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Abstract

These notes are based on Davi Maximo's lectures for the course "Geometric Analysis and Topology I" at UPenn along with John Lee's *Smooth Manifolds* and Michael Spivak's *A Comprehensive Introduction to Differential Geometry, Vol. 1.* Any mistake in what follows is my own.

Contents

1 Smooth manifolds

1.1 Lecture 1

Definition 1.1.1. A space M is a *(topological) n-dimensional manifold* (or *n-manifold*) if it is

- Hausdorff,
- second-countable, and
- locally Euclidean of dimension n, i.e., for any $x \in M$, there exist an open $U \ni x$ and a homeomorphism $\phi : U \to V$ for some open $V \subset \mathbb{R}^n$.

Definition 1.1.2.

1. Let M be an n-manifold. A *coordinate* chart is a tuple (U, ϕ) of an open subset $U \subset M$ and a homeomorphism $\phi : U \to \underset{\text{open}}{W} \subset \mathbb{R}^n$.
2. If (U, ϕ) is a coordinate chart and $\pi_i : \mathbb{R}^n \to \mathbb{R}$ denotes the i-th projection map, then we call elements of the set $\{(\pi_1(\phi(p)), \ldots, \pi_n(\phi(p))) \mid p \in U\}$ *local coordinates on U*.

Notation. We will use the symbols x^i and x_i interchangeably for local coordinates.

Definition 1.1.3.

1. Given charts (U, ϕ), (V, ψ) with $U \cap V \neq \emptyset$, we say that the two are *C^k-compatible* if the *transition map* $\psi \circ \phi^{-1}$
$$\begin{tikzcd} U \arrow[r, "\phi"] \arrow[dr, "\psi"'] & \phi(U \cap V) \arrow[d, "\psi \circ \phi^{-1}"] \\ & \psi(U \cap V) \end{tikzcd}$$
is C^k.
2. A collection of charts (U_α, ϕ_α) which covers a manifold M and is pairwise C^k-compatible is called a *C^k-atlas for M*.

Example 1.1.4. Consider $(\mathbb{R}, x \mapsto x)$ and $\big(\mathbb{R}, x \mapsto x^3\big)$. Since $x \mapsto x^{\frac{1}{3}}$ is not differentiable at 0, these charts do not form a C^1-atlas on $\mathbb{R}$.

Definition 1.1.5. An atlas A is *maximal* if it contains every chart that is C^∞- (or smoothly) compatible with every chart in A.

Lemma 1.1.6.

1. *Every smooth atlas is contained in a unique maximal atlas.*
2. *Two smooth atlases are contained in the same maximal atlas if and only if their union is also a smooth atlas.*

This shows that an atlas is maximal if and only if it's maximal in the usual in the set-theoretic sense.

Definition 1.1.7. A manifold M is *smooth* if it admits a maximal smooth atlas, also known as a *smooth structure.*

Lemma 1.1.6 shows that it's enough to construct any smooth atlas for M to show it's a smooth manifold.

Remark 1.1.8. An open problem is whether there is more than one smooth structure on $\mathbb{S}^4$. This is known for each $n \neq 4$. Milnor (1958) gave an affirmative answer for $\mathbb{S}^7$.

1.2 Lecture 2

Lemma 1.2.1. *If M admits a smooth structure, then M admits uncountably many smooth structures.*

Remark 1.2.2.

1. There exists a 10-dimensional topological manifold that admits no smooth structure (Kevaire 1961).

2. Any 2- or 3-dimensional manifold admits a smooth structure.

Example 1.2.3. The following are examples of smooth structures on topological manifolds.

1. Any real vector space V where $\dim(V) = n$ has a canonical smooth structure as follows. Endow V with any norm, since all norms on a finite-dimensional space are equivalent and hence generate the same topology. Pick any basis $B \coloneqq (b_1, \ldots, b_n)$ of V. Define the isomorphism $T : V \to \mathbb{R}^n$ by $b_i \mapsto e_i$ where e_i denotes the standard basis. This is also a diffeomorphism, implying that V is a topological manifold and that (V, T) is an atlas on V. If B' is any other basis of V and T' the corresponding isomorphism, then the transition map $T' \circ T^{-1} : \mathbb{R}^n \to \mathbb{R}^n$ is a linear isomorphism, hence a diffeomorphism. By Lemma 1.1.6(2), it follows that any two bases determine the same smooth structure on V.

2. The restriction of a smooth structure on a manifold M to an open subset $U \subset M$ yields a smooth structure on U, which is called an *open submanifold.*

3. By our previous two examples, $\mathrm{GL}(n, \mathbb{F}) \subset \mathrm{M}(n, \mathbb{F})$ is a smooth manifold.

4. Let $U \subset \mathbb{R}^n$ be open and $F : U \to \mathbb{R}^m$ be continuous. Let $\Gamma(F)$ be the graph of F and $\pi_1 \restriction_\Gamma (F)$ be the restriction of the projection $(x, y) \mapsto x$. This is a homeomorphism between $\Gamma(F)$ and U. Hence $(\pi_1 \restriction_\Gamma (F), \Gamma(F))$ is a smooth atlas.

5. For each $i = 1, 2, \ldots, n+1$, let $U_i^+ \coloneqq \{\vec{x} \in \mathbb{R}^{n+1} : x_i > 0\}$. Define U_i^- similarly. The $U_i^\pm$ cover $\mathbb{S}^n$. Define the map $f : B_1(0) \subset \mathbb{R}^n \to \mathbb{R}$ by $f(\vec{u}) = \sqrt{1 - |\vec{u}|^2}$. Define $x_i : B_1(0) \to \mathbb{R}$ by $f(x_1, \ldots, \widehat{x_i}, \ldots x_n)$. Then $\Gamma(x_i) = U_i^+ \cap \mathbb{S}^n$ and $\Gamma(-x_i) = U_i^- \cap \mathbb{S}^n$. By our previous example, these graphs with their corresponding projections form a smooth structure on $\mathbb{S}^n$.

6. Let $f : \underset{\text{open}}{U} \subset \mathbb{R}^m \to \mathbb{R}$ be smooth. For $c \in \mathbb{R}$, let $M_c \coloneqq f^{-1}(c)$. Assume that the total derivative $\nabla f(a)$ is nonzero for each $a \in M_c$. Then $f_{x_i}(a) \neq 0$ for some $1 \leq i \leq m$. Then, by the implicit function theorem, there is some smooth $F : \mathbb{R}^{m-1} \to \mathbb{R}$ given by $x_i = F(x_1, \ldots, \widehat{x_i}, \ldots, x_m)$ on some neighborhood $U_a \subset \mathbb{R}^m$ of a such that $f^{-1}(c) \cap U_a$ is the graph of F. Then the $f^{-1}(c) \cap U_a$ together with their graph coordinates define a smooth atlas on M_c.

7. For each $i = 1, \ldots, n+1$, let $\tilde{U_i} \coloneqq \{\vec{x} \in \mathbb{R}^{n+1} : x_i \neq 0\}$. Let $\pi : \mathbb{R}^{n+1} \setminus \{0\} \to \mathbb{RP}^n$ be the quotient map and $U_i \coloneqq \pi\left(\tilde{U_i}\right)$. Since $\tilde{U_i}$ is saturated and open, we know that $\pi \restriction_{\tilde{U_i}}$ is a quotient map.[1] Define $f_i : U_i \to \mathbb{R}^n$ by $[x_1, \ldots, x_{n+1}] \mapsto \left(\frac{x_1}{x_i}, \ldots, \frac{x^{i-1}}{x_i}, \frac{x^{i+1}}{x_i}, \ldots \frac{x_{n+1}}{x_i}\right)$, which has inverse $(x_1, \ldots, x_n) \mapsto [x_1, \ldots, x_{i-1}, 1, x_{i+1}, \ldots x_n]$. Since $f_i \circ \pi$ is continuous, so is f_i.[2] Hence f_i is a homeomorphism. It's easy to check that each transition $f_i \circ f_j^{-1}$ is smooth. Thus, the (U_i, f_i) define a smooth atlas on $\mathbb{RP}^n$.

8. Let $M_1 \times \cdots \times M_k$ be a product of n_i-dimensional smooth manifolds. Then this is a smooth manifold of dimension $n_1 + \cdots + n_k$.

Exercise 1.2.4. *Show that $\mathbb{RP}^n$ is second countable and Hausdorff.*

Proof. Recall that $\mathbb{S}^n/\sim \, \cong \mathbb{RP}^n$ where $x \sim y$ if $y = -x$. Thus it suffices to show these properties are true of $P^n \coloneqq \mathbb{S}^n/\sim$.

Let $B \coloneqq \{V_n\}$ denote the usual countable basis of $\mathbb{S}^n$ inherited from $\mathbb{R}^{n+1}$. If $p \in U \subset P^n$ is open, then $\pi^{-1}(U)$ is a neighborhood of $\pi^{-1}(p)$, which equals $\{a, -a\}$ for some point a on the sphere. There is some

[1] Munkres, James. Theorem 22.1. *Topology.*
[2] Munkres, James. Theorem 22.2. *Topology.*

ball $B \ni B_q(r) \cap \mathbb{S}^n \ni a$ with $q \in \mathbb{Q}$ and $r \in \mathbb{Q}^{n+1}$. Then $B \in B_q(-r) \cap \mathbb{S}^n \ni -a$. Note that the union of these two balls is contained in $\pi^{-1}(U)$ and is saturated, hence is mapped to a neighborhood $N \subset U$ of p. Thus $\pi(V_n)$ for $n \in \mathbb{N}$ is a countable basis of P^n.

Proving that $\mathbb{RP}^n$ is Hausdorff is pretty similar. $\square$

Lemma 1.2.5 (Smooth manifold construction). *Let M be a set and $\{U_\alpha\}$ a collection of subsets with injections $\phi_\alpha : U_\alpha \to \mathbb{R}^n$ such that*

1. *each $\phi_\alpha(U_\alpha)$ is open,*
2. *any $\phi_\alpha(U_\alpha \cap U_\beta)$, $\phi_\beta(U_\alpha \cap U_\beta)$ are open,*
3. *if $U_\alpha \cap U_\beta \neq \emptyset$, then $\phi_\alpha \circ \phi_\beta^{-1}$ is smooth,*
4. *countably many U_α cover M, and*
5. *if $p, q \in M$ with $p \neq q$, then either both are in U_α for some α or they can be separated by sets in $\{U_\alpha\}$.*

Then M has a unique smooth manifold structure with (U_α, ϕ_α) as charts.

Proof. We show that the U_a give a topology on M. $\square$

Definition 1.2.6. If M^n is an n-dimensional manifold and $f : M^n \to \mathbb{R}$ is a function, we say that f is *differentiable at p* if there is some chart (U_α, ϕ_α) such that the coordinate representation $f \circ \phi_\alpha^{-1} : \phi(U_\alpha) \to \mathbb{R}$ is differentiable at p.

Lemma 1.2.7. *If $f \circ \phi^{-1}$ is differentiable at $\phi(p)$ and $\psi : V \to \mathbb{R}^n$ is another coordinate neighborhood of $p \in M^n$, then $f \circ \psi^{-1} : \phi(V) \to \mathbb{R}$ is also differentiable at $\phi(p)$. In particular, Definition 1.2.6 is coordinate-independent.*

Proof. This holds because

$$\begin{tikzcd}
U \cap V \arrow[rr, "f"] \arrow[d, "\phi"'] \arrow[drr, "\psi"] & & \mathbb{R} \\
\phi(U \cap V) \arrow[urr, "f \circ \phi^{-1}"] & & \psi(U \cap V) \arrow[u, "f \circ \psi^{-1}"'] \arrow[ll, "\phi \circ \psi^{-1}"]
\end{tikzcd}$$

commutes. $\square$

2 Smooth maps

2.1 Lecture 3

Definition 2.1.1. Let M^n and N^k be smooth manifolds. We say that $F : M \to N$ is *smooth at $p \in M$* if there are charts $(V, \phi) \ni p$ and $(V', \psi) \ni F(p)$ with $F(V) \subset V'$ such that the coordinate representation $\psi \circ F \circ \phi^{-1}$ is smooth.

$$\begin{tikzcd}
V \arrow[r, "F"] \arrow[d, "\phi"'] & V' \arrow[d, "\psi"] \\
\phi(V) \arrow[r, "\psi \circ F \circ \phi^{-1}"] & \psi(V')
\end{tikzcd}$$

This definition is independent of coordinates. If $(U, \bar{\phi})$ and $(U', \bar{\psi})$ are other charts around p and $F(p)$, respectively, then

$$\bar{\psi} \circ F \circ \phi^{-1} = (\bar{\psi} \circ \psi^{-1}) \circ (\psi \circ F \circ \phi^{-1})$$
$$\psi \circ F \circ \bar{\phi}^{-1} = (\psi \circ F \circ \phi^{-1}) \circ (\phi \circ \bar{\phi}^{-1}),$$

which are smooth a p as compositions of smooth maps.

