continuous, which does not embed into a submanifold.

Lemma 9.6. If $i : Q \hookrightarrow M$ is an embedded submanifold, and $f : N \rightarrow M$ is a smooth map such that $f(N) \subseteq Q$, then $g : N \rightarrow Q$ with $g(n) = f(n)$ is C^∞ .

$$\begin{array}{ccc} N & \xrightarrow{f} & M \\ & \searrow g & \downarrow i \\ & & Q \end{array}$$

Proof. Since $Q \hookrightarrow M$ is embedded, for all $q \in Q$, there exists an adapted chart $\varphi = (x_1, \dots, x_n, x_{k+1}, \dots, x_m) : U \rightarrow \mathbb{R}^m$ such that $Q \cap U = \{x_k = \dots = x_n = 0\}$. Consider $\varphi \circ f|_{f^{-1}(U)} : f^{-1}(U) \rightarrow \mathbb{R}^m$, then $f(f^{-1}(U)) \subseteq Q \cap U$.



Then $\varphi \circ f|_{f^{-1}(U)} = \varphi(U \cap Q) = \{(r_1, \dots, r_k, r_{k+1}, \dots, r_m) \mid r_{k+1} = \dots = r_n = 0\}$, so $\varphi \circ f = (h_1, \dots, h_k, 0, \dots, 0)$ where $h_1, \dots, h_k \in C^\infty(f^{-1}(U))$. Therefore, $\varphi|_{U \cap Q} g|_{f^{-1}(U)} = (h_1, \dots, h_k)$. \square

Example 9.7. $O(n) \subseteq \text{GL}(n, \mathbb{R})$ is embedded, thus a Lie group.

Example 9.8. $\text{SL}(n, \mathbb{R}) = \{A \in \text{GL}(n, \mathbb{R}) \mid \det(A) = 1\}$ is also a Lie group.

Claim 9.9. $1 \in \mathbb{R}$ is a regular value of $\det : \text{GL}(n, \mathbb{R}) \rightarrow \mathbb{R}$.

Proof. The key fact is that $T_I(\det) : \mathbb{R}^{n^2} \rightarrow \mathbb{R}$ is an $(n \times n)$ -matrix given by $A \mapsto \text{tr}(A)$. Indeed, note that the trace is the differential of the determinant. \square

Definition 9.10. A (real) *Lie algebra* is a (real) vector space \mathfrak{g} with an \mathbb{R} -bilinear map

$$\begin{aligned} [\cdot, \cdot] : \mathfrak{g} \times \mathfrak{g} &\rightarrow \mathfrak{g} \\ (X, Y) &\mapsto [X, Y] \end{aligned}$$

such that for all $X, Y, Z \in \mathfrak{g}$,

- $[Y, X] = -[X, Y]$,
- $[X, [Y, Z]] = [[X, Y], Z] + [Y, [X, Z]]$.

Example 9.11. Let $\mathfrak{g} = M_n(\mathbb{R})$, $[X, Y] = XY - YX$ is the anti-commutator.

Example 9.12. Let M be a manifold, $\mathfrak{g} = \text{Der}(C^\infty(M)) = \{X : C^\infty(M) \rightarrow C^\infty(M) \mid X(fg) = X(f) \cdot g + f \cdot X(g)\}$. Therefore, \mathfrak{g} is a Lie algebra with the bracket $[X, Y](f) = X(Y(f)) - Y(X(f))$ for all $f \in C^\infty(M)$. This is the Lie algebra of vector fields on M .

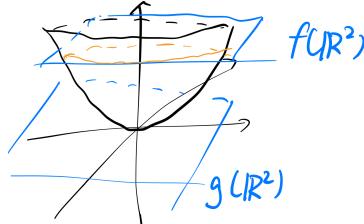
Example 9.13. Let $\mathfrak{g} = \mathbb{R}^3$, then $[v, w] := v \times w$ is a Lie algebra with cross product.

We will see that for all Lie group G , $\mathfrak{g} = \text{Lie}(G) = T_e G$ is naturally a Lie algebra.

Definition 9.14. Let $F : M \rightarrow N$ be a C^∞ -map, $Z \subseteq N$ be an embedded submanifold. We say F is *transverse* to Z , denoted $F \pitchfork Z$, if for all $x \in F^{-1}(Z)$, $T_x F(T_x M) + T_{F(x)} Z = T_{F(x)} N$.

Example 9.15. If $Z = \{c\}$, then $F \pitchfork c$ if and only if for all $q \in F^{-1}(c)$, $(T_q F)(T_q N) + T_c c = T_c N$, if and only if for all $q \in F^{-1}(c)$, $(T_q F)(T_q N) = T_c N$, if and only if c is a regular value of F .

Example 9.16. Let $M = \mathbb{R}^2$, $N = \mathbb{R}^3$, $Z = \{(x, y, z) \mid z = x^2 + y^2\}$, with $f(x, y) = (x, y, 1)$ and $g(x, y) = (x, y, 0)$, then $f \pitchfork Z$ but $g \nparallel Z$.



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Theorem 10.1. Suppose $f : M \rightarrow N$ is transverse to an embedded submanifold $Z \subseteq N$, then

- (i) $f^{-1}(z)$ is an embedded submanifold of M .
- (ii) If $f^{-1}(z) \neq \emptyset$, then $\dim(M) - \dim(f^{-1}(z)) = \dim(N) - \dim(Z)$, i.e., $\text{codim}(f^{-1}(z)) = \text{codim}(Z)$.

Proof. Fix $z_0 \in Z$ with $f^{-1}(z_0) \neq \emptyset$, let $\psi : V \rightarrow \mathbb{R}^n$ be a coordinate chart on N , adapted to Z such that $\psi(V \cap Z) = \psi(V) \cap (\mathbb{R}^k \setminus \{0\})$. Let $\pi : \mathbb{R}^k \times \mathbb{R}^{n-k} \rightarrow \mathbb{R}^{n-k}$ be the canonical projection, then

$$(\pi \circ \psi)^{-1}(0) = \psi^{-1}(\pi^{-1}(0)) = \psi^{-1}(\psi(V) \cap (\mathbb{R}^k \times \{0\})) = Z \cap V,$$

therefore

$$(\pi \circ \psi \circ f)^{-1}(0) = f^{-1}(Z \cap V) = f^{-1}(Z) \cap f^{-1}(V).$$

Claim 10.2. 0 is a regular value of $\pi \circ \psi \circ f|_{f^{-1}(V)}$.

Subproof. Take arbitrary $x \in (\pi \circ \psi \circ f)^{-1}(0) = f^{-1}(V) \cap f^{-1}(Z)$, then $T_x f(T_x M) + T_{f(x)} Z = T_{f(x)} N$. Note that $T_x M = T_x(f^{-1}(V))$. Therefore,

$$\mathbb{R}^k \times \mathbb{R}^{n-k} = T_{f(x)} \psi(T_{f(x)} N) = T_{f(x)} \psi(T_x f(T_x f^{-1}(V))) + T_{f(x)} \psi(T_{f(x)} Z)$$

by applying $T_{f(x)} \psi$ on both sides. Now apply $T_{\psi(f(x))} \psi$ on both sides, then $T_{f(x)} \psi(T_{f(x)} Z)$ vanishes, so we get

$$\begin{aligned} \mathbb{R}^{n-k} &= T_{\psi(f(x))} \pi(T_{f(x)} \psi(T_x f(T_x f^{-1}(V)))) \\ &= T_x(\pi \circ \psi \circ f)(T_x f^{-1}(V)). \end{aligned}$$

■
□

Definition 10.3. A C^∞ -map $f : Q \rightarrow M$ is an *embedding* if

- (i) $f(Q) \subseteq M$ is an embedded submanifold, and
- (ii) $f : Q \rightarrow f(Q)$ is a diffeomorphism.

Remark 10.4. We know $f : Q \rightarrow f(Q)$ is C^∞ since $f(Q) \subseteq M$ is embedded and $f : Q \rightarrow M$ is given by the composition of $i : f(Q) \hookrightarrow M$ and $f : Q \rightarrow f(Q)$.

Remark 10.5. 1. Since $f : Q \rightarrow f(Q)$ is a diffeomorphism, then it is a homeomorphism. Thus $f : Q \rightarrow M$ is a topological embedding.

- 2. For all $q \in Q$, then $T_q f : T_q Q \rightarrow T_{f(q)} M$ is injective, i.e., $T_q f(T_q Q) = T_{f(q)} f(Q)$.

Example 10.6 (Non-example). Let $Q = \mathbb{R}$ with discrete topology, then Q is a paracompact but not second countable as a 0-dimensional manifold. Consider

$$\begin{aligned} f : Q &\rightarrow \mathbb{R}^2 \\ x &\mapsto (x, 0) \end{aligned}$$

be a C^∞ -map, then this is not an embedding.

Example 10.7. Let M be a manifold with $f \in C^\infty(M)$, then

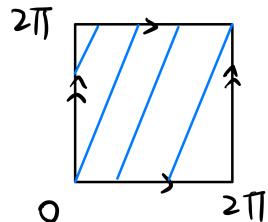
$$\begin{aligned} g : M &\rightarrow M \times \mathbb{R} \\ q &\mapsto (q, f(q)) \end{aligned}$$

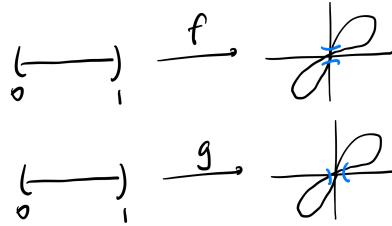
gives an embedding of M into $R \times \mathbb{R}$, as the graph of f .

Definition 10.8. A C^∞ -map $f : Q \rightarrow M$ is an *immersion* if for all $q \in Q$, $T_q f : T_q Q \rightarrow T_{f(q)} M$ is injective.

Example 10.9. Consider

$$\begin{aligned} f : \mathbb{R} &\rightarrow S^1 \times S^1 \\ \theta &\mapsto (e^{i\theta}, e^{i\sqrt{2}\theta}) \end{aligned}$$





Example 10.10. Now $g \circ f^{-1} : (0, 1) \rightarrow (0, 1)$ is not an embedding, as it is not continuous.

Definition 10.11. The *rank* of a C^∞ -map $f : M \rightarrow N$ at a point $q \in M$ is the rank of the linear map $T_q f : T_q M \rightarrow T_{f(q)} N$, i.e., $\text{rank}_q(f) = \dim(T_q f(T_q M))$.