Lemma 2.1.2. *Smoothness implies continuity.*

Proof. Using the notation from Definition 2.1.1, we see that for each $p \in M$, there is a neighborhood V of p such that $F\restriction_V = \psi^{-1} \circ \psi \circ F \circ \phi^{-1} \circ \phi$ is a composition of continuous maps (as we know smooth implies continuous for maps between Euclidean spaces) and thus itself continuous. We can glue these restrictions together to conclude that F is continuous. □

Remark 2.1.3.

1. Given $F : M \to N$, if every $p \in M$ has a neighborhood U_p so that $F\restriction_{U_p}$ is smooth, then F is smooth.

2. Conversely, the restriction of any smooth map to an open subset is smooth.

Example 2.1.4. The natural projection $\pi : \mathbb{R}^{n+1} \setminus \{0\} \to \mathbb{RP}^n$ is smooth. Let $v \in (\mathbb{R}^{n+1} \setminus \{0\}, \mathrm{id})$. Let $(U_i, \phi_i) \in A_n$ be a neighborhood of $\pi(p)$. Since π is continuous, $S \coloneqq \pi^{-1}(U_i) \cap (\mathbb{R}^{n+1} \setminus \{0\})$ is a neighborhood of v. Further, $\phi_i \circ \pi \circ \mathrm{id} : S \to \phi_i(U_i)$ is given by $x \mapsto \frac{(x_1,\ldots,\widehat{x_i},\ldots,x_{n+1})}{x_i}$, which is smooth.

Definition 2.1.5. A smooth map with a smooth inverse is a *diffeomorphism.*

Note 2.1.6.

1. This defines an equivalence relation $\approx$ between smooth manifolds.

2. If $M^n \approx N^k$, then $n = k$.

Example 2.1.7.

1. $(\mathbb{R}, \mathrm{id}) \approx \left(\mathbb{R}, x \mapsto x^{\frac{1}{3}}\right)$ via $F : x \mapsto x^3$.

2. $F : \mathbb{B}^n \to \mathbb{R}^n$ given by $F(x) = \frac{x}{\sqrt{1-|x|^2}}$ is a diffeomorphism with inverse $G(y) = \frac{y}{\sqrt{1+|y|^2}}$.

3. $\mathbb{S}^n/\sim \approx \mathbb{RP}^n$.

4. If M is a smooth manifold and (U, ϕ) is a chart, then $\phi : U \to \phi(U)$ is a diffeomorphism.

Definition 2.1.8. If M is any topological space and $f : M \to \mathbb{R}^n$ is continuous, then the *support of f* is

$$\operatorname{supp} f \coloneqq \operatorname{cl}\left(\{x \in M : f(x) \neq 0\}\right).$$

Lemma 2.1.9. *Given any $0 < r_1 < r_2$, there is some smooth function $H : \mathbb{R}^n \to \mathbb{R}$ such that $H = 1$ on $\bar{B}_{r_1}(0)$, $0 < H < 1$ on $B_{r_2}(0) \setminus \bar{B}_{r_1}(0)$, and $H = 1$ elsewhere.*

Proof. We construct such an H. First recall that $f : \mathbb{R} \to \mathbb{R}$ given by $e^{-\frac{1}{t}}$ for $t > 0$ and 0 otherwise is smooth. Now define $h : \mathbb{R} \to \mathbb{R}$ by $h(t) = \frac{f(r_2-t)}{f(r_2-t)+f(t-r_1)}$. Finally, define $H : \mathbb{R}^n \to \mathbb{R}$ by $H(x) = h(|x|)$. □

2.2 Lecture 4

Definition 2.2.1. Let $\mathcal{U}$ be an open cover of a topological space X. We say that

1. the open cover $\mathcal{V}$ is a *refinement* of $\mathcal{U}$ if for every $V \in \mathcal{V}$, there is some $U \in \mathcal{U}$ such that $V \subset U$.

2. $\mathcal{U}$ is *locally finite* if each $x \in X$ has some neighborhood that intersects only finitely many $U \in \mathcal{U}$.

3. X is *paracompact* if every open cover of X admits a locally finite refinement.

Definition 2.2.2. Let M be a topological space and $\mathbf{X} \coloneqq (X_\alpha)_{\alpha \in A}$ be an open cover. A *partition of unity subordinate to* $\mathbf{X}$ is a family $(\psi_\alpha)_{\alpha \in A}$ of continuous functions $\psi_\alpha : M \to \mathbb{R}$ such that

1. $0 \leq \psi_\alpha(x) \leq 1$ for each α and x.

2. $\operatorname{supp} \psi_\alpha \subset X_\alpha$ for each α.

3. The family $(\operatorname{supp}\psi_\alpha)$ is locally finite, in that every point $p \in M$ has a neighborhood V_p such that $V_p \cap \operatorname{supp}\psi_\alpha \neq \emptyset$ for at most finitely many α. In particular, M is paracompact.

4. $\sum_{\alpha\in A}\psi_\alpha(x) = \sup\left\{\sum_{\alpha\in F}\psi(x) : \underset{\text{finite}}{F} \subset A\right\} = 1$ for each x.

Lemma 2.2.3. *Every topological manifold M is paracompact.*

Proof. Since M has a countable atlas, it has a countable basis $\{B_n\}$ of precompact coordinate balls. (The continuous image of a precompact set into a Hausdorff space is also precompact.)

Step 1: By induction, we can build a countable covering $\{U_n\}$ of precompact sets such that $\operatorname{cl}(U_{n-1}) \subset U_n$ and $B_n \subset U_n$ for each n.

Step 2: We build a countable locally finite open cover $\{V_n\}$. Set $V_n = \operatorname{cl}(U_n) \setminus U_{n-2}$ for $n > 2$ and $V_n = U_n$ otherwise. Note that every V_n intersects only finitely many other V_j, hence $\{V_n\}$ is locally finite.

Step 3: Let $\{X_\alpha\}$ be any open cover. For any $p \in M$, there is some α with $p \in X_\alpha$ and some neighborhood W_p that intersects V_j for only finitely many natural j. Set $\widetilde{W}_p = W_p \cap X_\alpha$. Then the $\widetilde{W}_p$ cover M. Since each V_j is precompact by construction, we know V_j has a finite subcover $\widetilde{W}_{p_{j_{k_1}}}, \ldots, \widetilde{W}_{p_{j_{k_j}}}$. Then $V_j = (V_j \cap \widetilde{W}_{p_{j_{k_1}}}) \cup \cdots \cup (V_j \cap \widetilde{W}_{p_{j_{k_j}}})$. Therefore, $\left\{\left(V_j \cap \widetilde{W}_{p_{j_{k_1}}}\right), \ldots, \left(V_j \cap \widetilde{W}_{p_{j_{k_j}}}\right)\right\}_{j\in\mathbb{N}}$ is a locally finite refinement of $\{X_\alpha\}$, as desired. ☐

Remark 2.2.4. If X is connected, then X is paracompact if and only if it is second-countable.

Theorem 2.2.5 (Existence of partition of unity). *If M is a smooth manifold, then any open cover $\mathcal{X} \coloneqq \{X_\alpha\}_{\alpha\in A}$ of M admits a partition of unity.*

Proof. For each $\alpha \in A$, we can find a countable basis $\mathcal{C}_\alpha$ of precompact coordinate balls (centered at 0) for X_α. Then $\mathcal{C} \coloneqq \bigcup_\alpha \mathcal{C}_\alpha$ is a basis for M. Since M is paracompact, $\mathcal{X}$ admits a locally finite refinement $\{C_i\}$ consisting of elements of $\mathcal{C}$. Note that the cover $\{\operatorname{cl}(B_i)\}$ is also locally finite. There are coordinate balls $C_i' \subset X_{\alpha_i}$ such that $C_i' \supset \operatorname{cl}(C_i)$. For each i, let $\phi_i : C_i' \to \mathbb{R}^n$ be a smooth coordinate map so that $\phi_i(C_i') \supset \phi(C_i)$ and $\phi(\operatorname{cl}(C_i)) = \operatorname{cl}(\phi(C_i))$. Define $f_i : M \to \mathbb{R}$ by

$$f_i(x) = \begin{cases} H_i \circ \phi_i & x \in C_i' \\ 0 & x \in M \setminus \operatorname{cl}(C_i) \end{cases}$$

where $H_i : \mathbb{R}^n \to \mathbb{R}$ is a smooth function that is positive on $\phi_i(C_i)$ and zero elsewhere, as in Section 2.1. Note that f_i is well-defined because $f_i = 0$ on $C_i' \setminus \operatorname{cl}(C_i)$. Also, it is smooth by the gluing lemma for open sets.

Define $f : M \to \mathbb{R}$ by $f(x) = \sum_i f_i(x)$, which is a finite sum and hence well-defined. We see that f is a smooth function and that $f(x) > 0$ for each $x \in M$. Then $g_i(x) \equiv \frac{f_i(x)}{f(x)}$ defines a smooth function $M \to \mathbb{R}$ for each i, so that $\sum_i g_i(x) = 1$ and $0 \le g_i(x) \le 1$ for each $x \in M$. Note that $\operatorname{supp}(g_i) = \operatorname{cl}(C_i)$.

For each $\alpha \in A$, define $\psi_\alpha : M \to \mathbb{R}$ by

$$\psi_\alpha(x) = \sum_{i:\ \alpha_i = \alpha} g_i(x).$$

Interpret this as the zero function when there are no i such that $\alpha_i = \alpha$. Note that each ψ_α is smooth as a finite sum of smooth functions and satisfies $0 \le \psi_\alpha \le 1$. Moreover, we have that

$$\operatorname{supp}(\psi_\alpha) = \operatorname{cl}\left(\bigcup_{i:\ \alpha_i=\alpha} C_i\right) = \bigcup_{i:\ \alpha_i=\alpha} \operatorname{cl}(C_i).$$

Since $\{\operatorname{cl}(C_i)\}$ is locally finite, so is $\{\operatorname{supp}(\psi_\alpha)\}_{\alpha\in A}$. Finally, the fact that $\alpha_i \in A$ implies that

$$\sum_\alpha \psi_\alpha(x) = \sum_i g_i(x) = 1$$

for each $x \in M$. Therefore, we may take $\{\psi_\alpha\}$ as our desired partition of unity. ☐

Corollary 2.2.6. *If $A \subset U \subset M$ with A closed and U open in M, then there is a (smooth) bump function $f : M \to \mathbb{R}$ such that $f(x) = 1$ for each $x \in A$ and $f(x) = 0$ outside a neighborhood of A.*

Proof. Since $\{U, M \setminus A\}$ is an open cover of M, there is a partition of unity ϕ_1, ϕ_2 such that $\operatorname{supp} \phi_1 \subset U$, $\operatorname{supp} \phi_2 \subset M \setminus A$, and $\phi_1 + \phi_2 = 1$. Hence $\phi_1 \restriction_A = 1 - 0 = 1$. And $\phi_1 \restriction_{M \setminus U} = 0$. □

2.3 Lecture 5

Corollary 2.3.1 (Whitney). *Let M be a smooth manifold and $K \subset M$ be closed. Then there exists a non-negative smooth function $f : M \to \mathbb{R}$ such that $f^{-1}(0) = K$.*

Remark 2.3.2. This means that closed subsets of smooth manifolds are completely characterized as the 0-level sets of smooth maps. To be the 0-level set of analytic maps, such as polynomials, is much more special (cf. algebraic geometry).

Proof. First assume $M = \mathbb{R}^n$ for some n. We have $M \setminus K$ open, which is thus the union of countably many balls $B_{r_i}(x_i)$ with $r_i \leq 1$. Construct, as in Section 2.1, a smooth bump function $h : \mathbb{R}^n \to \mathbb{R}$ such that $h(x) = 1$ on $\bar{B}_{\frac{1}{2}}(0)$ and that h is supported in $B_1(0)$. By our construction of h, we can verify that for each $i \in \mathbb{N}$, there is some $C_i \geq 1$ that bounds any of the partials of h up through order i.

Define $f : \mathbb{R}^n \to \mathbb{R}$ by

$$\sum_{i=1}^{\infty} \frac{r_i^i}{2^i C_i} h\left(\frac{x - x_i}{r_i}\right)$$

Each i-th term is bounded by $\frac{1}{2^i}$, implying by Weierstrass M-test that f is well-defined and continuous. Since h is zero outside $B_1(0)$, we see that $f^{-1}(0) = K$. To see that f is smooth, assume by induction that f is C^{k-1} for a given $k \geq 1$. By the chain rule and induction, we can write any k-th partial D_k of the i-th term of the series defining f as $\frac{(r_i)^{i-k}}{2^i C_i} D_k h(\frac{x - x_i}{r_i})$. As h is smooth, this expression is C^1. And since $r_i \leq 1$ and C_i bounds all partials up to order i, it is eventually bounded by $\frac{1}{2^i}$. Hence the series of these expressions converges uniformly to a continuous function. By Theorem C.31 in *Lee*, it follows that $D_k f$ exists and is continuous, completing the induction.

Now, assume M is arbitrary. Find a cover (B_α) of smooth coordinate balls for M. Let $\{\phi_\alpha\}$ be a partition of unity subordinate to this cover. Note that each B_α is diffeomorphic to $\mathbb{R}^n$. Since the property of admitting a non-negative smooth $f : M \to \mathbb{R}$ with $f^{-1}(0) = K$ can be stated in the language of smooth manifolds, it is invariant under diffeomorphism. Thus, there is some non-negative smooth $f_\alpha : B_\alpha \to \mathbb{R}$ where $f^{-1}(0) = K \cap B_\alpha$ for each α. Then we can check that $g = \sum_\alpha \phi_\alpha f_\alpha$ is the desired function. □

Corollary 2.3.3. *Let M be a smooth manifold and $K \subset M$ be closed. Let $c > 0$. Then there exists a non-negative smooth $f : M \to \mathbb{R}$ such that $f^{-1}(c) = K$.*

Exercise 2.3.4. *Prove that the restriction of a smooth map on $\mathbb{R}^{n+1}$ to $\mathbb{S}^n$ is smooth.*

3 Tangent vectors

3.1 Lecture 6

Remark 3.1.1. Imagine the tangent space of $\mathbb{S}^n$ at a point p as all of the directions from p with respect to which I can find the rate of change of a smooth map f given that I'm only allowed to roam through $\mathbb{S}^n$.

Definition 3.1.2. Given $a \in \mathbb{R}^n$, a map $\omega : C^\infty(\mathbb{R}^n) \to \mathbb{R}$ is called a *derivation at a* if it

a. is linear over $\mathbb{R}$ and

b. satisfies $\omega(fg) = f(a)\omega(g) + g(a)\omega(f)$ for any $f, g \in C^\infty(\mathbb{R}^n)$.

Remark 3.1.3. If f is constant, then $\omega f = 0$ for any derivation ω.

Example 3.1.4. if $u \in \mathbb{R}^n$, recall the directional derivative of $f \in C^\infty(\mathbb{R}^n)$ in the direction u at a is defined as

$$D_u f(a) = \lim_{h \to 0} \frac{1}{h}(f(a+hu) - f(a)) = \frac{d}{dh}\Big|_{h=0} f(a+hu).$$

Then this is a derivation of f at a.

Notation. For any $a \in \mathbb{R}^n$, let $\mathbb{R}^n_a$ denote the vector space $\{(a, v) \mid v \in \mathbb{R}^n\}$.

Theorem 3.1.5. *For $a \in \mathbb{R}^n$, define $L_a : \mathbb{R}^n_a \to T_a\mathbb{R}^n$ by $v_a \mapsto D_v\big|_a$. This is an isomorphism.*

Proof. It is clear that L_a is linear. It remains to show that it is both injective and surjective.

Suppose $u, v \in \mathbb{R}^n_a$ and $L_a(u) = L_a(v)$. Then by linearity $L_a(u-v) = 0$, implying $\frac{d}{dt}\big|_{t=0} f(a+t(u-v)) = 0$ for any smooth function f. But if $u - v \neq 0$, then this says that, for any f, the directional derivative of f at a in the direction of a certain nonzero vector vanishes, which is clearly false. Hence $u = v$, and L_a is injective.

Next, suppose $\omega \in T_a\mathbb{R}^n$ and consider the coordinate projection $x^i : \mathbb{R}^n \to \mathbb{R}$ for each $i = 1, \dots, n$. Set $v_i = \omega(x^i)$ and write $v = v_i e_i$. We show that $L_a(v) = D_v\big|_a = \omega$. By Taylor's theorem, any $f \in C^\infty(\mathbb{R}^n)$ has an expansion

$$f(x) = f(a) + \sum_{i=1}^n f_{x_i}(a)(x_i - a_i) + c \sum_{i,j=1}^n (x_i - a_i)(x_j - a_j) \int_0^1 (1-t) \frac{\partial^2 f}{\partial x_i \partial x_j}(a + t(x-a))\, dt$$

for some $c > 0$. Each term of the second sum is the product of two smooth functions vanishing at a. We can apply the product rule and linearity of ω to conclude that

$$\begin{aligned} \omega f &= \omega\left(\sum_{i=1}^n f_{x_i}(a)(x_i - a_i)\right) \\ &= \sum_{i=1}^n \omega(f_{x_i}(a)(x_i - a_i)) \\ &= \sum_{i=1}^n f_{x_i}(a)(\omega(x_i) - \omega(a_i)) \\ &= \sum_{i=1}^n f_{x_i}(a) v_i \\ &= D_v\big|_a f. \end{aligned}$$

□

Corollary 3.1.6. *We have* $\dim(T_a\mathbb{R}^n) = n$*, and the partial derivatives* $\left\{\frac{\partial}{\partial x_i}\big|_a\right\}_{1 \le i \le n}$ *form a basis for* $T_a\mathbb{R}^n$*.*

Definition 3.1.7. If M is a smooth manifold and $p \in M$, an $\mathbb{R}$-linear map $v : C^\infty(M) \to \mathbb{R}$ is called a *derivation at* p if

$$v(fg) = f(p)v(g) + v(f)g(p)$$

for any f and g.

Definition 3.1.8. The tangent space of M at p is

$$T_pM \equiv \{\omega : C^\infty(M) \to \mathbb{R} : \omega \text{ is a derivation of } M \text{ at } p\}.$$

Definition 3.1.9 (Differential of a smooth map). Given smooth manifolds M and N, a smooth map $F : M \to N$, and $p \in M$, we define the *differential of* F *at* p as the map $dF_p : T_pM \to T_{F(p)}N$ defined by

$$dF_p(v)(f) = v(f \circ F).$$

This is linear because v is linear, and it's easy to verify that it satisfies the product rule.

Terminology. We call $dF_p(v)$ the *pushforward of v by dF*.

Proposition 3.1.10. *Given M, N, P smooth manifolds, $F : M \to N$, $G : N \to P$ smooth maps, and $p \in M$, we have the following.*

1. *$dF_p : T_pM \to T_{F(p)}N$ is linear.*
2. *$d(G \circ F)_p = dG_{F(p)} \circ dF_p : T_pM \to T_{G(F(p))}P$.*
3. *$d(\mathrm{id}_M)_p = \mathrm{id} : T_pM \to T_pM$.*
4. *If F is a diffeomorphism, then dF_p is an isomorphism with inverse $d(F^{-1})_{F(p)}$.*

Aside. This shows that mapping (M, p) to T_pM and $F : (M, p) \to (N, F(p))$ to $dF\big|_p$ defines a functor from Diff_* to $\mathsf{Vec}_{\mathbb{R}}$, called the tangent space functor.

Lemma 3.1.11. *Let $v \in T_pM$ and $f, g \in C^\infty(M)$. Then if f and g agree on some neighborhood N_p of p, then $vg = vf$.*

Proof. Set $h = f - g$, so that h vanishes on N_p. Find a smooth bump function $\phi : M \to \mathbb{R}$ such that $\phi \equiv 1$ on $\mathrm{supp}(h)$ and $\mathrm{supp}(\phi) \subset M \setminus \{p\}$. Then $\phi h(x) = h(x)$ for any $x \in M$. Since ϕ and h vanish at p, it follows that $vf - vg = vh = v(\phi h) = 0$. ☐

Proposition 3.1.12. *If M is an n-dimensional smooth manifold, then* $\dim(T_pM) = n$ *for every $p \in M$. In particular, we identify the standard basis by $e_i \leftrightarrow \Big(0, \ldots, 0, \frac{\partial}{\partial x_i}\big|_p, 0 \ldots, 0\Big)$.*

3.2 Lecture 7

Remark 3.2.1. Given $p \in M$, find a chart $(U, \phi) \ni p$. Then $d\phi_p : T_pM \cong T_pU \to T_{\phi(p)}\phi(U) \cong T_p\mathbb{R}^n$ is an isomorphism. This choice of chart yields a natural choice of basis for T_pM:

$$\left\{\frac{\partial}{\partial x_i}\Big|_p\right\}_{1 \le i \le n}$$

where

$$\frac{\partial}{\partial x_i}\Big|_p \coloneqq (d\phi_p)^{-1}\left(\frac{\partial}{\partial x_i}\Big|_{\phi(p)}\right) = (d\phi^{-1})_{\phi(p)}\left(\frac{\partial}{\partial x_i}\Big|_{\phi(p)}\right).$$

.

Let $F : M \to N$ be smooth with $M \subset \mathbb{R}^n$ and $N \subset \mathbb{R}^m$ open. Then by the chain rule we get

$$\begin{aligned}
dF_p\left(\frac{\partial}{\partial x_i}\Big|_p\right) f &= \frac{\partial}{\partial x_i}\Big|_p (f \circ F) \\
&= \frac{\partial}{\partial x_i}\Big|_p (f(F_1, \ldots, F_m)) \\
&= \sum_{j=1}^m \frac{\partial f}{\partial F_j}(F(p)) \frac{\partial F_j}{\partial x_i}(p) \\
&= \sum_{j=1}^m \frac{\partial F_j}{\partial x_i}(p)\left(\frac{\partial}{\partial y_j}\Big|_{F(p)}\right) f.
\end{aligned}$$

Therefore, dF_p can be represented by the familiar $m \times n$ Jacobian matrix of F at p,

$$DF(p) \coloneqq \begin{bmatrix} \vdots & & \vdots \\ \frac{\partial F_j}{\partial x_1}(p) & \cdots & \frac{\partial F_j}{\partial x_n}(p) \\ \vdots & & \vdots \end{bmatrix},$$

which acts on $\mathbb{R}^n \cong T_pM$.

Now consider the general case $F : M \to N$ smooth between manifolds. For $p \in M$, choose charts $(U, \phi) \ni p$ and $(V, \psi) \ni F(p)$. Then the Euclidean map $\hat{F} := \psi \circ F \circ \phi^{-1} : \phi(F^{-1}(V) \cap U) \to \psi(V)$ is smooth. If $\hat{p} := \phi(p)$, it follows from Remark 3.2.1 that $d\hat{F}_{\hat{p}}$ is represented by the Jacobian of $\hat{F}$ at $\hat{p}$. Noting that $F \circ \phi^{-1} = \psi^{-1} \circ \hat{F}$, we compute

$$\begin{aligned} dF_p\left(\frac{\partial}{\partial x_i}\Big|_p\right) &= dF_p\left(d(\phi^{-1})\big|_{\hat{p}}\left(\frac{\partial}{\partial x_i}\Big|_{\hat{p}}\right)\right) \\ &= d(\psi^{-1})\big|_{\hat{F}(\hat{p})}\left(d\hat{F}\big|_{\hat{p}}\left(\frac{\partial}{\partial x_i}\Big|_{\hat{p}}\right)\right) \\ &= d(\psi^{-1})\big|_{\hat{F}(\hat{p})}\left(\sum_{j=1}^{m} \frac{\partial \hat{F}_j}{\partial x_i}(\hat{p}) \frac{\partial}{\partial y_j}\Big|_{\hat{F}(\hat{p})}\right) \\ &= \sum_{j=1}^{m} \frac{\partial \hat{F}_j}{\partial x_i}(\hat{p}) \frac{\partial}{\partial y_j}\Big|_{F(p)}. \end{aligned}$$

Therefore, dF_p can be represented by the Jacobian matrix of $\hat{F}$ at $\hat{p}$.