Example 10.12. If $f : M \rightarrow N$ is an immersion, then $\text{rank}_q(f) = \dim_q(M)$.

Remark 10.13. Immersions are embeddings.

Theorem 10.14 (Rank Theorem). Let $F : M \rightarrow N$ be a C^∞ -map of constant rank k . Then for all $q \in M$, there exists coordinates $\varphi = (x_1, \dots, x_m) : U \rightarrow \mathbb{R}^m$ on M with $q \in U$, and $\psi = (y_1, \dots, y_n) : V \rightarrow \mathbb{R}^n$ with $F(q) \in V$ such that $(\psi \circ F \circ \varphi^{-1})(r_1, \dots, r_m) = (r_1, \dots, r_k, 0, \dots, 0)$ for all $r = (r_1, \dots, r_m) \in \varphi(F^{-1}(V) \cap U)$.

Notation. Given a collection of sets $\{S_\alpha\}_{\alpha \in A}$, $\coprod_{\alpha \in A} S_\alpha$ is the disjoint union of the collection.

We will give the following construction of a tangent bundle.

Remark 10.15. Given a manifold M , we form a set $TM = \coprod_{q \in M} T_q M$. Given a chart $\varphi = (x_1, \dots, x_n) : U \rightarrow \mathbb{R}^m$ on M , the corresponding candidate chart is $\tilde{\varphi} : TU = \coprod_{q \in U} T_q M \rightarrow \varphi(U) \times \mathbb{R}^m$. One can check that if $\varphi : U \rightarrow \mathbb{R}^m$ and $\psi : V \rightarrow \mathbb{R}^m$ are charts on M with $U \cap V \neq \emptyset$, then $\tilde{\varphi} \tilde{\varphi}^{-1} : \varphi(U \cap V) \times \mathbb{R}^m \rightarrow \psi(U \cap V) \times \mathbb{R}^m$ is C^∞ . Now we give TM the topology making $\tilde{\varphi}$'s homeomorphic onto their images, then $\{\tilde{\varphi} : TU \rightarrow \varphi(U) \times \mathbb{R}^m\}$ will be an atlas on TM .

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Definition 11.1. A map $f : M \rightarrow N$ is a *submersion* if for all $p \in M$, the differential $T_p f : T_p M \rightarrow T_{f(p)} N$ is onto.

Remark 11.2. Every value over a submersion is regular.

Recall. For a manifold M , we defined the set $TM = \coprod_{q \in M} T_q M = \bigcup (\{q\} \times T_q M)$, which is called a tangent bundle, with additional structures. We will show that TM is a manifold, and

$$\begin{aligned}\pi : TM &\rightarrow M \\ (q, v) &\mapsto q\end{aligned}$$

is C^∞ and a submersion.

Proof. Let $\varphi = (x_1, \dots, x_m) : U \rightarrow \mathbb{R}^m$ be a coordinate chart on M . For any $q \in U$, let $\left\{ \frac{\partial}{\partial x_1} \Big|_q, \dots, \frac{\partial}{\partial x_m} \Big|_q \right\}$ be a basis of $T_q M$. The dual basis is $\{(dx_1)_q, \dots, (dx_m)_q\}$. For any $v \in T_q M$, we have $v = \sum v(x_i) \frac{\partial}{\partial x_i} \Big|_q := \sum (dx_i)_q(v) \frac{\partial}{\partial x_i} \Big|_q$, and

$$\begin{aligned}T_q M &\rightarrow \mathbb{R} \\ v &\mapsto ((dx_1)_q(v), \dots, (dx_m)_q(v))\end{aligned}$$

is a linear isomorphism. Define

$$\begin{aligned}\tilde{\varphi} : TU &= \coprod_{q \in M} T_q M \rightarrow \mathbb{R}^m \times \mathbb{R}^m \\ (q, v) &\mapsto (x_1(q), \dots, x_m(q), (dx_1)_q(v), \dots, (dx_m)_q(v)).\end{aligned}$$

Suppose $\psi = (y_1, \dots, y_m) : V \rightarrow \mathbb{R}^m$ is another chart, we then have

$$\begin{aligned}\tilde{\psi} : TV &\rightarrow \mathbb{R}^m \times \mathbb{R}^m \\ (q, v) &\mapsto (y_1(q), \dots, y_m(q), (dy_1)_q(v), \dots, (dy_m)_q(v)).\end{aligned}$$

Claim 11.3. For any $(r, w) \in \varphi(U \cap V) \times \mathbb{R}^m$, we have

$$\begin{aligned}(\tilde{\psi} \circ \tilde{\varphi}^{-1})(r, w) &= ((\psi \circ \varphi^{-1})(r), \sum_j \frac{\partial y_1}{\partial x_j}(\varphi^{-1}(r))w_i, \dots, \sum_j \frac{\partial y_m}{\partial x_j}(\varphi^{-1}(r))w_i) \\ &= \left((\psi \circ \varphi^{-1})(r), \left(\frac{\partial y_i}{\partial x_j}(\varphi^{-1}(r)) \right) \begin{pmatrix} w_1 \\ \vdots \\ w_m \end{pmatrix} \right)\end{aligned}$$

Subproof.

Recall. If $T : A \rightarrow B$ is a linear map, with $\{e_1, \dots, e_n\}$ basis of A , $\{f_1, \dots, f_n\}$ is a basis of B , with dual basis $\{f_1^*, \dots, f_n^*\}$, then we set $t_{ij} = f_u^*(Te_j)$, i.e.,

$$\begin{array}{ccc} \mathbb{R}^n & \xrightarrow{(t_{ij})} & \mathbb{R}^n \\ (v_1, \dots, v_n) \mapsto \sum v_i e_i & \downarrow & \downarrow \\ A & \xrightarrow{T} & B \end{array}$$

In our case, we have $A = B = T_q M$ with $T = \text{id}$, with basis $\left\{ \frac{\partial}{\partial x_i} \Big|_q \right\}$ of A , $\{f_1, \dots, f_n\} = \left\{ \frac{\partial}{\partial y_1} \Big|_q, \dots, \frac{\partial}{\partial y_m} \Big|_q \right\}$ and dual basis $\{f_1^*, \dots, f_m^*\} = \{(dy_1)_q, \dots, (dy_m)_q\}$, then

$$\begin{aligned}t_{ij} &= (dy_i)_q \left(\frac{\partial}{\partial x_j} \Big|_q \right) \\ &= \frac{\partial}{\partial x_j} (y_i)(q) \\ &= \frac{\partial y_i}{\partial x_j}(\varphi^{-1}(q)).\end{aligned}$$

■

We define the topology on TM to be the topology generated by the sets of form $\tilde{\varphi}^{-1}(W)$ where $\varphi : U \rightarrow \mathbb{R}^m$ is a coordinate chart with open subset $W \subseteq \mathbb{R}^m \times \mathbb{R}^m$. Given an atlas $\{\varphi_\alpha : U_\alpha \rightarrow \mathbb{R}^m\}$ on M , we get an induced atlas $\{\tilde{\varphi}_\alpha : TU_\alpha \rightarrow \mathbb{R}^m \times \mathbb{R}^m\}$ on TM . One can check that the choice of an atlas on M does not matter. □

Exercise 11.4. • If M is Hausdorff, then so is TM .

- If M is second countable, then so is TM .

Lemma 11.5. The canonical projection $\pi : TM \rightarrow M$ is C^∞ and is a submersion.

Proof. Let $\varphi = (x_1, \dots, x_m) : U \rightarrow \mathbb{R}^m$ be a coordinate chart, $\tilde{\varphi} : TU \rightarrow \mathbb{R}^m \times \mathbb{R}^m$ be the induced chart on TM , then

$$\begin{aligned} (\varphi \circ \pi \circ \tilde{\varphi}^{-1})(r, w) &= \varphi \circ \pi \left(\varphi^{-1}(r), \sum_i w_i \frac{\partial}{\partial x_i} \Big|_q \right) \\ &= \varphi(\varphi^{-1}(r)) \\ &= r. \end{aligned}$$

Moreover,

$$(T_{(r,w)}(\varphi \circ \pi \circ \tilde{\varphi}^{-1})) (v, w') = v$$

where $(v, w') \in T_{(r,w)}(\varphi(U) \times \mathbb{R}^m) \cong \mathbb{R}^n \times \mathbb{R}^m$. Therefore, $T_{(q,v)}\pi : T_{(q,v)}TM \rightarrow T_q M$ is onto, hence a submersion. \square

Definition 11.6. A (*algebraic*) *vector field* on a manifold M is a derivation $v : C^\infty(M) \rightarrow C^\infty(M)$, i.e., v is \mathbb{R} -linear and $v(fg) = v(f)g + fv(g)$ for all $f, g \in C^\infty(M)$.

Definition 11.7. A (*geometric*) *vector field* on a manifold M is a section of the tangent bundle TM of M , i.e., $X : M \rightarrow TM$ is C^∞ with $\pi \circ X = \text{id}_M$. Geometrically, this depicts tangent vectors over a point with directions in $X(q)$.

Notation.

- $\text{Der}(C^\infty(M))$ is the set of all derivations of $C^\infty(M)$.

- $\mathfrak{X}(M) = \Gamma(TM)$ is the set of sections of $\pi : TM \rightarrow M$.

Proposition 11.8. Given a section $v : M \rightarrow TM$ in $\mathfrak{X}(M)$, we can try and define

$$\begin{aligned} D_v : C^\infty(M) &\rightarrow C^\infty(M) \\ (D_v(f))(q) &\mapsto v(q)f \end{aligned}$$

and this assignment $v \mapsto D_v$ is a linear isomorphism.

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Recall. $TM = \coprod_{q \in M} T_q M$ is a manifold. To show this, given chart $\varphi = (x_1, \dots, x_m) : U \rightarrow \mathbb{R}^m$ on M , we set

$$\begin{aligned} \tilde{\varphi} = (x_1, \dots, x_m, dx_1, \dots, dx_m) : TU &\equiv \coprod_{q \in U} T_q M \rightarrow \mathbb{R}^m \rightarrow \mathbb{R}^m \\ (q, v) &\mapsto (\varphi(q), (dx_1)_q(v), \dots, (dx_m)_q(v)) \end{aligned}$$

with inverse

$$\tilde{\varphi}^{-1}(r, u) = (\varphi^{-1}(r), \sum_i u_i \frac{\partial}{\partial q_i} \Big|_{\varphi(r)}).$$

Also,

$$\begin{aligned} \pi : TM &\rightarrow M \\ (q, v) &\mapsto q \end{aligned}$$

is a C^∞ -submersion.

We defined vector fields in two ways,

- as sections of tangent bundle $\pi : TM \rightarrow M$, i.e., as C^∞ -maps $X : M \rightarrow TM$ such that $\pi X = \text{id}$, i.e., $X(q) \in T_q M$, and
- as derivations $c : C^\infty(M) \rightarrow C^\infty(M)$, i.e., as \mathbb{R} -linear maps such that $c(fg) = fv(g) + fv(f)g$ for all $f, g \in C^\infty(M)$.

Remark 12.1. Both $\Gamma(TM)$ and $\mathfrak{X}(M)$ are \mathbb{R} -vector spaces, and $C^\infty(M)$ -modules.

We now prove [Proposition 11.8](#).

Proof. Given $v \in \Gamma(TM)$ and $f \in C^\infty(M)$, consider a function

$$\begin{aligned} D_v f : M &\rightarrow \mathbb{R} \\ (D_v(f))(q) &= v(q)f \end{aligned}$$

To go back, given $X \in \text{Der}(C^\infty(M))$, for any $q \in M$, we have $\text{ev}_q : C^\infty(M) \rightarrow \mathbb{R}$, and then $\text{ev}_q \circ X : C^\infty(M) \rightarrow \mathbb{R}$ is a tangent vector. Define $v_X(q) = \text{ev}_q \circ X$, and we can check other requirements like C^∞ and so on.

Claim 12.2. $D_v f$ is C^∞ .

Subproof. Given a chart $\varphi = (x_1, \dots, x_m) : U \rightarrow \mathbb{R}^m$, we have

$$\begin{aligned} \tilde{\varphi} : TU &\rightarrow \mathbb{R}^m \times \mathbb{R}^m \\ (q, v) &\mapsto (\varphi(q), dx_1(v), \dots, dx_m(v)) \end{aligned}$$

Since v is C^∞ , the map $\tilde{\varphi} \circ v|_U : U \rightarrow \mathbb{R}^m \times \mathbb{R}^m$, defined by $(\tilde{\varphi} \circ v)(q) = (\varphi(q), (dx_1)_q(v(q)), \dots, (dx_m)_q(v(q)))$, is C^∞ . Therefore, the assignment $q \mapsto (dx_i)_q(v(q))$ are C^∞ on U . Hence, $v = \sum v_i \frac{\partial}{\partial x_i}$ where $v_i(q) = (dx_i)_q(v(q))$ for all i . So $(D_v f)|_U = \left(\sum v_i \frac{\partial}{\partial x_i} \right) f = \sum v_i \frac{\partial f}{\partial x_i}$. This concludes the proof. \blacksquare

Also, for all $f, g \in C^\infty(M)$ and all q , we have

$$\begin{aligned} (D_v(fg))(q) &= v(q)(fg) \\ &= (v(q)f)g(q) + f(q)(v(q)g) \\ &= ((D_v f)g + f(D_v g))(q). \end{aligned}$$

Recall that derivations are local, i.e., for $X \in \text{Der}(C^\infty(M))$ and $f \in C^\infty(M)$ and $f|_U \equiv 0$, then $Xf|_U \equiv 0$. As a consequence, for $U \subseteq M$ open, define $X|_U : C^\infty(U) \rightarrow C^\infty(U)$ such that $(X|_U)(f|_U) = (Xf)|_U$ for all $f \in C^\infty(M)$. Now given a chart $\varphi = (x_1, \dots, x_m) : U \rightarrow \mathbb{R}^m$, we know x_i 's are in $C^\infty(U)$, then $(X|_U)(x_i)$ is a smooth function on U . Therefore,

$$\begin{aligned} v_X|_U &= \sum (dx_i)(v_X) \frac{\partial}{\partial x_i} \\ &= \sum v_X X(x_i) \frac{\partial}{\partial x_i} \\ &= \sum X|_U(x_i) \frac{\partial}{\partial x_i}, \end{aligned}$$

and thus $v_X|_U : U \rightarrow TU$ is C^∞ , and since U is arbitrary, then $v_X \in \Gamma(TM)$. \square

Recall. For any $X, Y \in \text{Der}(C^\infty(M))$, $[X, Y] \in \text{Der}(C^\infty(M))$. Therefore, $\text{Der}(C^\infty(M))$ is a real Lie algebra with bracket $(X, Y) \mapsto [X, Y]$. Note that $\text{Der}(C^\infty(M)) \subseteq \text{Hom}_{\mathbb{R}}(C^\infty(M), C^\infty(M))$.

Recall. If (A, \circ) is a real associative algebra, then $[a, b] := a \circ b - b \circ a$ gives A the structure of a Lie algebra, and $\text{Der}(C^\infty(M)) \subseteq \text{Hom}_{\mathbb{R}}(C^\infty(M), C^\infty(M))$.

Now given a C^∞ -map $f : M \rightarrow N$ of manifolds, we get a map

$$\begin{aligned} Tf : TM &\rightarrow TN \\ (q, v) &\mapsto (f(q), T_q f v) \end{aligned}$$

Exercise 12.3. Tf is C^∞ .

Remark 12.4. Given $f : M \rightarrow N$ and $v \in \Gamma(TM)$, we may not have a commutative diagram:

$$\begin{array}{ccc} TM & \xrightarrow{Tf} & TN \\ v \uparrow & & \uparrow ? \\ M & \xrightarrow{f} & N \end{array}$$

Definition 12.5. Let $f : M \rightarrow N$ be a smooth map on manifolds, then $v \in \Gamma(TM)$ and $w \in \Gamma(TN)$ are f -related if we have a commutative diagram

$$\begin{array}{ccc} TM & \xrightarrow{Tf} & TN \\ v \uparrow & & \uparrow w \\ M & \xrightarrow{f} & N \end{array}$$

That is, for any $q \in M$, $w(f(q)) = (f(q), T_q f(v(q)))$.

Equivalently, for $f : M \rightarrow N$, we say $X \in \text{Der}(C^\infty(M))$ is f -related to $Y \in \text{Der}(C^\infty(N))$ if for all $h \in C^\infty(N)$, we have $Y(h) \circ f = X(h \circ f)$ in $C^\infty(M)$.

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Recall. Let M be a manifold, we have a bijection

$$\begin{aligned} \Gamma(TM) &\rightarrow \text{Der}(C^\infty(M)) \\ v &\mapsto D_v : (Dv f)(q) = v_q(f) \quad \forall f, q \end{aligned}$$

with inverse by assignment $X \mapsto v_X$ where $v_X(q)f = (Xf)(q)$.

Lemma 13.1. Let $f : M \rightarrow N$, then $v \in \Gamma(TM)$ is f -related to $w \in \Gamma(TN)$ if and only if $D_v \in \text{Der}(C^\infty(M))$ is f -related to $D_w \in \text{Der}(C^\infty(N))$.

Proof. v is f -related to w if and only if $(T_q f)(v(q)) = w(f(q))$ for all q , if and only if $((T_q f)(v(q)))h = (w(f(q)))h$ for all q and all h , if and only if $(D_v(h \circ f))(q) = (D_w h)(f(q))$, if and only if $D_v(h \circ f) = D_w(h \circ f)$. \square

Lemma 13.2. Suppose $f : M \rightarrow N$, let $X_1, X_2 \in \text{Der}(C^\infty(M))$, and $Y_1, Y_2 \in \text{Der}(C^\infty(N))$ such that X_i is f -related to Y_i for $i = 1, 2$, then $[X_1, X_2]$ is f -related to $[Y_1, Y_2]$.

Proof. For any $h \in C^\infty(N)$, $X_i(h \circ f) = Y_i(h) \circ f$ for $i = 1, 2$. Therefore,

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

\square

Definition 13.3. Let $Q \subseteq M$ be an embedded submanifold. A vector field $Y \in \Gamma(TM)$ is tangent to Q if for all $q \in Q$, $Y(q) \in T_q Q$.

Example 13.4. If $M = \mathbb{R}^2$, let $Q = \mathbb{R} \times \{0\}$, then $Y(x_1, x_2) = x_1 \frac{\partial}{\partial x_1} + x_2 \frac{\partial}{\partial x_2}$, so $Y(x, 0) = x_1 \frac{\partial}{\partial x_1} + 0 \in T_{(x, 0)} Q$. Equivalently, we have $i : Q \hookrightarrow M$ to be an inclusion, so $Ti : TQ \hookrightarrow TM$ is an embedding since i is, as $Y(q) \in T_q Q$ for all $q \in Q$ indicates $(Y \circ i)(Q) \subseteq TQ$:

$$\begin{array}{ccc} Q & \xrightarrow{i} & M \\ Y \circ i \downarrow & & \downarrow Y \\ TQ & \xhookrightarrow[Ti]{} & TM \end{array}$$

Hence, $Y \circ i : Q \rightarrow TQ$ is a vector field on Q , and $Y \circ i$ is i -related to Y .

Lemma 13.5. Let $Q \subseteq M$ be an embedded submanifold, let $Y_1, Y_2 \in \Gamma(TM)$ which are tangent to Q , then $[Y_1, Y_2]$ is tangent to Q .

Proof. Since $Y_i|_Q$ is i -related to Y_i , then $[Y_1, Y_2]|_Q$ is i -related to $[Y_1, Y_2]$. \square

Definition 13.6. Let G be a Lie group, then we give $T_e G$ the structure of a Lie algebra. A vector field $X : G \rightarrow TG$ is *left-invariant* if for all $a \in G$, $TL_a(X(g)) = X(L_a g)$ for all $g \in G$ and all $a \in G$, that is, X is L_a -related to X where $L_a(g) = ag$ is the left translation.

Recall. • $(La)^{-1} = L_{a^{-1}}$.

- By [Lemma 13.2](#), if X and Y are left-invariant, then so is $[X, Y]$.

Notation. We denote $\mathfrak{g} = \text{Lie}(G)$ to be the Lie algebra of the left-invariant vector fields.

Lemma 13.7. Let G be a Lie group, let \mathfrak{g} be the space of left-invariant vector fields, then the evaluation map

$$\begin{aligned}\text{ev}_e : \mathfrak{g} &\rightarrow T_e G \\ X &\mapsto X(e)\end{aligned}$$

is an \mathbb{R} -linear bijection. In particular, they have the same dimension.