Note 3.2.2. Given any two pairs of coordinates for p and $F(p)$, the respective Jacobian matrices are related by the familiar change-of-basis matrix. In particular, they are similar.

Definition 3.2.3. Given a smooth manifold M, we define a notion of a smoothly varying tangent space, called the *tangent bundle of M* by the set

$$TM = \coprod_{p \in M} T_pM$$

endowed with a natural topology induced by the projection $\pi : TM \to M$, $(\phi, p) \mapsto p$.

Example 3.2.4. As $\mathbb{R}^n_a$ is canonically isomorphic to $\mathbb{R}^n$, we have $T\mathbb{R}^n \cong \coprod_{a \in \mathbb{R}^n} \{a\} \times \mathbb{R}^n = \mathbb{R}^n \times \mathbb{R}^n$.

3.3 Lecture 8

Proposition 3.3.1. *For any smooth n-dimensional manifold M, the tangent bundle TM has a natural topology and smooth structure so that it's a $2n$-dimensional smooth manifold and the projection $\pi : TM \to M$ is smooth.*

Proof. Given a chart (U, ϕ), define $\tilde{\phi} : \pi^{-1}(U) \to \mathbb{R}^n$ by $v_i \frac{\partial}{\partial x_i}\big|_p \mapsto (x^1(p), \ldots, x^n(p), v_1, \ldots, v_n)$ where $\phi = (x^1, \ldots, x^n)$.

Terminology. We call the $\tilde{\phi}\,((f,p))$ the *natural coordinates* on TM.

This is continuous with $\operatorname{Im} \tilde{\phi} = \phi(U) \times \mathbb{R}^n$, which is open. Further, $\tilde{\phi}^{-1}$ on $\phi(U) \times \mathbb{R}^n$ is given by $(x_1, \ldots, x_n, v_1, \ldots, v_n) \mapsto v_i \frac{\partial}{\partial x_i}\big|_{\phi^{-1}(x)}$. Define $\left\{(\pi^{-1}(U), \tilde{\phi})\right\}$ as charts on TM. Given charts $\left(\pi^{-1}(U), \tilde{\phi}\right)$ and $\left(\pi^{-1}(V), \tilde{\psi}\right)$, it's straightforward to check that $\tilde{\psi} \circ \tilde{\phi}^{-1} : \phi(U \cap V) \times \mathbb{R}^n \to \psi(U \cap V) \times \mathbb{R}^n$ is smooth.

Next, notice that if we take a countable cover $\{U_i\}$ of M by smooth coordinate domains, then $\{\pi^{-1}(U_i)\}$ satisfies the conditions of Lemma 1.2.5.

Finally, to see that $\pi : TM \to M$ is smooth, note that its coordinate representation at every point is given by the projection $\pi : \mathbb{R}^{2n} \to \mathbb{R}^n$, $(x, v) \mapsto x$. $\square$

Definition 3.3.2. Given $F : M \to N$ is smooth, define the *global differential* $dF : TM \to TN$ of F by $dF(\phi, p) = dF_p(\phi)$.

Proposition 3.3.3. *The global differential $dF : TM \to TN$ is smooth.*

Aside. This shows that mapping M to TM and F to dF defines a functor from Diff to itself, called the *tangent functor*.

Note 3.3.4. If F is a diffeomorphism, then so is dF with $d(F^{-1}) = (df)^{-1}$.

Definition 3.3.5. Given a smooth curve $\gamma : J \to M$ and $t_0 \in J$, the *velocity of* γ *at* t_0 is

$$\gamma'(t_0) \equiv d\gamma\left(\frac{d}{dt}\Big|_{t_0}\right) \in T_{\gamma(t_0)}M.$$

Remark 3.3.6. Let $(U, \phi) \ni \gamma(t_0)$ be a chart on M. Then $\gamma'(t_0) = \frac{d\gamma^i}{dt}\frac{\partial}{\partial x_i}\big|_{\gamma(t_0)}$.

Lemma 3.3.7. *Every $v \in T_pM$ is the velocity of some smooth curve $\gamma : J \to M$ at 0 such that $\gamma(0) = p$.*

Proof. Let (U, ϕ) be a chart centered at p. Write $v = v_i\frac{\partial}{\partial x_i}\big|_p$. For $\epsilon > 0$ small, define $\gamma : (-\epsilon, \epsilon) \to U$ by $\gamma(t) = \phi^{-1}(tv_1, \ldots, tv_n)$. Remark 3.3.6 implies that $\gamma'(0) = v$. □

Proposition 3.3.8. *Let $v \in T_pM$. Then $dF_p(v) = (F \circ \gamma)'(0)$ for any smooth $\gamma : J \to M$ such that $\gamma(0) = p$ and $\gamma'(0) = v$.*

Aside. A *smooth function element on* M is a pair (f, U) with $U \subset M$ open and $f : M \to \mathbb{R}$ smooth. Say that $(f, U) \sim (g, V)$ if $p \in U \cap V$ and $f \equiv g$ on some neighborhood of p. The class $[(f, U)] := [f]_p$ is called the *germ of f at p*. The set of such classes is denoted by $C_p^\infty(M)$. This is an associative algebra over $\mathbb{R}$.

Define a *derivation of* $C_p^\infty(M)$ as a linear map $v : C_p^\infty(M) \to \mathbb{R}$ such that $v[fg]_p = f(p)v[g]_p + g(p)v[f]_p$. The tangent space $\mathcal{D}_pM$ of such derivations serves as an equivalent (via isomorphism) definition of the tangent space of M at p.

3.4 Lecture 9

Theorem 3.4.1 (Inverse function theorem). *If $F : M \to N$ is smooth and dF_p is invertible, then there are connected neighborhoods U_0 of p and V_0 of $F(p)$ such that $F\restriction_{U_0}: U_0 \to V_0$ is a diffeomorphism.*

Proof. Notice that M and N have equal dimension (say n) because dF_p is invertible. Choose charts (U, f) centered at p and (V, g) centered at $F(p)$ such that $F(U) \subset V$. Then $\widehat{F} := g \circ F \circ f^{-1}$ is smooth map from $\widehat{U} := f(U) \subset \mathbb{R}^n$ to $\widehat{V} := g(V) \subset \mathbb{R}^n$ with $\widehat{F}(0) = 0$. Now $d\widehat{F}_0$ is invertible as the composition of three invertible maps. The Euclidean inverse function theorem implies that there are open balls $B_r(0)$ and $B_s(0)$ such that $\widehat{F} : B_r(0) \to B_s(0)$ is a diffeomorphism. Then $F : f^{-1}(B_r(0)) \to g^{-1}(B_s(0))$ is a diffeomorphism. □

Corollary 3.4.2. *If dF_p is nonsingular at each $p \in M$, then F is a local diffeomorphism.*

Proposition 3.4.3.

1. *The finite product of local diffeomorphisms is a local diffeomorphism.*
2. *The composition of two local diffeomorphisms is a local diffeomorphism.*
3. *Any bijective local diffeomorphism is a diffeomorphism.*
4. *A map F is a local diffeomorphism if and only if each point in* $\mathrm{dom}(F)$ *has a neighborhood where F's coordinate representation is a local diffeomorphism.*

Definition 3.4.4. The *rank of a smooth map F at a point p* is the rank of dF_p. If the rank of F is equal at each point, then we say F has constant rank.

Theorem 3.4.5 (Constant rank). *Let $F : M^m \to N^n$ be smooth with constant rank $r \leq m, n$. Then for each $p \in M$, there are charts (U, f) centered at p and (V, g) centered at $F(p)$ with $F(U) \subset V$ where the coordinate representation of F is given by*

$$\widehat{F}(x_1, \ldots, x_r, x_{r+1}, \ldots x_m) = (x_1, \ldots, x_r, 0, \ldots, 0).$$

Note 3.4.6.

- If $m = n = r$, then this follows immediately from the inverse function theorem.
- The global condition on the rank of F cannot be weakened, as the space of $n \times m$ matrices of rank r need not be open. For example, consider $A(t) = \begin{bmatrix} 1 & t \\ 1 & 1 \end{bmatrix}$, which has rank 2 for $t \neq 1$ and rank 1 otherwise.

Proof. Since our statement is local, we may assume that $M \subset \mathbb{R}^m$ and $N \subset \mathbb{R}^n$ are open subsets. Since $DF(p)$ has rank r, it has some invertible $r \times r$ sub-matrix, which we may assume is the upper left sub-matrix $\left(\frac{\partial F^i}{\partial x^j}\right)_{i,j \in [r]}$. Write $(x, y) = (x^1, \dots, x^r, y^1, \dots, y^{m-r})$ and $(v, w) = (v^1, \dots, v^r, w^1, \dots, w^{n-r})$ for the standard coordinates on $\mathbb{R}^m$ and $\mathbb{R}^n$, respectively. By applying translations, we may assume that $p = (0, 0)$ and $F(p) = (0, 0)$. Let $F(x, y) = (Q(x, y), R(x, y))$ for some smooth $Q : M \to \mathbb{R}^r$ and $R : M \to \mathbb{R}^{n-r}$. Then the Jacobian matrix $\left(\frac{\partial Q^i}{\partial x^j}\right)$ is invertible at $(0, 0)$ by hypothesis.

Define $f : M \to \mathbb{R}^m$ by $(x, y) \mapsto (Q(x, y), y)$. Define the *Kronecker delta* symbol δ_i^j by

$$\delta_i^j = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}.$$

Then

$$D[f](0,0) \begin{bmatrix} \frac{\partial Q^i}{\partial x^j}(0,0) & \frac{\partial Q^i}{\partial y^j}(0,0) \\ 0 & \delta_j^i \end{bmatrix}.$$

Since

$$\det(D[f](0,0)) = \det\left(\frac{\partial Q^i}{\partial x^j}(0,0)\right) \cdot \det(\delta_j^i) = \det\left(\frac{\partial Q^i}{\partial x^j}(0,0)\right) \neq 0,$$

it follows that $D[f]$ is invertible at $(0, 0)$.

Thus, we can apply the inverse function theorem to get a connected open set $U_0 \ni (0, 0)$ and an open cube $\widetilde{U}_0 \ni f(0, 0) = (0, 0)$ such that $f : U_0 \to \widetilde{U}_0$ is a diffeomorphism. Let $f^{-1}(x, y) = (A(x, y), B(x, y))$. Then $(x, y) = f(A(x, y), B(x, y)) = (Q(A(x, y), B(x, y)), B(x, y))$, so that $y = B(x, y)$. Hence

$$f^{-1}(x, y) = (A(x, y), y).$$

Additionally, $Q(A(x, y), y) = x$ since $f \circ f^{-1} = \mathrm{id}_{\widetilde{U}_0}$. If $\widetilde{R} : \widetilde{U}_0 \to \mathbb{R}^{n-r}$ is defined by $(x, y) \mapsto R(A(x, y), y)$, then

$$F \circ f^{-1}(x, y) = (x, \widetilde{R}(x, y)).$$

Therefore,

$$D[F \circ f^{-1}](x, y) = \begin{bmatrix} \delta_j^i & 0 \\ \frac{\partial \widetilde{R}^i}{\partial x^j}(x, y) & \frac{\partial \widetilde{R}^i}{\partial y^j}(x, y) \end{bmatrix}$$

for any $(x, y) \in \widetilde{U}_0$. It's clear that the first r columns of this matrix are linearly independent. But since f^{-1} is a diffeomorphism, it has rank r on $\widetilde{U}_0$. It follows that $\frac{\partial \widetilde{R}^i}{\partial y^j}(x, y) = 0$ for each $(x, y) \in \widetilde{U}_0$. But $\widetilde{U}_0$ was chosen to be an open cube, so that $\widetilde{R}(x, y) = \widetilde{R}(x, 0)$. If $S(x) \coloneqq \widetilde{R}(x, 0)$, then $F \circ f^{-1}(x, y) = (x, S(x))$.