Proof. Obviously ev_e is linear. If $X(e) = 0$, then for all $a \in G$, $X(a) = X(L_a e) = (TL_a)_e(X(e)) = 0$, so ev_e is injective. Conversely, given $v \in T_e G$, define

$$\begin{aligned}\tilde{v} : G &\rightarrow TG \\ a &\mapsto (TL_a)_e v\end{aligned}$$

then \tilde{v} is left-invariant. We know

$$\begin{aligned}m : G \times G &\rightarrow G \\ (a, b) &\mapsto ab\end{aligned}$$

is C^∞ , so $T_m : TG \times TG \rightarrow TG$ is C^∞ . Consider

$$\begin{aligned}f : G &\rightarrow TG \times TG \\ a &\mapsto ((a, 0), (e, v)).\end{aligned}$$

Claim 13.8. $(T_m \circ f)(a) = (T_e L_a)(v)$.

Subproof. Pick $\gamma : I \rightarrow G$ such that $\gamma(0) = e$ and $\dot{\gamma}(0) = v$, then

$$\begin{aligned}\sigma : I &\rightarrow G \times G \\ t &\mapsto (a, \gamma(t))\end{aligned}$$

is C^∞ where $\sigma(0) = (a, e)$, and $\frac{d}{dt}|_0 (a, \gamma(t)) = (0, v) \in T_{(a,e)}(G \times G)$. Now

$$\begin{aligned}T_m(f(a)) &= (T_m)_{(a,e)}(0, v) \\ &= \frac{d}{dt}|_0 m(\sigma(t)) \\ &= \frac{d}{dt}|_0 a\gamma(t) \\ &= \frac{d}{dt}|_0 L_a(\gamma(t)) \\ &= (T_e L_a)(\dot{\gamma}(0)) \\ &= (T_e L_a)(v) \\ &= \tilde{v}(a).\end{aligned}$$

■

□

Therefore, the left-invariant vector field $\text{Lie}(G)$ is isomorphic to $T_e G$ as \mathbb{R} -vector spaces.

Definition 13.9. Let $X : M \rightarrow TM$ be a vector field. An *integral curve* $\gamma : I \rightarrow M$ of X passing through q at $t = 0$ is a C^∞ -map $\gamma : I \rightarrow M$ such that $\gamma(0) = q$ and $\dot{\gamma}(t) = X(\gamma(t))$ for all $t \in I$. Here $\dot{\gamma}(t) = (T_t \gamma) \left(\frac{d}{dt}|_t \right) \in T_{\gamma(t)} M$. Equivalently, $\dot{\gamma}(t)f = X(\gamma(t))f = \frac{d}{dt}|_t (f \circ \gamma)$ for all $f \in C^\infty(M)$.

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Remark 14.1. if $\varphi = (x_1, \dots, x_m) : U \rightarrow \mathbb{R}^m$ is a coordinate chart and v is a vector field on U , so $v = \sum v_i \frac{\partial}{\partial x_i}$ for v_1, \dots, v_m in $C^\infty(U)$. This is a section $q \mapsto \sum v_i(q) \frac{\partial}{\partial x_i} \Big|_q \in \Gamma(TU)$ and for all $f \in C^\infty(U)$, $f \mapsto \sum v_i \frac{\partial f}{\partial x_i} \in C^\infty(U)$ which is a derivation.

Recall. An integral curve of $X \in \Gamma(TM)$ is a curve $\gamma : I \rightarrow M$ with $\gamma(0) = q$ such that $\frac{d\gamma}{dt} \Big|_t = X(\gamma(t))$.

Example 14.2. Let $M = U$ be open in \mathbb{R}^m , and $X = \sum x_i \frac{\partial}{\partial x_i}$. Let $\gamma(t) = (\gamma_1(t), \dots, \gamma_m(t))$ for $\gamma_i \in C^\infty(I)$, then $\frac{d\gamma}{dt} \Big|_t = \sum \gamma'_i(t) \frac{\partial}{\partial \gamma_i}$. Therefore, $\frac{d\gamma}{dt} = X(\gamma(t))$ amounts to $\sum \gamma'_i(t) \frac{\partial}{\partial \gamma_i} = \sum x_i(\gamma(t)) \frac{\partial}{\partial \gamma_i}$. Therefore, $\gamma'_i(t) = x_i(\gamma_1(t), \dots, \gamma_m(t))$.

Hence, γ is an integral curve of X if and only if γ solves such a system of equations with initial condition $\gamma(0) = q$.

Theorem 14.3. Let $U \subseteq \mathbb{R}^m$ be open, $X = (x_1, \dots, x_m) : U \rightarrow \mathbb{R}^m$ be C^∞ , then for all $q_0 \in U$, there exists an open neighborhood V of q_0 in U and $\varepsilon > 0$, and a C^∞ -map $\Phi : V \times (-\varepsilon, \varepsilon) \rightarrow U$ such that for all $q \in V$, $\gamma_q(t) := \Phi(q, t)$ solves $\gamma'_i(t) = x_i(\gamma_1(t), \dots, \gamma_m(t))$ with initial condition $\gamma_q(0) = q$. Moreover, such mapping Φ is unique.

Proof. Apply contraction mapping principle. \square

Example 14.4. Say $U = (-1, 1)$, let

$$\begin{aligned} X : (-1, 1) &\rightarrow \mathbb{R} \\ x &\mapsto \frac{d}{dx} \end{aligned}$$

with $X(q) = 1$ be the ODE, i.e., $\frac{dX}{dt} = 1$ with $X(0) = q$, then $\Phi(q, t) = q + t$. The domain of definition of Φ is $W = \{(q, t) \mid q \in (-1, 1), q + t \in (-1, 1)\}$.

Remark 14.5. We need to keep track of the initial conditions. Say $\gamma : (a, b) \rightarrow M$ is an integral curve of vector field X on M with $\gamma(0) = q$, then for all $t_0 \in (a, b)$, we know

$$\begin{aligned} \sigma : (a - t_0, b - t_0) &\rightarrow M \\ s &\mapsto \gamma(s + t_0) \end{aligned}$$

is also an integral curve. Therefore, γ and σ has the same image.

Proof.

$$\begin{aligned} \frac{d}{dt} \Big|_t \sigma &= \frac{d}{ds} \Big|_t \gamma(s + t_0) \\ &= \frac{d}{du} \Big|_{u=t+t_0} \gamma(u) \\ &= X(\gamma(t + t_0)) \\ &= X(\sigma(t)). \end{aligned}$$

\square

Lemma 14.6. Let $X : M \rightarrow TM$ be a vector field, $\varphi = (x_1, \dots, x_m) : U \rightarrow \mathbb{R}^m$ be a coordinate chart and $X = \sum x_i \frac{\partial}{\partial x_i}$ where $x_i \in C^\infty(U)$, then $\gamma : I \rightarrow U$ with $\gamma(0) = q$ is an integral curve of X if and only if $(x_1 \circ \gamma, \dots, x_m \circ \gamma) : I \rightarrow \mathbb{R}^m$ solves $y'_i = Y_i(Y_1, \dots, y_m)$ with $y_i(0) = x_i(\gamma(0))$. Here $Y_i = X_i \circ \varphi^{-1} \in C^\infty(\varphi^{-1}(U))$.

Proof. We have $\dot{\gamma}(t) = \sum dx_i(\dot{\gamma}(t)) \frac{\partial}{\partial x_i} = \sum (x_i \circ \gamma)'(t) \frac{\partial}{\partial x_i}$. Therefore, $\dot{\gamma}(t) = X(\gamma(t))$ if and only if $(X_i \circ \gamma)' = X_i(\gamma(t)) = (X_i \circ \varphi^{-1})(\varphi(\gamma(t))) = Y_i(X_1 \circ \gamma(t), \dots, X_m \circ \gamma(t))$ for all i . \square

Corollary 14.7. Let $X : M \rightarrow TM$ be a vector field, then for all $q \in M$, there exists an integral curve $\gamma : I \rightarrow M$ of X such that $\gamma(0) = q$. Moreover, γ depends smoothly on q , and is locally unique: for all integral curve $\sigma : J \rightarrow M$ of X mapping $0 \mapsto q$, there exists $\delta > 0$ such that $(-\delta, \delta) \in I \cap J$ and $\gamma|_{(-\delta, \delta)} = \sigma|_{(-\delta, \delta)}$.

Remark 14.8. It may not be the case that $\gamma|_{I \cap J} = \sigma|_{I \cap J}$. This is true if M is Hausdorff.

Example 14.9. Consider line with two origins in [Example 1.10](#), with translations that agree before the origins.

Lemma 14.10. Suppose $\gamma : I \rightarrow M$ and $\sigma : J \rightarrow M$ are continuous curves, and M is Hausdorff, then the set $Z = \{t \in I \cap J \mid \gamma(t) = \sigma(t)\}$ is closed in $I \cap J$.

Proof. Note that

$$\begin{aligned} (\gamma, \sigma) : I \cap J &\rightarrow M \times M \\ t &\mapsto (\gamma(t), \sigma(t)) \end{aligned}$$

is continuous, and $Z = (\gamma, \sigma)^{-1}(\Delta_M)$. \square

Lemma 14.11. Let $\gamma : I \rightarrow M$ and $\sigma : J \rightarrow M$ be two integral curves of a vector field X on M with $\sigma(0) = \gamma(0)$, then $W = \{t \in I \cap J \mid \gamma(t) = \sigma(t)\}$ is open in $I \cap J$.

Proof. Given $t_0 \in W$, then $t_0 \in I \cap J$ and $\sigma(t_0) = \gamma(t_0)$, and we consider $\tilde{\sigma}(t) := \sigma(t + t_0)$ and $\tilde{\gamma}(t) = \gamma(t + t_0)$, then $\tilde{\sigma}(0) = \sigma(t_0) = \gamma(t_0) = \tilde{\gamma}(0)$. Both $\tilde{\gamma}$ and $\tilde{\sigma}$ are integral curves of X with $\tilde{\sigma}(0) = \tilde{\gamma}(0)$, therefore by [Corollary 14.7](#), there exists $\delta > 0$ such that $\tilde{\sigma}|_{(-\delta, \delta)} = \tilde{\gamma}|_{(-\delta, \delta)}$, then $t_0 + (-\delta, \delta) = (t_0 - \delta, t_0 + \delta) \subseteq W$. \square

Lemma 14.12. Let M be a Hausdorff manifold, $X \in \Gamma(TM)$, $\gamma : I \rightarrow M$ and $\sigma : J \rightarrow M$ be two integral curves with $\gamma(0) = \sigma(0)$, then $\gamma|_{I \cap J} = \sigma|_{I \cap J}$.

Proof. Since I and J are intervals, then $I \cap J$ is connected. By [Lemma 14.11](#) and [Lemma 14.10](#), $W = \{t \in I \cap J \mid \gamma(t) = \sigma(t)\}$ is clopen, thus $W = I \cap J$. \square

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Recall. We introduced integral curves of vector fields, and in particular we introduced [Lemma 14.12](#).

Corollary 15.1. For any vector field $X \in \Gamma(TM)$ and any $q \in M$, there exists a unique maximal integral curve $\gamma_q : I_q \rightarrow M$ of X with $\gamma_q(0) = q$. Here *maximal* means that if $\sigma : J \rightarrow M$ is another integral curve of X with $\sigma(0) = q$, then $J \subseteq I_q$ and $\sigma = \gamma_q|_J$.

Proof. Consider the subset $\Gamma \subseteq \mathbb{R} \times M$ defined as follows: let Y be the set of all integral curves γ of X with $\gamma(0) = q$, then define $\Gamma = \bigcup_{\gamma \in Y} \text{graph}(\gamma)$. By [Lemma 14.12](#), Γ is a graph of a smooth curve, which is the desired maximal integral curve γ_q of X with $\gamma_q(0) = q$. \square

Lemma 15.2. Let $f : M \rightarrow N$ be a map of manifolds, with $X \in \Gamma(TM)$ and $Y \in \Gamma(TY)$, and $Tf \circ X = Y \circ f$, i.e., X and Y are f -related, then for any integral curve γ of X , $f \circ \gamma$ is an integral curve of Y .

Proof. We have

$$\begin{aligned} \frac{d}{dt} (f \circ \gamma)|_t &= T_t(f \circ \gamma) \left(\frac{d}{dt} \right) \\ &= T_{\gamma(t)}f \left(T_t \gamma \left(\frac{d}{dt} \right) \right) \\ &= T_{\gamma(t)}f(X(\gamma(t))) \\ &= Y(f(\gamma(t))) \\ &= Y((f \circ \gamma)(t)). \end{aligned}$$

\square

Example 15.3. Let $M = (-1, 1)$, $N = \mathbb{R}$, $f : (-1, 1) \hookrightarrow \mathbb{R}$ be the inclusion. Let $X = \frac{d}{dt}$ and $Y = \frac{d}{dt}$, then

$$\begin{aligned}\gamma : (-1, 1) &\rightarrow M \\ t &\mapsto t\end{aligned}$$

is a maximal integral curve of X with $\gamma(0) = 0$. Note that it is not a maximal integral curve of Y because $f \circ \gamma$ is not an integral curve of Y that is not maximal.

Example 15.4. Let $M = \mathbb{R}^2$ and $N = \mathbb{R}$, then consider $f(x, y) = x$ with $X = \frac{\partial}{\partial x} + y^2 \frac{\partial}{\partial y}$, with $Y(x) = \frac{d}{dx}$, then $\gamma_x(t) = x + t$ is the integral curve of Y with $\gamma_x(0) = x$. It is defined for all $t \in \mathbb{R}$.

To compute integral curves of X , we solve

$$\begin{cases} \dot{x} = 1, x(0) = x_0 \\ \dot{y} = y^2, y(0) = y_0, \end{cases}$$

then $x(t) = x_0 + t$ and $\frac{1}{y} \frac{dy}{dt} = 1$, therefore

$$\int_0^t \frac{1}{y^2} \frac{dy}{dt} dt = \int_0^t dt$$

and so $t = -\frac{1}{y} \Big|_0^t = \frac{1}{y_0} - \frac{1}{y(t)}$, hence $y(t) = \frac{y_0}{1-y_0 t}$. Thus, $t \in (-\infty, \frac{1}{y_0})$. That is, the curve runs off to ∞ in finite time.

Definition 15.5. Let X be a vector field on a (Hausdorff) manifold M , and let $\gamma_q : I_q \rightarrow M$ be the unique maximal integral curve with $\gamma_q(0) = q$. Let $W = \bigcup_{q \in M} \{q\} \times I_q \subseteq M \times \mathbb{R}$, then the (*local*) flow of X is the map

$$\begin{aligned}\Phi : W &\rightarrow M \\ (q, t) &\mapsto \gamma_q(t)\end{aligned}$$

We say Φ is a *global flow* if $W = M \times \mathbb{R}$, and in this case we say X is *complete*.

Theorem 15.6. Let $\Phi : M \rightarrow M$ be a flow of a vector field, then

1. $M \times \{0\} \subseteq W$,
2. W is open, and
3. Φ is C^∞ .

Proof. See Lee. □

Example 15.7. Let $X = y^2 \frac{d}{dy} \in \Gamma(\mathbb{R})$, then $W = \{(y, t) \in \mathbb{R} \times \mathbb{R} \mid t < \frac{1}{y} \text{ when } y > 0, t \text{ arbitrary when } y = 0, t > \frac{1}{y} \text{ if } y < 0\}$. The flow is $\Phi(y, t) = \frac{y}{1-yt}$.

Lemma 15.8. Let $\Phi : W \rightarrow M$ be a local flow of a vector field X , then $\Phi(q, s+t) = \Phi(\Phi(q, s), t)$ whenever both sides are defined.

Remark 15.9. Note that if $s = -t$, then the left-hand side is defined, but the right-hand side is not.

Proof. Fix q and fix s such that $(q, s) \in W$. Consider $\sigma(t) = \Phi(q, s+t) = \gamma_q(s+t)$, and $\tau(t) = \Phi(\Phi(q, s), t) = \gamma_{\Phi(q, s)}(t)$, then $\tau(0) = \Phi(q, s) = \gamma_q(s) = \sigma(0)$. Both $\sigma(t)$ and $\tau(t)$ are integral curves, and that they agree at $t = 0$, then $\sigma(t) = \tau(t)$ for all t in the intersection of their domains of definition. Therefore, the two equations agree whenever both sides are defined. □

Definition 15.10. An (*left*) *action* of a Lie group G on a manifold M is a C^∞ -map

$$\begin{aligned}G \times M &\rightarrow M \\ (g, q) &\mapsto g \cdot q\end{aligned}$$

such that

1. $e \cdot q = q$ for all q , and
2. $g_1 \cdot (g_2 \cdot q) = (g_1 g_2) \cdot q$.

Claim 15.11. If X is complete, then its flow is an action of the Lie group $(\mathbb{R}, +, \cdot)$.

Proof. Define $t \cdot q = \Phi(q, t)$, then

$$\begin{aligned} t \cdot (s \cdot q) &= \Phi(\Phi(q, s), t) \\ &= \Phi(q, s + t) \\ &= (t + s) \cdot q \end{aligned}$$

and $0 \cdot q = \Phi(q, 0) = q$. □

Remark 15.12. If we have a group action, we determine the groupoid structure, and therefore we recover the groupoid version of the lemma.

Remark 15.13. For a Lie group G , the multiplication $m : G \times G \rightarrow G$ is a left action of G on G , with $e \cdot g = g$ and $a \cdot (b \cdot g) = (a \cdot b) \cdot g$.

Remark 15.14. For any manifold, there exists a group $\text{Diff}(M) = \{f : M \rightarrow M \mid f \text{ is a diffeomorphism}\}$, where the operation is function composition, and the identity is the identity map.

Exercise 15.15. An (left) action $G \times M \rightarrow M$ of a Lie group G on a manifold M gives rise to a homomorphism

$$\begin{aligned} \rho : G &\rightarrow \text{Diff}(M) \\ (\rho(g))(q) &\mapsto g \cdot q \end{aligned}$$

In particular, the multiplication $m : G \times G \rightarrow G$ gives rise to

$$\begin{aligned} L : G &\rightarrow \text{Diff}(G) \\ a &\mapsto L_a \end{aligned}$$

Definition 15.16. An *abstract local flow* on a manifold M is a C^∞ -map $\psi : W \rightarrow M$, where W is an open neighborhood of $M \times \{0\}$ in $M \times \mathbb{R}$, so that $\psi(q, 0) = q$ for all $q \in M$ and $\psi(q, s + t) = \psi(\psi(q, s), t)$ whenever both sides are defined.

We will show that any abstract local flow is part of a flow on a vector field.

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Recall. Given a vector field X on a manifold M , we define the flow to be $\Phi : W \rightarrow \mathbb{R}$ for some open neighborhood of $M \times \{0\}$ in $M \times \mathbb{R}$. The defining property of Φ would be that for every $q \in M$, $W \cap (\{q\} \times \mathbb{R}) = \{q\} \times I_q$ and $I_q \ni t \mapsto \Phi(q, t)$ is the maximal integral curve of X . We also proved that $\Phi(q, t + s) = \Phi(\Phi(q, t), s)$ for all q, t, s such that both sides are defined.

We say the flow is a global flow if $W = M \times \mathbb{R}$, that is, for all $q \in M$, the maximal integral curve $\gamma_q \in I_q \rightarrow M$ of X with $\gamma_q(0) = q$ is defined for all $t \in \mathbb{R}$, i.e., $I_q = \mathbb{R}$.

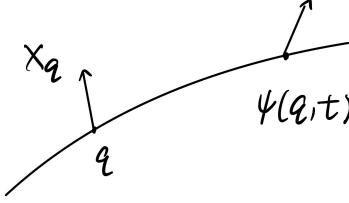
Lemma 16.1. Let M be a manifold, $U \subseteq M \times \mathbb{R}$ be an open neighborhood of $M \times \{0\}$ with $U \cap (\{q\} \times \mathbb{R})$ connected for all $q \in M$, and $\psi : U \rightarrow M$ a smooth map such that

1. $\psi(q, 0) = q$ for all q , and
2. $\psi(q, s + t) = \psi(\psi(q, s), t)$ whenever both sides are defined,

then there exists a vector field X on M such that for all $q \in M$, the assignment $t \mapsto \psi(q, t)$ is an integral (but not necessarily maximal) curve of X with $\psi(q, 0) = q$.