Now, let $V_0 = \left\{(v, w) \in N \mid (v, 0) \in \widetilde{U}_0\right\}$, which is a neighborhood of $(0, 0)$ in N. Since $\widetilde{U}_0$ is a cube, we see that $F \circ f^{-1}(\widetilde{U}_0) \subset V_0$. Hence $F(U_0) \subset V_0$. Define $g : V_0 \to \mathbb{R}^n$ by $(v, w) \mapsto (v, w - S(v))$, which is smooth with inverse $g^{-1}(s, t) = (s, t + S(s))$. Then

$$\widehat{F}(x, y) = g \circ F \circ f^{-1}(x, y) = (x, S(x) - S(x)) = (x, 0),$$

as desired. $\square$

3.5 Lecture 10

Definition 3.5.1. A smooth map $F : M \to N$ is a *(smooth) submersion* if it has constant rank equal to $\dim(N)$. It is a *(smooth) immersion* if it has constant ranl equal to $\dim(M)$.

Definition 3.5.2. A *topological embedding* is a continuous map $F : M \to N$ which is a homeomorphism onto $F(M)$.

Example 3.5.3.

1. The map $\gamma : \mathbb{R} \to \mathbb{R}^2$ defined by $t \mapsto (t^3, 0)$ is a smooth topological embedding but not an immersion, since $\gamma'(0) = 0$.

2. The curve $f : (-\pi, \pi) \to \mathbb{R}^2$ defined by $f(t) = (\sin 2t, \sin t)$ is known as a *lemniscate*, describing a figure-eight curve. This is not a topological embedding, because the figure-eight is compact whereas $(-\pi, \pi)$ is not. But it is a smooth immersion as f' never vanishes.

Definition 3.5.4. A map is a *smooth embedding* if it both a topological embedding and a smooth immersion.

Example 3.5.5.

1. There is a smooth embedding of $\mathbb{RP}^2$ into $\mathbb{R}^4$ but not into $\mathbb{R}^3$

2. If $U \subset M$ is open, then the inclusion $U \hookrightarrow M$ is a smooth embedding.

Definition 3.5.6. A manifold $S \subset M$ in the subspace topology is an *embedded* (or *regular*) *submanifold* if it has a smooth structure such that the inclusion $S \hookrightarrow M$ is smooth.

Remark 3.5.7. The image of a smooth embedding is an embedded submanifold.

Definition 3.5.8. If $S \subset M$ is an embedded submanifold, then $\dim M - \dim S$ is called the *codimension of S in M*.

Proposition 3.5.9. *Let $U \subset M$ be open and $f : U \to N$ be smooth where $\dim M = m$ and $\dim N = n$. If $\Gamma(f)$ denotes the graph of f, then it is an embedded m-dimensional manifold of $M \times N$.*

Proof. Define $\gamma_f(x) : U \to M \times N$ by $\gamma_f(x) = (x, f(x))$. It's easy to check this is a smooth embedding. □

Definition 3.5.10. We say S has the *local k-slice condition* if for each $p \in S$, there is a chart $(U, f) \ni p$ for M such that $f(U \cap S) = \{x \in \mathbb{R}^n : x^{k+1} = \cdots = x^m = 0\}$, where $m = \dim M$.

Theorem 3.5.11. *Let M^n be a smooth manifold. If $S \subset M$ is an embedded manifold with $\dim S = k$, then S has the local k-slice condition. Conversely, if $S \subset M$ has the local k-slice condition, then S is a manifold in the subspace topology and has a smooth structure making it an embedded submanifold of dimension k.*

Proof. See *Lee*, Theorem 5.8. □

Example 3.5.12. For any n, $\mathbb{S}^n \subset \mathbb{R}^{n+1}$ is an embedded hypersurface because it is locally the graph of smooth map and thus has the local n-slice condition.

Theorem 3.5.13. *Let $F : M^m \to N^n$ be smooth with constant rank r. Each level set of F is an embedded submanifold of codimension r in M.*

Proof. Set $k = m - r$. Let $c \in N$ and $p \in F^{-1}(c)$. By the constant rank theorem, there are charts (U, f) centered at p and (V, g) centered at $F(p) = c$ for which F has coordinate representation $(x_1, \ldots, x_r, x_{r+1}, \ldots, x_m) \mapsto (x_1, \ldots, x_r, 0, \ldots, 0)$, which must send each point in $f(F^{-1}(c) \cap U)$ to 0. Thus, $f(F^{-1}(c) \cap U)$ equals the k-slice $\{x \in \mathbb{R}^m : x_1 = \cdots = x_r = 0\}$. By Theorem 3.5.11, S is an embedded submanifold of dimension k. □

3.6 Lecture 11

Question. Can M^n with $n \geq 1$ be homeo-/diffeomorphic to $M \setminus \{p\}$?

Remark 3.6.1. We can generalize Theorem 3.5.13 to maps that are not necessarily of constant rank.

Definition 3.6.2. Let $\phi : M \to N$ be smooth. We say that $p \in M$ is a

1. *regular point* if $d\phi_p$ is surjective.
2. *critical point* otherwise.

Definition 3.6.3. With notation as before, we say that $c \in N$ is a

1. *regular value* if each point in $\phi^{-1}(c)$ is regular.
2. *critical value* otherwise.

Theorem 3.6.4. *Every regular level set of a smooth map $F : M^m \to N^n$ is an embedded submanifold of codimension n.*

Proof. Let $c \in N$. Note that since the subspace of full-rank matrices is open, the set U of points $p \in M$ where dF_p is surjective is open in M. Hence $F \restriction_U : U \to N$ is a smooth submersion. In particular it has constant rank n, so that $F^{-1}(c)$ is an embedded submanifold with codimension n of U , which itself is an open submanifold of M. □

Example 3.6.5. $\mathbb{S}^n$ is the regular level set of the smooth function $x \mapsto |x|^2$.

Theorem 3.6.6 (Sard). *If $F : M \to N$ is smooth, then the set of all critical values of F has measure zero in N.*

Proposition 3.6.7. *Suppose M is smooth and $S \subset M$ is embedded. Then for any $f \in C^\infty(S)$, then there is some neighborhood U of S in M and $\hat{f} \in C^\infty(U)$ such that $\hat{f} \restriction_S = f$.*

Proposition 3.6.8. *The tangent space of a submanifold $S \subset M$ at $p \in S$ is just the image of the injective canonical map $di_p : T_pS \to T_pM$ where i denotes inclusion. More concretely, this is equal to*

$$A := \{\gamma'(0) \in T_pM : \gamma : (-\epsilon, \epsilon) \to S \text{ and } \gamma(0) = p\}.$$

Proof. Let $v \in T_pS$. We know that $v = \gamma'(0)$ for some curve γ in S. Then $i \circ \gamma$ is a curve in M with $(i \circ \gamma)' = di_p(v)$. Conversely, let $v := w'(0) \in A$. We have $w = j \circ w$ where $j : i(S) \to S$ is the reverse inclusion. Since $(j \circ w)'(0) = dj_p(v) \in T_pS$, it follows that $d_i((j \circ w)'(0)) = v$. □

Remark 3.6.9. Let $F : \mathbb{R}^n \to \mathbb{R}$ be smooth. The gradient ∇F has two main properties.

1. It is orthogonal to the level sets of F.
2. $dF_p(v) = \langle \nabla F_p, v\rangle$.

But we don't necessarily have an inner product on M unless M is a *Riemannian manifold*, which by definition has a smoothly varying inner product.

3.7 Lecture 12

Definition 3.7.1. If $\pi : M \to N$ is a continuous map, a *section of* π is a continuous right inverse for π.

Definition 3.7.2. A *(smooth) vector field* X is a smooth section of the projection $\pi : TM \to M$, i.e., $X_p := F(p) \in T_pM$ for each $p \in M$. Let $\mathscr{X}(M)$ denote the space of smooth vector fields in M.

Remark 3.7.3. Given a chart U on M, if $p \in U$, then we can write $X_p = \sum_i r_i \frac{\partial}{\partial x_i}\big|_p$ for some unique real coefficients r_i. Define each $X^i : U \to \mathbb{R}$ by $X_i(p) = r_i$. Then $X_p = \sum_i X_i(p) \frac{\partial}{\partial x_i}\big|_p$.

Terminology. We call such X_i the *component functions of* X for the chart U.

Proposition 3.7.4. *A vector field X is smooth if and only if each component function in any given chart is smooth.*

Remark 3.7.5. $\mathscr{X}(M)$ is a module over $C^\infty(M)$ by the action $f \cdot X = (p \mapsto f(p)X_p)$.

Lemma 3.7.6. *If S is a closed subset of M and X a smooth vector field along S, then there is an extension of X to a smooth vector field on M.*

Definition 3.7.7. Let $U \subset M^n$ be open and $X_1, \dots, X_k \in \mathscr{X}(M)$.

1. $X_1, \dots, X_k$ are *linearly independent* if for any $p \in U$, we have $\{X_1(p), \dots, X_k(p)\}$ linearly independent in T_pM.
2. If $k = n$ and $X_1, \dots, X_k$ are linearly independent, then $\{X_1, \dots, X_k\}$ is a *local frame* in U.

Example 3.7.8. The basis vectors $p \mapsto \frac{\partial}{\partial x_i}\big|_p$ form a local frame for a given chart U around p, called the *coordinate frame*.

Definition 3.7.9. A local frame for U is called a *global frame* if $U = M$. If such a frame exists, then M is called *parallelizable*.

Example 3.7.10. $\mathbb{R}^n$ is parallelizable via the standard coordinate vector fields.

Lemma 3.7.11. *M is parallelizable if and only if $TM \approx M \times \mathbb{R}^n$.*

Theorem 3.7.12 (Kervaire). *$\mathbb{S}^n$ is parallelizable if and only if $n \in \{0, 1, 3, 7\}$.*

Definition 3.7.13 (Lie group). A *Lie group* is a group G equipped with a smooth structure such that both $\cdot : G \times G \to G$ and $-^{-1} : G \to G$ are smooth maps.

Example 3.7.14. Any Lie group is parallelizable.

Remark 3.7.15. Note that $\mathscr{X}(M)$ acts on $C^\infty(U)$ for any $U \subset M$ via $X \cdot f = (p \mapsto X_p(f))$. Given $X \in \mathscr{X}(M)$ fixed, this induces a linear map $X : C^\infty(U) \to C^\infty(U)$ satisfying the product rule $X(fg) = fXg + gXf$. We call such a map a *derivation* of $C^\infty(U)$.

Moreover, if $F : M \to N$ is smooth, then we have $dF_pX(p) \in T_{F(p)}N$ for each $p \in M$. But this may not define a vector field on N, since F may not be surjective.

Example 3.7.16. Note that for $X, Y \in \mathscr{X}(M)$, $X(Yf)$ need not be a derivation. Indeed, let $M = \mathbb{R}^2$, $X = \frac{\partial}{\partial x}$, and $Y = x\frac{\partial}{\partial y}$. If $f(x, y) = x$ and $g(x, y) = y$, then $XY(fg) = 2x$ whereas $fXY(g) + gXY(f) = x$, so that $XY(f)$ is not a derivation.

Definition 3.7.17. Let $X, Y \in \mathscr{X}(M)$. The *Lie bracket of X and Y* is

$$[X, Y] \equiv XY - YX : C^\infty(M) \to C^\infty(M).$$

Proposition 3.7.18 (Clairaut). *If $X_i = \frac{\partial}{\partial x_i} \in \mathscr{X}(M)$, then $[X_i, X_j] = 0$ for any $1 \leq i, j \leq n$.*

Lemma 3.7.19. *A map $D : C^\infty(M) \to C^\infty(M)$ is a derivation if and only if there is some $X \in \mathscr{X}(M)$ such that $Df = Xf$ for any f.*

Proof. We've established the backward implication. Conversely, assume that D is a derivation. Define $X : M \to TM$ by $X_p(f) = (Df)(p)$. Since $Df = Xf$ is smooth for each X, it follows that X is smooth by *Lee*, Proposition 8.14. ☐

Proposition 3.7.20. *Any Lie bracket $[X, Y]$ is a smooth vector field.*

Proof. By Lemma 3.7.19, it suffices to show that $[X,Y]$ is a derivation. Let f,g be smooth functions on M. Then

$$\begin{aligned}
[X,Y](fg) = X(Y(fg)) - Y(X(fg)) &= X(fYg + gYf) - Y(fXg + gXf) \\
&= XfYg + XgYf - YfXg - YgXf \\
&= fXYg + YgXf + gXYf + YfXg \\
&- fYXg - XgYf - gYXf - XfYg \\
&= fXYg + gXYf - fYXg - gYXf \\
&= f[X,Y]g + g[X,Y]f.
\end{aligned}$$

□

3.8 Lecture 13

Definition 3.8.1. The function $[X,Y] : M \to TM$ is given by $p \mapsto (f \mapsto X_p(Yf) - Y_p(Xf))$.