Proof. For all $q \in M$, we define $X(q) = \left. \frac{d}{dt} \right|_0 \psi(q, t)$, then

$$\begin{aligned} \left. \frac{d}{dt} \right|_t \psi(q, t) &= \left. \frac{d}{dt} \right|_0 \psi(q, t + s) \\ &= \left. \frac{d}{ds} \right|_0 \psi(\psi(q, t), s) \\ &= X(\psi(q, t)). \end{aligned}$$



□

Lemma 16.2. Let $\Phi : W \rightarrow M$ be a flow of a vector field X on a manifold M . Suppose there exists $\varepsilon > 0$ such that $M \times [-\varepsilon, \varepsilon] \subseteq W$, then $W = M \times \mathbb{R}$, i.e., the vector field X is complete.

Proof. We want to show that for all $q \in M$, $I_q := \{t \in \mathbb{R} \mid (q, t) \in W\}$ is \mathbb{R} . Since I_q is connected, then it suffices to show that I_q is unbounded. By assumption, $\varphi_\varepsilon(q) := \varphi(q, \varepsilon)$ and $\varphi_{-\varepsilon}(q) := \varphi(q, -\varepsilon)$ are defined for all $q \in M$, since $q = \varphi(q, 0) = \varphi(\varphi(q, \varepsilon), -\varepsilon) = \varphi(\varphi(q, -\varepsilon), \varepsilon)$, therefore $(\varphi_\varepsilon)^{-1}$ exists and is just $\varphi_{-\varepsilon}$.

Given $q \in M$, we consider $\mu(t) = \varphi(q, t + \varepsilon) = \gamma_q(\varepsilon + t)$, and it is easy to check that $\mu'(t) = X(\mu(t))$, therefore μ is an integral curve of X with $\mu(0) = \gamma_q(\varepsilon)$. Since γ_q is defined on I_q , then μ is defined for all t such that $t + \varepsilon \in I_q$, that is, $t \in I_q - \varepsilon$. Since $\gamma_{\varphi_\varepsilon(q)} : I_{\varphi_\varepsilon(q)} \rightarrow M$ is a maximal integral curve of X such that $\gamma_{\varphi_\varepsilon(q)}(0) = \Phi_\varepsilon(q) = \gamma_q(\varepsilon)$, so $I_q - \varepsilon \subseteq I_{\varphi_\varepsilon(q)}$, and similarly $I_q + \varepsilon \subseteq I_{\varphi_{-\varepsilon}(q)}$, therefore $I_{\varphi_\varepsilon(q)} + \varepsilon \subseteq I_{\varphi_{-\varepsilon}}(\varphi_\varepsilon(q)) = I_q$. Therefore, $I_q - \varepsilon = I_{\varphi_\varepsilon(q)}$. By induction, we conclude that for all $n > 0$, $I_q - n\varepsilon = I_{(\varphi_\varepsilon)^n(q)}$. Since $0 \in I_{q'}'$ for all q' , and $0 \in I_q - n\varepsilon$, so $n\varepsilon \in I_q$ for all $n \in \mathbb{N}$. Similar argument shows that $-n\varepsilon \in I_q$ for all $n \in \mathbb{N}$. That is, I_q is neither bounded above nor bounded below. □

Definition 16.3. The support of a vector field $X \in \Gamma(TM)$ is $\text{supp}(X) = \overline{\{q \in M \mid X(q) \neq 0\}}$.

Corollary 16.4. Suppose $X \in \Gamma(TM)$ has compact support, then X is complete: its flow exists for all time.

Proof. Note that $X \equiv 0$ on $M \setminus \text{supp}(X)$, so for all $q \in M \setminus \text{supp}(X)$. Note that $\gamma_q(t) = q$ is the maximal integral curve of X , which exists for all t , so $(M \setminus \text{supp}(X)) \times \mathbb{R} \subseteq W$, which is the domain of the flow φ . Since $\text{supp}(X)$ is compact, then $(\text{supp}(X) \times \{0\}) \subseteq W$ is compact. Since W is open, then by tube lemma, there exists $\varepsilon > 0$ such that $\text{supp}(X) \times (-2\varepsilon, 2\varepsilon) \subseteq W$, hence $\text{supp}(X) \times [-\varepsilon, \varepsilon] \subseteq W$. Therefore,

$$(M \setminus \text{supp}(X)) \times [-\varepsilon, \varepsilon] \subseteq (M \setminus \text{supp}(X)) \times \mathbb{R} \subseteq W,$$

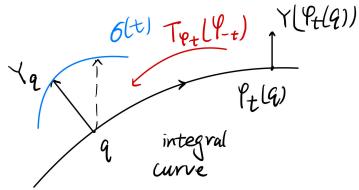
so $M \times [-\varepsilon, \varepsilon] \subseteq W$. Now apply Lemma 16.2. □

We will start talking about Lie derivatives. Let $X, Y \in \Gamma(TM)$ be two vector fields. For simplicity we assume X and Y have global flow $\varphi(q, t) = \varphi_t(q)$, and $\psi(q, t) = \psi_t(q)$, respectively. (It suffices to have the flow maintained for small neighborhood of time.) Fix $q \in M$. Consider

$$\begin{aligned} \sigma : \mathbb{R} &\rightarrow T_q M \\ t &\mapsto (T_{\varphi_t(q)} \varphi_{-t})(Y(\varphi_t(q))) \end{aligned}$$

Remark 16.5. For any curve $\gamma : \mathbb{R} \rightarrow M$, $\dot{\gamma}(t) \in T_{\gamma(t)}(T_q M) = T_q M$ since $\gamma_q M$ is a vector space. In particular,

$$\left. \frac{d\sigma}{dt} \right|_0 = \left. \frac{d}{dt} \right|_0 (T_{\varphi_t(q)} \varphi_{-t}(Y(\varphi_t(q)))) \in T_q M.$$



Definition 16.6. The *Lie derivative* $L_X Y$ of Y with respect to X is defined by

$$(L_X Y)(q) = \left. \frac{d}{dt} \right|_0 T_{\varphi_t(q)} \varphi_{-t}(Y(\varphi_t(q))) = \lim_{t \rightarrow 0} \frac{1}{t} (T_{\varphi_t(q)} \varphi_{-t}(Y(\varphi_t(q))) - Y_q).$$

Theorem 16.7. For any two vector fields $X, Y \in \Gamma(TM)$, $L_X Y = [X, Y]$.

To prove this, we will prove the following.

Lemma 16.8. Let M be a manifold and $\gamma : I \rightarrow T_q M$ be a curve. Let $f \in C^\infty(M)$, then

$$\left. \frac{d}{dt} \right|_0 (\gamma(t)f) = \left(\left. \frac{d\gamma}{dt} \right|_0 \right) f.$$

Proof. Choose a chart $(x_1, \dots, x_n) : U \rightarrow \mathbb{R}^m$ with $q \in U$, then $\gamma(t) = \sum \gamma_i(t) \left. \frac{\partial}{\partial x_i} \right|_q$, where each $\gamma_i : I \rightarrow \mathbb{R}$ is C^∞ .

Now $\left. \frac{d\gamma}{dt} \right|_0 = \sum \gamma'_i(0) \left. \frac{\partial}{\partial x_i} \right|_q$. We also know that $\gamma(t)f = \sum \gamma_i(t) \left. \frac{\partial f}{\partial x_i} \right|_q$, therefore $\left. \frac{d}{dt} \right|_0 \gamma(t) = \left. \frac{d}{dt} \right|_0 \left(\sum \gamma_i(t) \left. \frac{\partial f}{\partial x_i} \right|_q \right) = \sum \gamma'_i(0) \left. \frac{\partial f}{\partial x_i} \right|_q$ as well. \square

Lemma 16.9. Let X and Y be two vector fields with flows $\{\varphi_t\}$ and $\{\psi_t\}$, viewed as family of diffeomorphisms with \mathbb{R} -actions. For any $f \in C^\infty(M)$,

$$(L_X Y)(q)f = \left. \frac{\partial^2}{\partial s \partial t} \right|_{(0,0)} (f \circ \varphi_{-t} \circ \psi_s \circ \varphi_t)(q).$$

Proof. We have

$$\begin{aligned} (L_X Y)(q)f &= \left(\left. \frac{d}{dt} \right|_0 T_{\varphi_{-t}}(Y(\varphi_t(q))) \right) f \\ &= \left. \frac{d}{dt} \right|_0 (T_{\varphi_{-t}}(Y(\varphi_t(q))f)) \\ &= \left. \frac{d}{dt} \right|_0 Y(\varphi_t(q))(f \circ \varphi_{-t}) \\ &= \left. \frac{d}{dt} \right|_0 \left. \frac{\partial}{\partial s} \right|_0 (f \circ \varphi_{-t})(\psi_s(\varphi_t(q))) \\ &= \left. \frac{\partial^2}{\partial t \partial s} \right|_{(0,0)} (f \circ \varphi_{-t} \circ \psi_s \circ \varphi_t)(q) \\ &= \left. \frac{\partial^2}{\partial s \partial t} \right|_{(0,0)} (f \circ \varphi_{-t} \circ \psi_s \circ \varphi_t)(q). \end{aligned}$$

\square

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Recall. Let $X, Y \in \Gamma(TM)$ be two vector fields, and we assume for simplicity that X, Y have global flows $\{\varphi_t\}_{t \in \mathbb{R}}$ and $\{\psi_s\}_{s \in \mathbb{R}}$. We define the Lie derivative $L_X Y$ of Y with respect to X by

$$(L_X Y)(q) = (L_X Y)(q) = \frac{d}{dt} \Big|_0 T_{\varphi_t(q)} \varphi_{-t}(Y(\varphi_t(q))).$$

Theorem 17.1. $L_X Y = [X, Y]$.