Proposition 3.8.2. *Write $X = X^i \frac{\partial}{\partial x_i}$ and $Y = Y^j \frac{\partial}{\partial x_j}$ in local coordinates. Then*

$$[X,Y] = \sum_{i,j} \left(X^i \frac{\partial Y^j}{\partial x_i} - Y^i \frac{\partial X^j}{\partial x_i} \right) \frac{\partial}{\partial x_j}.$$

Proof. Since $[X,Y]$ is a vector field, $([X,Y]f) \restriction_U = [X,Y](f \restriction_U)$ for any open $U \subset M$. Therefore, we can compute, say, Xf in a coordinate expression for X. We can apply the product rule and Clairaut's theorem to get

$$\begin{aligned}
[X,Y]f &= X^i \frac{\partial}{\partial x_i} \left(Y^j \frac{\partial f}{\partial y_j} \right) - Y^j \frac{\partial}{\partial x_j} \left(X^i \frac{\partial f}{\partial x_i} \right) \\
&= X^i \frac{\partial Y^j}{\partial x_i} \frac{\partial f}{\partial x_j} + X^i Y^j \frac{\partial^2 f}{\partial x_i x_j} - Y^j \frac{\partial X^i}{\partial x_j} \frac{\partial f}{\partial x_i} - Y^j X^i \frac{\partial^2 f}{\partial x_j x_i} \\
&= X^i \frac{\partial Y^j}{\partial x_i} \frac{\partial f}{\partial x_j} - Y^j \frac{\partial X^i}{\partial x_j} \frac{\partial f}{\partial x_i} \\
&= \sum_{i,j} \left(X^i \frac{\partial Y^j}{\partial x_i} - Y^i \frac{\partial X^j}{\partial x_i} \right) \frac{\partial}{\partial x_j}.
\end{aligned}$$

□

Remark 3.8.3. If $X_1, \ldots, X_n \in \mathscr{X}(U)$ such that $[X_i, X_j] = 0$, then there are local coordinates $x^i : V \to \mathbb{R}$ such that $X_i = \frac{\partial}{\partial x^i}$. This is a converse to Clairaut's theorem.

Proposition 3.8.4.

1. *(Bilinearity) For any $a, b \in \mathbb{R}$,*

$$[aX + bY, Z] = a[X,Z] + b[Y,Z]$$

$$[Z, aX + bY] = a[Z,X] + b[Z,Y].$$

2. *(Antisymmetry)*

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

3. *(Jacobi Identity)*

$$[X,[Y,Z]] + [Y,[Z,X]] + [Z,[X,Y]] = 0.$$

4. *For any $f, g \in C^\infty(M)$,*

$$[fX, gY] = fg[X,Y] + (fXg)\,Y - (gYf)\,X,$$

where fX denotes the module action $f \cdot X$.

Proof. Compute directly. $\square$

Definition 3.8.5 (Pushforward). Let $X \in \mathscr{X}(M)$ and $Y \in \mathscr{X}(N)$. Let $F : M \to N$ be a diffeomorphism. The *pushforward of X by F*, denoted by F_*X, is the vector field on N given by $q \mapsto dF_{F^{-1}(q)}\left(X_{F^{-1}(q)}\right)$.

Definition 3.8.6. Let $X \in \mathscr{X}(M)$ and $Y \in \mathscr{X}(N)$. If $F : M \to N$ is a diffeomorphism, then X and Y are *F-related* if $Y = F_*X$.

Remark 3.8.7. $X(f \circ F) = (Yf) \circ F$ if and only if X and Y are F-related.

Theorem 3.8.8 (Naturality of the Lie bracket). *Suppose $F : M \to N$ is a diffeomorphism and $X, Y \in \mathscr{X}(M)$. Then $F_*[X,Y] = [F_*X, F_*Y]$.*

Proof. Let $f \in C^\infty(M)$. By Remark 3.8.7, we see that $XY(f \circ F) = X(F_*Yf \circ F) = F_*X(F_*Yf) \circ F$, and likewise $YX(f \circ F) = F_*Y(F_*Xf) \circ F$. Thus,

$$[X,Y](f \circ F) = F_*X(F_*Yf) \circ F - F_*Y(F_*Xf) \circ F = ([F_*X, F_*Y]f) \circ F.$$

We conclude by again applying Remark 3.8.7. $\square$

Corollary 3.8.9. *Let $S \subset M$ be a submanifold. If $X, Y \in \mathscr{X}(M)$ have $X_p, Y_p \in T_p(S)$ for each $p \in S$, then $[X,Y]_p \in T_p(S)$ as well.*

Proof. Let $i : S \to M$ denote inclusion. Then there are $X', Y' \in \mathscr{X}(S)$ with X' i-related to $X \restriction_S$ and Y' to $Y \restriction_S$. This implies $[X', Y']$ is i-related to $[X,Y] \restriction_S$, which in turn implies that $[X,Y]_p \in T_p(S)$ for any $p \in S$. $\square$

4 Vector bundles

Definition 4.0.1. Let M be a topological space. A *(real) vector bundle of rank k over M* is a topological space E endowed with the following structure.

1. A surjective continuous map $\pi : E \to M$.
2. For each $p \in M$, $E_p := \pi^{-1}(p)$ is endowed with the structure of a k dimensional real vector space.
3. For each $p \in M$, there is a neighborhood U_p in M and a homeomorphism $\phi : \pi^{-1}(U) \to U \times \mathbb{R}^k$ such that
   (a) $\pi_U \circ \phi = \pi \restriction_{\pi^{-1}(U)}$, where $\pi_U : U \times \mathbb{R}^k \to U$ is the projection.
   (b) For each $q \in U$, $\phi \restriction_{E_q}$ is a linear isomorphism $E_q \cong \{q\} \times \mathbb{R}^k \cong \mathbb{R}^k$.

If M and E are smooth manifolds and π and the ψ are smooth, then E is called a *smooth vector bundle.*

Example 4.0.2. The Mobius strip and $\mathbb{S}^1 \times \mathbb{R}$ are different vector bundles over $\mathbb{S}^1$.

Remark 4.0.3. We can always construct a global section for a smooth vector bundle by using partition of unity. But we cannot always ensure that it is non-vanishing, as shown by the hairy ball theorem (Corollary 7.3.4) for bundles over $\mathbb{S}^2$.

4.1 Lecture 14

Lemma 4.1.1 (Vector bundle construction). *Let M^n be a smooth manifold and suppose that for any $p \in M$, there is some vector space E_p of some fixed dimension k. Let $E := \coprod_{p \in M} E_p$ and $\pi : E \to M$ be the projection map. Further, suppose we have the following data:*

1. *an open cover $\{U_\alpha\}$.*
2. *for each α, a bijective $\phi_\alpha : \pi^{-1}(U_\alpha) \to U_\alpha \times \mathbb{R}^k$ whose restriction to each E_p is a linear isomorphism to $\{p\} \times \mathbb{R}^k$.*

3. *for each $U_\alpha \cap U_\beta \neq \emptyset$, a smooth map $\tau_{\alpha\beta} : U_\alpha \cap U_\beta \to \mathrm{GL}(k, \mathbb{R})$ such that $\phi_\alpha \circ \phi_\beta^{-1}(p, v) = (p, \tau_{\alpha\beta}(p)v)$.*

Then E has a unique topology and smooth structure making it into a smooth vector bundle of rank k over M.

Remark 4.1.2. The matrices $\tau_{\alpha\beta}(p)$ are called the *transition functions* of the vector bundle E. They satisfy the so-called cocycle condition:

$$\tau_{\alpha\alpha}(p) = I_k \qquad \tau_{\alpha\beta}(p)\tau_{\beta\gamma}(p)\tau_{\gamma\alpha}(p) = I_k.$$

Definition 4.1.3. If V is a real vector space, then define the *dual space* $V^* = \mathrm{Hom}(V, \mathbb{R})$.

Proposition 4.1.4.

1. *If $\dim(V) = n$, then $\dim(V^*) = n$.*

2. *There is a canonical isomorphism $V \cong (V^*)^*$ via $v \mapsto (\phi \mapsto \phi(v))$.*

Definition 4.1.5. Let $v_1, \ldots, v_n$ be a basis for V. Then the *dual basis* consists of $\phi_i : V \to \mathbb{R}$ given by $\phi_i(v_j) = 1$ when $i = j$ and $\phi_i(v_j) = 0$ otherwise.

Notation. If $A : V \to W$ is linear, then let A^* denote the linear map $W^* \to V^*$ defined by $w \mapsto (v \mapsto w(Av))$.

Definition 4.1.6. Let M^n be a smooth manifold.

1. Define the *cotangent space at p* as T_p^*M.

2. Define the *cotangent bundle of M* as $T^*M = \coprod_p T_p^*M$.

Lemma 4.1.7. *T^*M is a smooth n-vector bundle over M.*

Proof. Let (U, ϕ) be a smooth chart for M. Define $\phi : \pi^{-1}(U) \to U \times \mathbb{R}^n$ by $a_i\lambda^i\big|_p \mapsto (p, a_1, \ldots, a_n)$, where $\{\lambda^i\big|_p\}$ is a dual basis for T_pM. Now we apply the vector bundle construction lemma, the details of which can be found in *Lee*, Proposition 11.9. ☐

Remark 4.1.8. Let (U, x^i) be smooth coordinates for M^n. Then $\psi : a_i\lambda^i\big|_p \mapsto (x^1(p), \ldots, x^n(p), a_1, \ldots, a_n)$ is a local chart $(\pi^{-1}(U), \psi)$ for T^*M.

Definition 4.1.9. A section of T^*M is called a *covector field* or a *(differential/smooth) 1-form.*

4.2 Lecture 15

Definition 4.2.1 (Differential of a smooth function). Define $C^\infty(M) \to \Gamma(T^*M)$ by $f \mapsto (p \mapsto df_p)$ where

$$df_p(v) \equiv vf$$

for every $v \in T_pM$. We call df the *differential of f*.

Remark 4.2.2. Let (U, x^i) be local coordinates for M. Let (dx^i) denote the corresponding coordinate coframe on U. Write $df_p = A_i(p)dx^i\big|_p$ for some functions $A_i : U \to \mathbb{R}$. Then $A_i(p) = df_p\left(\frac{\partial}{\partial x^i}\big|_p\right) = \frac{\partial f}{\partial x^i}(p)$, so that $df_p = \frac{\partial f}{\partial x^i}(p)dx^i\big|_p$. In this way, the differential of f generalizes the gradient of a smooth function on $\mathbb{R}^n$.