Proof. It suffices to show that for all $f \in C^\infty(M)$ and all $q \in M$,

$$((L_X Y)(q))f = ([X, Y](q))f = ([X, Y]f)(q).$$

Consider

$$\begin{aligned} H : \mathbb{R}^3 &\rightarrow \mathbb{R} \\ (x, y, z) &\mapsto (f \circ \Phi_x \circ \psi_y \circ \Phi_z)(q), \end{aligned}$$

then by Lemma 16.8,

$$((L_X Y)(q))f = \frac{\partial^2}{\partial t \partial s} \Big|_{(0,0)} (H(-t, s, t)) = \frac{d}{ds} \Big|_{s=0} \left(\frac{\partial}{\partial t} \Big|_{(0,s)} H(-t, s, t) \right),$$

and by the chain rule,

$$\frac{\partial}{\partial t} \Big|_{(0,s)} H(-t, s, t) = -\frac{\partial H}{\partial x}(0, s, 0) + \frac{\partial H}{\partial z}(0, s, 0).$$

Hence,

$$\begin{aligned} ((L_X Y)(q))f &= \frac{d}{ds} \Big|_0 \left(-\frac{\partial}{\partial x} \Big|_{(0,s)} (f \circ \varphi_x \circ \psi_s \circ \varphi_0)(q) + \frac{\partial}{\partial z} \Big|_{(0,s)} (f \circ \psi_s \circ \varphi_z)(q) \right) \\ &= \frac{d}{ds} \Big|_0 \left(-\frac{\partial}{\partial x} \Big|_{(0,s)} (f \circ \varphi_x \circ \psi_s \circ \varphi_0)(q) + \frac{\partial}{\partial z} \Big|_{(0,s)} (f \circ \psi_s \circ \varphi_z)(q) \right) \\ &= \frac{d}{ds} \Big|_0 (- (Xf)(\psi_s(q)) + \frac{d}{dz} \Big|_0 (Yf)(\varphi_z(q))) \\ &= (-Y(Xf))(q) + (X(Yf))(q) \\ &= ((XY - YX)f)(q) \\ &= ([X, Y](q))f. \end{aligned}$$

□

Corollary 17.2. Let $X, Y \in \Gamma(TM)$ be two complete vector fields with flows $\{\varphi_t\}_{t \in \mathbb{R}}, \{\psi_s\}_{s \in \mathbb{R}}$, then $[X, Y] = 0$ if and only if $\varphi_t \circ \psi_s = \psi_s \circ \varphi_t$ for all s and t .

Proof. (\Leftarrow): Suppose $\varphi_t \circ \psi_s = \psi_s \circ \varphi_t$ for all t, s , then for all $f \in C^\infty(M)$, we have

$$\begin{aligned} ([X, Y]f)(q) &= (L_X Y)(q)f \\ &= \frac{\partial^2}{\partial t \partial s} \Big|_{(0,0)} (f \circ \varphi_{-t} \circ \psi_s \circ \varphi_t)(q) \\ &= \frac{\partial^2}{\partial s \partial t} \Big|_{(0,0)} (f \circ \psi_s \circ \varphi_{-t} \circ \varphi_t)(q) \\ &= \frac{\partial^2}{\partial s \partial t} \Big|_{(0,0)} (f \circ \psi_s)(q) \\ &= 0. \end{aligned}$$

(\Rightarrow): Suppose $0 = [X, Y] = L_X Y$, consider $\sigma(t) = (T\varphi_{-t})_{\varphi_t(q)}(Y(\varphi_t(q)))$, then we have $\sigma(0) = (T\varphi_0)(Y(q)) = Y(q)$, therefore

$$\begin{aligned}\sigma'(t) &= \frac{d}{ds} \Big|_{s=0} \sigma(t+s) \\ &= \frac{d}{ds} \Big|_0 (T\varphi_{-t-s})(Y(\varphi_s(q))) \\ &= \frac{d}{ds} \Big|_{s=0} (T\varphi_{-t})(T\varphi_{-s})(Y(\varphi_s(\varphi_t(q)))) \\ &= (T\varphi_{-t}) \left(\frac{d}{ds} \Big|_0 (T\varphi_{-s})_{\varphi_t(q)}(Y(\varphi_s(\varphi_t(q)))) \right) \\ &= (T\varphi_{-t}) \left(\frac{d}{ds} \Big|_0 (T\varphi_{-s})_{q'}(Y(\varphi_s(q'))) \right)\end{aligned}$$

where $(T\varphi_{-s})(Y(\varphi_s(\varphi_t(q))))$ is a path in $T_{\varphi_t(q)}(M)$. Therefore, the expression is just applying a linear map onto $(L_X Y)(q')$, but this term is now just zero.

Therefore, for all t , we know that

$$Y(q) = \sigma(0) = \sigma(t) = (T\varphi_{-t})_{\varphi_t(q)}(Y(\varphi_t(q))),$$

so $(T\varphi_t)_q(Y(q)) = Y(\varphi_t(q))$, therefore $T\varphi_t \circ Y = Y \circ \varphi_t$, therefore this means Y is φ_t -related to Y , that means for all q , we know $\varphi_t(\psi_s(q)) = \psi_s(\varphi_t(q))$ for all s, t . \square

We will now talk about linear algebra a bit. The blanket assumption is that all vector spaces are real and has finite dimensions.

Recall. Given vector spaces V_1, \dots, V_n and U , we say $f : V_1 \times \dots \times V_n \rightarrow U$ is multi-linear if it is linear in each slot, that is, for all i , the assignment $v \mapsto f(v_1, \dots, v_{i-1}, v, \dots, v_n)$ is a linear map.

Example 17.3.

$$\begin{aligned}\det : (\mathbb{R}^n)^n &\rightarrow \mathbb{R} \\ (v_1, \dots, v_n) &\mapsto \det(v_1, \dots, v_n)\end{aligned}$$

is n -linear.

Example 17.4. For any inner product g on a vector space V , the map

$$\begin{aligned}g : V &\rightarrow V \times \mathbb{R} \\ (v_1, v_2) &\mapsto g(v_1, v_2)\end{aligned}$$

is bilinear.

Example 17.5. If \mathfrak{g} is a Lie algebra, then the Lie bracket $[\cdot, \cdot] : \mathfrak{g} \times \mathfrak{g} \rightarrow \mathfrak{g}$ is bilinear.

Notation. We say $\text{Mult}(V_1, \dots, V_n; U)$ is the set of n -linear maps $f : V_1 \times \dots \times V_n \rightarrow U$.

Fact. $\text{Mult}(V_1, \dots, V_n; U)$ is an \mathbb{R} -vector space.

Lemma 17.6. Let V, W, U be three vector spaces with bases $\{v_i\}$, $\{w_j\}$, and $\{u_k\}$, respectively, and let $\{v_i^*\}$, $\{w_j^*\}$, and $\{u_k^*\}$ be their duals, respectively. We now define

$$\begin{aligned}\varphi_{ij}^k : V \times W &\rightarrow U \\ (v, w) &\mapsto v_i^*(v) \cdot w_j^*(w) \cdot u_k \\ (-, \cdot) &\mapsto v_i^*(-) \cdot w_j^*(\cdot) u_k,\end{aligned}$$

then $\{\varphi_{ij}^k\}$ is a basis of $\text{Mult}(V, W; U)$.

Proof. Given a bilinear map $b : V \times W \rightarrow U$ with $(x, y) \in V \times W$, then

$$\begin{aligned} b(x, y) &= b\left(\sum v_i^*(x)y_j, \sum w_j^*(y)w_j\right) \\ &= \sum_{i,j} v_i^*(x)w_j^*(y)b(v_i, w_j) \\ &= \sum_{i,j,k} v_j^*(x)w_j^*(y)u_k^*(b(v_i, w_j))u_k \\ &= \sum_{i,j,k} u_k^*(b(v_i, w_j))\varphi_{ij}^k(x, y), \end{aligned}$$

therefore $\{\varphi_{ij}^k\}$ spans $\text{Mult}(V, W; U)$.

Suppose $\sum_{i,j,k} c_k^{ij} \varphi_{ij}^k = 0$, then for all r, l , we know $\varphi_{ij}^k(v_r, w_l) = v_i^*(v_r)w_j^*(w_l)u_k = \delta_{ir}\delta_{jl}u_k$, so

$$0 = \sum_{i,j,k} c_k^{ij} \varphi_{ij}^k(v_r, w_l) = \sum_{i,j,k} c_k^{ij} \delta_{ir}\delta_{il}u_k = \sum_k c_k^{rl}u_k.$$

□

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Definition 18.1. Let V and W be two (finite-dimensional) vector spaces over \mathbb{R} . The tensor product $V \otimes W$ of V and W is a vector space together with a unique bilinear map

$$\begin{aligned} \otimes : V \times W &\rightarrow V \otimes W \\ (v, w) &\mapsto v \otimes w \end{aligned}$$

with the following universal property: for any bilinear map $b : V \times W \rightarrow U$, there exists a unique linear map $\bar{b} : V \otimes W \rightarrow U$ so that the diagram

$$\begin{array}{ccc} V \otimes W & \xrightarrow{\bar{b}} & U \\ \otimes \uparrow & \nearrow b & \\ V \times W & & \end{array}$$

commutes, i.e., $b(v, w) = \bar{b}(v \otimes w)$ for all $(v, w) \in V \times W$.

Lemma 18.2. For any two vector spaces V and W , the tensor product $V \otimes W$ with respect to $\otimes : V \times W \rightarrow V \otimes W$ exists and is unique up to unique isomorphism.

Corollary 18.3. For any three vector spaces U, V , and W , the map

$$\begin{aligned} \varphi : \text{Hom}(V \otimes W, U) &\rightarrow \text{Mul}(V, W; U) \\ A &\mapsto \varphi(A) = A \circ \otimes \end{aligned}$$

is an isomorphism of vector spaces.

Proof. The uniqueness follows from the universal property. To prove existence, recall that for any set X , there is a construction of free vector space which has a copy of X as a basis. Define the tensor product to be the categorical product quotiented out by the obvious equivalence relations, given by additions and scalar multiplications, then this gives a tensor product construction over the free vector space. To prove the universal property, write down the canonical mapping, then the bilinear map $b : V \times W \rightarrow U$ induces $\bar{b} : F(V \times W) \rightarrow U$, then it satisfies the universal property and we are done. □

Lemma 18.4. For any two finite-dimensional vector spaces V and W , then $V \otimes W$ is a finite-dimensional vector space and $\dim(V \otimes W) = \dim(V) \cdot \dim(W)$.

Proof. We know $\text{Hom}(V \otimes W, \mathbb{R}) = \text{Mult}(V, W; \mathbb{R})$, and we know that $\dim(\text{Mult}(V, W; \mathbb{R})) = \dim(V) \cdot \dim(W) \cdot \dim(\mathbb{R})$, therefore $\dim(\text{Hom}(V \otimes W, \mathbb{R})) < \infty$, so $\dim(V \otimes W) < \infty$, and then $\dim(V \otimes W) = \dim(\text{Hom}(V \otimes W, \mathbb{R})) = \dim(V) \cdot \dim(W)$. \square

Corollary 18.5. If $\{v_i\}_{i=1}^n$ is a basis of V and $\{w_j\}_{j=1}^m$ a basis of W , then $\{v_i \otimes w_j\}$ for $1 \leq i \leq n$ and $1 \leq j \leq m$ is a basis of $V \otimes W$.