Proposition 4.2.3. *If M is connected, then f is constant if and only if $df = 0$.*

Proof. Since $vf = 0$ for any derivation v and constant f, the forward direction is clear. Conversely, suppose that $df = 0$ and let $p \in M$. Set $C = \{q \in M : f(q) = f(p)\}$. We want $C = M$. It suffices to show that C is clopen. For any $q \in C$, choose a coordinate ball $U \ni p$. Then since $0 = df = \frac{\partial f}{\partial x^i}dx^i$, it follows that $\frac{\partial f}{\partial x^i} = 0$ for each i. Elementary calculus implies that f must be constant on U. Hence C is open. Since $C = f^{-1}(p)$, it is also closed. ☐

Note 4.2.4 (Transition functions for changing coordinates). Let $p \in M$ and suppose that $\left(x^i\right)_{1\le i\le n}$ and $\left(y^i\right)_{1\le i\le n}$ are two coordinate charts around p. The chain rule for partial derivatives states that

$$\frac{\partial}{\partial x^j}\Big|_p = \sum_k \frac{\partial y^k}{\partial x^j}(\hat{p})\frac{\partial}{\partial y^k}\Big|_p$$

where $\hat{p} \equiv \left(x^1(p), \ldots, x^n(p)\right)$. Dually, for each $i \in \{1, \ldots, n\}$, we have that

$$dx^i\big|_p = \sum_l A^i_l dy^l\big|_p$$

for some $A^i_l \in \mathbb{R}$, $l = 1, \ldots, n$. It follows that

$$\begin{aligned}
\delta^j_i &= dx^i\big|_p\left(\frac{\partial}{\partial x^j}\Big|_p\right)\\
&= dx^i\big|_p\left(\sum_k \frac{\partial y^k}{\partial x^j}\frac{\partial}{\partial y^k}\Big|_p\right)\\
&= \sum_k \frac{\partial y^k}{\partial x^j} dx^i\big|_p\left(\frac{\partial}{\partial y^k}\Big|_p\right)\\
&= \sum_k \frac{\partial y^k}{\partial x^j}\sum_l A^i_l dy^l\big|_p\left(\frac{\partial}{\partial y^k}\Big|_p\right)\\
&= \sum_k \frac{\partial y^k}{\partial x^j}\sum_l A^i_l \delta^k_l\\
&= \sum_k A^i_k \frac{\partial y^k}{\partial x^j}.
\end{aligned}$$

Therefore, if A denotes the $n\times n$ matrix $\left(A^i_l\right)$ and J denotes the Jacobian of $\left(y^1, \ldots, y^n\right)$ at $\hat{p}$, then $I_n = JA$, so that $A = J^{-1}$.

Definition 4.2.5. Let $F : M \to N$ be smooth. Let $\omega \in \Gamma(T^*N)$. Define the *pullback* $F^*\omega$ *of* ω as the element of $\Gamma(T^*M)$ given by

$$F^*\omega\big|_p\left(X\big|_p\right) = \omega\big|_{F(p)}\left(F_*\big|_p X_p\right).$$

Note that, unlike the pushforward, the pullback requires just that F be smooth.

Lemma 4.2.6. *Let $F : M \to N$ be smooth, $\alpha, \beta \in \Gamma(T^*N)$ and $f, g \in C^\infty(N)$. Then*

$$F^*(f\alpha + g\beta) = (f\circ F)F^*\alpha + (g\circ F)F^*\beta.$$

Proof. Let $X \in \mathscr{X}(M)$. We have that

$$\begin{aligned}
F^*(f\alpha + g\beta)\big|_p(X_p) &= (f\alpha + g\beta)\big|_{F(p)}\left(F_*\big|_p X_p\right)\\
&= f\left(F(p)\right)\alpha_{F(p)}\left(F_*\big|_p X_p\right) + g\left(F(p)\right)\beta_{F(p)}\left(F_*\big|_p X_p\right)\\
&= \left[(f\circ F)F^*\alpha\right]_p(X_p) + \left[(g\circ F)F^*\beta\right]_p(X_p).
\end{aligned}$$

□

Let $\gamma : J \subset \mathbb{R} \to M$ be a curve in M. Note that $\Gamma(T^*\mathbb{R}) = \{f(t)dt : f : T \to \mathbb{R}\}$. Then

$$\omega \in \Gamma(T^*M) \implies \gamma^*\omega \in \Gamma(T^*\mathbb{R}) \implies \gamma^*\omega = f(t)dt$$

for some curve f along J.

Definition 4.2.7. The *integral of ω along γ* is

$$\int_\gamma \omega \equiv \int_J \gamma^*\omega.$$

Proposition 4.2.8. *Suppose ϕ is a positive reparameterization of γ. Then $\int_\gamma \omega = \int_{\gamma\circ\phi} \omega$.*

Proof. See *Lee*, Proposition 11.31. $\square$

Definition 4.2.9. A differential 1-form is *closed* if $\frac{\partial w_i}{\partial x^j} - \frac{\partial w_j}{\partial x^i} = 0$ for any i, j where $w = w_i dx^i$.

Exercise 4.2.10. *Show that being closed is a well-defined property.*

Example 4.2.11. By Clairaut's theorem, *df* is closed for any $f \in C^\infty(M)$.

5 Differential forms

5.1 Lecture 16

Theorem 5.1.1 (Universal property of the tensor product). *Let $V_1, \dots, V_k$ be (real) vector spaces. There exists a vector space $V_1 \otimes \cdots \otimes V_k$ (called the tensor product of the V_i) and map $: \otimes : V_1 \times \cdots \times V_k$ so that for any multilinear map $T : V_1 \times \cdots \times V_k \to W$, there is some unique linear $\widetilde{T} : V \otimes \cdots \otimes V_k \to W$ such that the following commutes.*

$$\begin{tikzcd} V_1 \times \cdots \times V_k \arrow[r, "T"] \arrow[d, "\otimes"'] & W \\ V_1 \otimes \cdots \otimes V_k \arrow[ur, dashed, "\widetilde{T}"'] & \end{tikzcd}$$

Proof. If we prove it when $k = 2$, then we're done by induction. Let $\mathbb{R}\langle V_1 \times V_2\rangle$ denote the free vector space on $V_1 \times V_2$, i.e., the set of all finite formal linear combinations of $V_1 \times V_2$. Set

$$G = \langle (av_1, v_2) - a(v_1, v_2), (v_1, av_2) - a(v_1, v_2), (v_1 + w_1, v_2) - (v_1, v_2) - (w_1, v_2), (v_1, w_2 + v_2) - (v_1, w_2) - (v_1, v_2)\rangle.$$

Given $T : V_1 \times V_2 \to W$ multilinear, define $\widetilde{T} : \mathbb{R}\langle V_1 \times V_2\rangle \to W$ by $\sum a_{(v_1,v_2)}(v_1, v_2) \mapsto \sum a_{(v_1,v_2)}T(v_1, v_2)$. Since T is multilinear, $G \subset \ker \widetilde{T}$. Therefore, if $V_1 \otimes V_2 := \mathbb{R}\langle V_1 \times V_2\rangle / G$, then we get

$$\begin{tikzcd} \mathbb{R}\langle V_1 \times V_2\rangle \arrow[r, "\tilde{T}"] \arrow[d, "\pi"'] & W \\ V_1 \otimes V_2 \arrow[ur, dashed, "\tilde{\tilde{T}}"'] & \end{tikzcd}.$$

Thus, if $i : V_1 \times V_2 \to \mathbb{R}\langle V_1 \times V_2\rangle$ denotes inclusion, then $\widetilde{\widetilde{T}} \circ \pi \circ i = \widetilde{T} \circ i$, which yields the desired diagram. We see that $\widetilde{\widetilde{T}}$ is unique because it is uniquely determined by elements of the form

$$v_1 \otimes v_2 \equiv [(v_1, v_2)]$$

by T and every element of $V_1 \otimes V_2$ can be written as some linear combination of such elements. $\square$

Proposition 5.1.2. *If $a, b \in \mathbb{R}$, then $(av_1 + bw_1) \otimes v_2 = a(v_1 \otimes v_2) + b(w_1 \otimes v_2)$.*

Proposition 5.1.3.

1. $(\mathbf{Vect}_\mathbb{R}, \oplus, \otimes)$ *is a semiring.*
2. $V \otimes W \cong W \otimes V$.
3. $V \otimes \mathbb{R} \cong V$.

4. $(V \otimes W)^* \cong V^* \otimes W^*$.

Proposition 5.1.4. *$V^* \otimes W^* \cong B(V,W)$ canonically where $B(V,W)$ denotes the space of bilinear maps $V \times W \to \mathbb{R}$.*

Proof. Define $\Phi : V^* \times W^* \to B(V,W)$ by $(\omega, \eta) \mapsto ((v,w) \mapsto \omega(v)\eta(w))$. This is linear and hence induces a commutative diagram

$$\begin{tikzcd} V^* \times W^* \arrow[r, "\Phi"] \arrow[d, "\pi"'] & B(V,W) \\ V^* \otimes W^* \arrow[ur, dashed, "\tilde{\Phi}"'] & \end{tikzcd}.$$

One can show that $\tilde{\Phi}$ is a natural isomorphism. $\square$

Proposition 5.1.4 can be generalized so that

$$V_1^* \otimes \cdots \otimes V_k^* \cong L(V_1, \ldots, V_k; \mathbb{R}).$$

Definition 5.1.5 (Tensor type). We say that an element of

$$V_l^k := \underbrace{V^* \otimes \cdots \otimes V^*}_{k \text{ copies}} \otimes \underbrace{V \otimes \cdots \otimes V}_{l \text{ copies}}$$

is a (k,l)-*tensor*.

Terminology.

1. A $(k,0)$-tensor is called *covariant*.
2. A $(0,l)$-tensor is called *contravariant*.

Definition 5.1.6. Let M be a manifold. Define the (k,l)-*tensor bundle* as

$$T_l^k M \equiv \coprod_{p \in M} (T_p)_l^k M.$$

Exercise 5.1.7. *Find the dimension of $T_l^k M$.*

Example 5.1.8. $T^1 M = T^* M$, and $T_1 M = TM$.

Remark 5.1.9. Suppose that (x^i) and (y^i) are two local coordinate systems for $p \in M$. Then

$$dx^{i_1} \otimes dx^{i_2} \otimes \cdots dx^{i_k} = \left(\frac{\partial x^{i_1}}{\partial y^{l_1}} dy^{p_1} \right) \otimes \cdots \otimes \left(\frac{\partial x^{i_k}}{\partial y^{l_k}} dy^{p_k} \right)$$

$$= \sum_{p_1, \ldots, p_k} \frac{\partial x^{i_1}}{\partial y^{l_1}} \cdots \frac{\partial x^{i_k}}{\partial y^{l_k}} \otimes dy^{p_1} \otimes \cdots \otimes dy^{p_k}.$$

Definition 5.1.10. A (k,l)-*tensor field* is a (smooth) section of $T_l^k M$. Let $\mathcal{T}_l^k(M) := \Gamma(T_l^k M)$.

5.2 Lecture 17

Remark 5.2.1. Let (U, x^i) be local coordinates for M. Then $A \in \mathcal{T}_k^l(M)$ can be written as

$$A\big|_p = A_{i_1 \ldots i_k}^{j_1 \ldots j_l} dx^{i_1}\big|_p \otimes \cdots \otimes dx^{i_k}\big|_p \otimes \frac{\partial}{\partial x^{j_1}}\big|_p \otimes \cdots \otimes \frac{\partial}{\partial x^{j_l}}\big|_p$$

summed over $n^k \cdot n^l$ tensors.

Example 5.2.2. Define $\sigma = \delta^i_j dx^j \otimes \frac{\partial}{\partial x^i}$, $X = X^k \frac{\partial}{\partial x^k}$, and $w = w_l dx^l$. Then

$$\begin{aligned}\sigma(X, w) &= \delta^i_j dx^j \otimes \frac{\partial}{\partial x^i}(X^k \frac{\partial}{\partial x^k}, w_l dx^l)\\ &= \delta^i_j dx^j (X^k \frac{\partial}{\partial x^k}) \frac{\partial}{\partial x^i} w_l dx^l\\ &= \delta^i_j \delta^j_k X^k w_l \delta^l_i\\ &= w_k X^k\\ &= w(X).\end{aligned}$$

We say that σ is *invariant* in this case.

Example 5.2.3. Show that the tensor $\delta^j_i dx^i \otimes dx^j$ is *not* invariant.

Proposition 5.2.4.

1. *Any $\sigma \in \mathcal{T}^k_l(M)$ induces a $C^\infty(M)$-multilinear map*

$$\hat{\sigma} : \underbrace{\mathscr{X}(M) \times \cdots \times \mathscr{X}(M)}_{k \text{ copies}} \times \underbrace{\mathscr{X}^*(M) \times \cdots \times \mathscr{X}^*(M)}_{l \text{ copies}} \to C^\infty(M)$$

$$(X_1, \ldots, X_k, w_1, \ldots, w_l) \mapsto \left(p \mapsto \sigma\left(X_1\big|_p, \ldots, X_k\big|_p, w_1\big|_p, \ldots, w_l\big|_p\right)\right).$$

2. *Any multilinear map over $C^\infty(M)$ is of the above form for some (k, l)-tensor field.*

Example 5.2.5. The Lie bracket is not multilinear over $C^\infty(M)$, as $[fX + gY, Z] = f[X, Y] + g[Y, Z] - Z(f)X - Z(g)Y$.

Notice that the smooth function $\hat{\sigma}_p$ above is determined completely by the values $X_1(p)$, ..., $X_k(p)$, $w_1(p)$, ..., $w_l(p)$.