Proof. By construction of the tensor product, we know this set spans $V \otimes W$ already. For any element $x \otimes y \in V \otimes W$, then write down each element with respect to the basis, reorder them, then we get a sum with respect to the given basis $\{v_i \otimes w_j\}$, and we know this spans indeed. Moreover, the dimension matches and we are done. \square

Lemma 18.6. There exists a unique linear map

$$\begin{aligned} T : V \otimes W &\rightarrow W \otimes V \\ v \otimes w &\mapsto w \otimes v \end{aligned}$$

for all $v \in V$ and $w \in W$.

Proof. The uniqueness is easy: this is given by the assignment. To show the existence, consider

$$\begin{aligned} b : V \times W &\rightarrow W \otimes V \\ (v, w) &\mapsto w \otimes v \end{aligned}$$

which is a bilinear map and then take the universal property and we are done. \square

Remark 18.7. T is an isomorphism, and the tensor product \otimes gives rise to a symmetric monoidal category structure on the category of vector spaces.

Lemma 18.8. For any two finite-dimensional vector space V and W , there exists a unique linear map

$$\begin{aligned} \varphi : V^* \otimes W &\rightarrow \text{Hom}(V, W) \\ l \otimes w &\mapsto l(-)w. \end{aligned}$$

Proof. Consider the bilinear map

$$\begin{aligned} b : V^* \times W &\rightarrow \text{Hom}(V, W) \\ (l, w) &\mapsto l(-)w \end{aligned}$$

then by the universal property φ is the unique linear map as specified above. This is an isomorphism if we check the basis. \square

19 OCT 4, 2023

Remark 19.1. The universal property of \otimes can be explained by 1) the universal property over bilinear maps; 2) the universal property over categorical product; 3) the natural bijection between bilinear maps to U and homomorphisms to U .

Remark 19.2. If V and W are finite-dimensional, then there exists a natural transformation

$$\begin{aligned} V^* \otimes W^* &\xrightarrow{\sim} \text{Mult}(V, W; \mathbb{R}) \\ l \otimes \eta &\mapsto l(-)\eta(-) \end{aligned}$$

Remark 19.3. Since $\text{Mult}(V, W; \mathbb{R}) \cong \text{Hom}(V \otimes W, \mathbb{R}) = (V \otimes W)^*$, so $(V \otimes W)^* \cong V^* \otimes W^*$.

Recall. An \mathbb{R} -algebra is a vector space A with a bilinear map $\circ : A \times A \rightarrow A$. An algebra A is associative if $a \circ (b \circ c) = (a \circ b) \circ c$ for all $a, b, c \in A$.

Definition 19.4. An $(\mathbb{Z}_{\geq 0})$ -graded vector space A is a sequence of vector spaces $\{V_i\}_{i \geq 0}$. Equivalently, a graded vector space V is a direct sum $V = \bigoplus_{i=0}^{\infty} V_i$.

Recall.

$$\bigoplus_{i=0}^{\infty} V_i = \left\{ \{v_i\}_{i=0}^{\infty} \mid v_i \in V_i, v_i = 0 \text{ for all but finitely many } i \right\}.$$

Definition 19.5. A $(\mathbb{Z}_{\geq 0})$ -graded algebra is a graded vector space $A = \bigoplus_{i \geq 0} A_i$ together with a bilinear map $\circ : A \times A \rightarrow A$ such that for all $i, j, a_i \in A_i$ and $a_j \in A_j$, $a_i \circ a_j \in A_{i+j}$.

We are mostly interested in two types of graded associative algebras:

- the tensor algebra of a vector space V , given by $\mathcal{T}(V) = \bigoplus_{k=0}^{\infty} V^{\otimes k}$, and
- the Grassmannian/exterior algebra $\bigwedge^*(V) = \bigoplus_{i=0}^{\infty} \bigwedge^k V$.

Definition 19.6. We define the *exterior algebra* as follows: $V^{\otimes 0} = \mathbb{R}$, $V^{\otimes 1} = V$, and $V^{\otimes 2} = V \otimes V$. For $k > 2$, there exists a unique (up to isomorphism) vector space $V^{\otimes k}$ together with a k -linear map

$$\begin{aligned} \otimes^k : V^k &\rightarrow V^{\otimes k} \\ (v_1, \dots, v_k) &\mapsto v_1 \otimes v_2 \otimes \cdots \otimes v_k, \end{aligned}$$

so that it satisfies the following universal property, that is, for any vector space U , we have $\text{Hom}(V^{\otimes k}, U) = \text{Mult}(V^k = (V, \dots, V); U)$. To define each of them, we can

- either define it inductively, using the fact that tensor products are associative up to unique isomorphism, or
- we construct it using the free vector space, that is, $V^{\otimes k} = F(V^k)/S$ where S is an appropriate subspace, imitating the construction of the tensor product. Therefore, we want $\otimes^k(v_1, \dots, v_k) = \delta_{(v_1, \dots, v_k)} + S \cdots$

Remark 19.7. Consider the tensor product $\mathbb{R}^2 \otimes \mathbb{R}^2$. We have

$$\begin{aligned} (1, 1) \otimes (1, -1) &= ((1, 0) + (0, 1)) \otimes ((1, 0) + (0, -1)) \\ &= (1, 0) \otimes (1, 0) - (0, 1) \otimes (0, 1) - (1, 0) \otimes (0, 1) + (0, 1) \otimes (1, 0) \\ &= \dots \end{aligned}$$

Definition 19.8. To make $\mathcal{T}(V) = \bigoplus V^{\otimes k}$ into an algebra, we need bilinear maps $\circ_{k,l} : V^{\otimes k} \times V^{\otimes l} \rightarrow V^{\otimes(k+l)}$. We would want

$$(v_1 \otimes \cdots \otimes v_k) \circ_{k,l} (v_{k+1} \otimes \cdots \otimes v_{k+l}) = v_1 \otimes \cdots \otimes v_k \otimes v_{k+1} \otimes \cdots \otimes v_{k+l}.$$

To start with, we take

$$\begin{aligned} \varphi : V^k \times V^l &\rightarrow V^{\otimes(k+l)} \\ ((v_1, \dots, v_k), (v_{k+1}, \dots, v_{k+l})) &\mapsto v_1 \otimes \cdots \otimes v_k \otimes v_{k+1} \otimes \cdots \otimes v_{k+l}, \end{aligned}$$

then this is a $(k+l)$ -linear map. We now fix $(v_{k+1}, \dots, v_{k+l}) \in V^l$, then

$$\begin{aligned} \varphi_{(v_{k+1}, \dots, v_{k+l})} : V^k &\rightarrow V^{\otimes(k+l)} \\ (v_1, \dots, v_k) &\mapsto v_1 \otimes \cdots \otimes v_k \otimes v_{k+1} \otimes \cdots \otimes v_{k+l} \end{aligned}$$

which is k -linear, then by universality there exists a unique map $\bar{\varphi}_{(v_{k+1}, \dots, v_{k+l})} : V^{\otimes k} \rightarrow V^{\otimes(k+l)}$, then for any each fixed t in $V^{\otimes k}$, we get a map

$$\begin{aligned} V^l &\rightarrow V^{\otimes(k+l)} \\ (v_{k+1}, \dots, v_{k+l}) &\mapsto \bar{\varphi}_{(v_{k+1}, \dots, v_{k+l})}(t) \end{aligned}$$

and therefore we get a bilinear map

$$\circ_{k,l} : V^{\otimes k} \times V^{\otimes l} \rightarrow V^{\otimes(k+l)}$$

with $(v_1 \otimes \cdots \otimes v_k) \circ_{k,l} (v_{k+1}, \dots, v_{k+l}) = v_1 \otimes \cdots \otimes v_{k+l}$. It now remains to check that for all k, l, m , we have

$$\begin{array}{ccc}
 & V^{\otimes k} \times V^{\otimes l} \times V^{\otimes m} & \\
 \circ_{k,l} \times \text{id} \swarrow & & \searrow \text{id} \times \circ_{l,m} \\
 V^{\otimes(k+l)} \times V^{\otimes m} & & V^{\otimes k} \times V^{\otimes(l+m)} \\
 \searrow \circ_{k+l,m} & & \swarrow \circ_{k,l+m} \\
 & V^{\otimes(k+l+m)} &
 \end{array}$$

To show this, we just have to check on the generators, since all maps are already well-defined. It is enough to check on generators, given by

$$\begin{array}{ccc}
 & (v_1 \otimes \cdots \otimes v_k, v_{k+1} \otimes \cdots \otimes v_{k+l}, v_{k+l+1} \otimes \cdots \otimes v_{k+l+m}) & \\
 \swarrow & & \searrow \\
 (v_1 \otimes \cdots \otimes v_{k+l}, v_{k+l+1} \otimes \cdots \otimes v_{k+l+m}) & & (v_1 \otimes \cdots \otimes v_k, v_{k+1} \otimes \cdots \otimes v_{k+l+m}) \\
 \searrow & & \swarrow \\
 & v_1 \otimes \cdots \otimes v_{k+l+m} &
 \end{array}$$

Therefore, this proves associativity.

Definition 19.9. The *Grassmann/exterior algebra* on a vector space V is a graded associative algebra $\bigwedge^* V = \bigoplus_{k=0}^{\infty} \bigwedge^k V$ with an injective linear map $i : V \hookrightarrow \bigwedge^* V$ so that $\bigwedge^0 V = \mathbb{R}$, $i(V) = \bigwedge^1 V$, that has the following universal property: for any associative algebra A , for all linear map $j : V \rightarrow A$ such that $j(v) \cdot j(v) = 0$ for all $v \in V$, there exists a unique map of algebras (i.e., linear map that preserves multiplications) $\bar{j} : \bigwedge^* V \rightarrow A$ such that

$$\begin{array}{ccc}
 \bigwedge^* V & \xrightarrow{\exists! \bar{j}} & A \\
 i \uparrow & \nearrow j & \\
 V & &
 \end{array}$$

Remark 19.10. The pair $(\bigwedge^* V, i : V \hookrightarrow \bigwedge^* V)$ is unique up to a unique isomorphism.