Definition 5.2.6. A covariant k-tensor T is *alternating* if for any vectors $Y, X_1, \ldots, X_{k-1}$, it follows that

$$T(X_1, X_2, \ldots, Y, \ldots, Y, \ldots, X_{k-1}) = 0.$$

This is also called an *exterior form*.

Example 5.2.7. If σ is a 0-tensor or a 1-tensor, then it is alternating.

Proposition 5.2.8. *TFAE.*

1. *T is alternating.*

2. *$T(X_1, \ldots, X_k) = 0$ whenever $\{X_1, \ldots, X_k\}$ is linearly dependent.*

3. *$T(X_1, \ldots, X_i, X_{i+1}, \ldots, X_k) = -T(X_1, \ldots, X_{i+1}, X_i, \ldots, X_k)$.*

Notation. The subspace of $T^k(V)$ consisting of alternating covariant k-tensors will be denoted by $\bigwedge^k(V)$.

Definition 5.2.9. Given $T \in T^k(V)$, define the *alternation of T* as

$$\operatorname{Alt}(T) : (V_1, \ldots, V_k) \mapsto \frac{1}{k!} \sum_{\sigma \in S_k} \operatorname{sgn}(\sigma) T\left(V_{\sigma(1)}, \ldots, V_{\sigma(k)}\right).$$

Example 5.2.10.

$$\begin{aligned}&\operatorname{Alt}(T)(X, Y, Z)\\ &= \frac{1}{6}\left(T(X, Y, Z) + T(Y, Z, X) + T(Z, X, Y) - T(Y, X, Z) - T(Z, Y, X) - T(X, Z, Y)\right).\end{aligned}$$

Example 5.2.11. Let $\{w^1, \ldots, w^n\}$ be a cobasis for the real vector space V. Then

$$\begin{aligned}
&\operatorname{Alt}(w^1 \otimes \cdots \otimes w^n)(e_1, \ldots, e_n) \\
&= \frac{1}{n!} \sum_{\sigma \in S_n} \operatorname{sgn}(\sigma) w^1 \otimes \cdots \otimes w^n \left(e_{\sigma(1)}, \ldots, e_{\sigma(n)}\right) \\
&= \frac{1}{n!} \operatorname{sgn}\left(\mathrm{id}_n\right) w^1 \otimes \cdots \otimes w^n \left(e_1, \ldots, e_n\right) \\
&= \frac{1}{n!}.
\end{aligned}$$

Proposition 5.2.12.

1. $\operatorname{Alt}(T) \in \bigwedge^k(V)$.
2. $\operatorname{Alt}(T) = T \iff T \in \bigwedge^k(V)$.
3. $\operatorname{Alt} : T^k(V) \to \bigwedge^k(V)$ *is linear.*

5.3 Lecture 18

Lemma 5.3.1. *Let* $\{w^1, \ldots, w^n\}$ *be a cobasis for the real vector space* V*. Let* $k \leq n$*. Then*

$$A \coloneqq \left\{\operatorname{Alt}(w^{i_1} \otimes \cdots \otimes w^{i_k}) : 1 \leq i_1 < \cdots < i_k \leq n\right\}$$

is a basis for $\bigwedge^k(V)$*.*

Proof. It's clear from Proposition 5.2.12, that A spans $\bigwedge^k(V)$. It remains to show that A is linearly independent.

Exercise 5.3.2. *Prove the following statements.*

1. *If* $(i_1, \ldots, i_k)$ *is not pairwise distinct, then* $\operatorname{Alt}(w^{i_1} \otimes \cdots \otimes w^{i_k}) = 0$.
2. $\operatorname{Alt}(w^{i_1} \otimes \cdots \otimes w^{i_j} \otimes w^{i_{j+1}} \otimes \cdots \otimes w^{i_k}) = -\operatorname{Alt}(w^{i_1} \otimes \cdots \otimes w^{i_{j+1}} \otimes w^{i_j} \otimes \cdots \otimes w^{i_k})$.

Therefore, $\operatorname{span}(A) = \operatorname{span}\left\{\operatorname{Alt}(w^{i_1} \otimes \cdots \otimes w^{i_k}) : 1 \leq i_1 \leq \cdots \leq i_k \leq n\right\}$.

Exercise 5.3.3. *Show that this implies that* A *is linearly independent.*

□

Corollary 5.3.4. *If* $\dim(V) = n$*, then* $\dim \bigwedge^k(V) = \binom{n}{k} = \frac{n!}{k!(n-k)!}$.

Definition 5.3.5. Define the *wedge product* as the map

$$\wedge : \bigwedge^k(V) \times \bigwedge^l(V) \to \bigwedge^{k+l}(V) \qquad (w, q) \mapsto w \wedge q \equiv \frac{(k+l)!}{k!l!} \operatorname{Alt}(w \otimes q).$$

This is like the tensor product. The *exterior algebra* A^* is the algebra of alternating tensors under the wedge product.

Terminology. An element of A^* is known as an *exterior form.*

Corollary 5.3.6. *The set* $\left\{w^{i_1} \wedge \cdots \wedge w^{i_k} : 1 \leq i_1 < \cdots < i_k \leq n\right\}$ *is a basis for* $\bigwedge^k(V)$*.*

Proof. For each $(i_1, \ldots, i_k)$, one can show that $w^{i_1} \wedge \cdots \wedge w^{i_k}$ and $\operatorname{Alt}(w^{i_1} \otimes \cdots \otimes w^{i_k})$ differ by a real factor. □

Remark 5.3.7. Consider the standard basis $B \coloneqq \{e_1, \dots, e_n\}$ for V. Note that $\det_B \in \bigwedge^n(V)$ by Proposition 5.2.12. But $\bigwedge^n(V) = 1$, so that $\det_B = c(w^1 \wedge \cdots \wedge w^n)$. But evaluating both sides at $(e_1, \dots, e_n)$ yields $1 = c(1) = c$. Thus,

$$\det_B = w^1 \wedge \cdots \wedge w^n.$$

Proposition 5.3.8. *Suppose that ω, ω, η, and η' are exterior forms. The following are properties of the wedge product.*

1. *(Bilinearity) If $a, a' \in \mathbb{R}$, then*
$$\begin{aligned}(a\omega + a'\omega') \wedge \eta &= a(\omega \wedge \eta) + a'(\omega' \wedge \eta)\\ \eta \wedge (a\omega + a'\omega') &= a(\eta \wedge \omega) + a'(\eta \wedge \omega').\end{aligned}$$

2. *(Associativity)*
$$(\eta \wedge \omega) \wedge \omega' = \eta \wedge (\omega \wedge \omega').$$

3. *(Anticommutativity) If $\omega \in \bigwedge^k(V)$ and $\eta \in \bigwedge^l(V)$, then*
$$\omega \wedge \eta = (-1)^{kl} \eta \wedge \omega.$$

 Corollary 5.3.9. *If ω is a 1-form, then $\omega \wedge \omega = 0$.*

4. *If $\omega^1, \dots, \omega^k \in \bigwedge^1(V)$, then*
$$\omega^1 \wedge \cdots \wedge \omega^k(v_1, \dots, v_k) = \det(\omega^j(v_i)).$$

Definition 5.3.10. Let M^n be a smooth manifold. Define the *alternating bundle of rank k* as

$$\bigwedge^k(M) \equiv \coprod_{p \in M} \bigwedge^k(T_p M).$$

A smooth section of $\bigwedge^k(M)$ is called a *(differential) k-form.*

Notation. Let both $\Omega^k(M)$ and $A^k(M)$ stand for the vector space of differential k-forms on the manifold M.

Note that $\Omega^k(M)$ is infinite-dimensional.

In local coordinates we have a basis $\left\{ \frac{\partial}{\partial x^i}\big|_p \right\}_{1 \le i \le n}$ for $T_p M$ and a corresponding dual basis $\{dx^i\}$. Then for any $w \in \bigwedge^k(M)$, we can write

$$w = \sum_{1 \le i_1 < \cdots < i_k \le n} w_{i_1, \dots, i_k} dx^{i_1} \wedge \cdots \wedge dx^{i_k}$$

locally at p. Let $I = \{i_1 < \cdots < i_k\}$. Since

$$dx^{i_1} \wedge \cdots \wedge dx^{i_l} \left(\frac{\partial}{\partial x^{j_1}}, \dots, \frac{\partial}{\partial x^{j_k}} \right) = \delta^I_J$$

where $\delta^I_J = 1$ if and only if $I = J$ as sets, it follows that $w_{i_1, \dots, i_k} = w\left(\frac{\partial}{\partial x^{i_1}}, \dots, \frac{\partial}{\partial x^{i_k}}\right)$. We abbreviate this by writing

$$w = w_I dx^I,$$

where we tacitly sum over the I.

Remark 5.3.11. Let $w = w_I dx^I$ and $w = \tilde{w}_J d\tilde{x}^J$ locally. A direct computation shows that

$$\tilde{w}_J = w\left(\frac{\partial}{\partial x^{j_1}}, \dots, \frac{\partial}{\partial x^{j_k}} \right) = \sum_I \det(k \times k \text{ minor of } \frac{\partial x}{\partial \tilde{x}} \text{ relative to } i_1, \dots, i_k \text{ and } j_1, \dots, j_k).$$

5.4 Lecture 19

Definition 5.4.1 (Pullback). Let $F : M \to N$ be smooth and $\omega \in \bigwedge^k(N)$. Define the *pullback* $F^*\omega$ *of* ω *by* F as the differential k-form on M given pointwise by

$$F^*\omega\big|_p(v_1,\dots,v_k) = \omega_{F(p)}\left(dF_p(v_1),\dots,dF_p(v_k)\right),$$

Note 5.4.2. The pullback $F : \Omega^k(N) \to \Omega^k(M)$ is a linear map over $\mathbb{R}$.

Lemma 5.4.3 (Naturality of the pullback). $F^*\left(\omega \wedge \eta\right) = F^*\left(\omega\right) \wedge F^*\left(\eta\right).$

Proof. This is easily seen from Definition 5.4.1 along with Definition 5.3.5. □

Lemma 5.4.4. *In any local coordinates, we have that*

$$F^*\left(\sum_I \omega_I dy^{i_1} \wedge \dots \wedge dy^{i_k}\right) = \sum_I \left(\omega_I \circ F\right) d\left(y^{i_1} \circ F\right) \wedge \dots \wedge d\left(y^{i_k} \circ F\right).$$

Proof. It is easy to check that $F^*\omega\left(X_1,\dots,X_k\right) = \sum_I w_I \circ F dy^I\left(F_*X_1,\dots,F_*X_k\right)$. Hence it suffices to show that

$$d\left(y^{i_1} \circ F\right) \wedge \dots \wedge d\left(y^{i_k} \circ F\right)\left(X_1,\dots,X_k\right) = dy^I\left(F_*X_1,\dots,F_*X_k\right).$$

For this, it suffices to show that $d\left(y^i \circ F\right)(X) = dy^i\left(F_*X\right)$ for each $i = i_1,\dots,i_k$. Let $\left(x^i\right)$ denote local coordinates on M. On the one hand, from Definition 4.2.1, we get

$$d\left(y^i \circ F\right)(X) = X\left(y^i \circ F\right) = X^j \frac{\partial F^i}{\partial x^j}.$$

On the other hand,

$$\begin{aligned} dy^i\left(F_*X\right) &= dy^i\left(X^j \frac{\partial F^r}{\partial x^j}\frac{\partial}{\partial y^r}\right) \\ &= X^j \frac{\partial F^i}{\partial x^j}. \end{aligned}$$

□

Example 5.4.5. Consider the transformation to polar coordinates $\mathbb{R}^2 \to \mathbb{R}^2$ given by $(r,\theta) \mapsto (r\cos\theta, r\sin\theta)$. This is precisely the identity map with respect to different atlases on $\mathbb{R}^2$. Lemma 5.4.4 together with certain computational properties of $\wedge$ yields

$$\begin{aligned} dx \wedge dy &= d(r\cos\theta) \wedge d(r\sin\theta) \\ &= (\cos\theta dr - r\sin\theta d\theta) \wedge (\sin\theta dr + r\cos\theta d\theta) \\ &= (\cos\theta dr - r\sin\theta d\theta) \wedge \sin\theta dr + (\cos\theta dr - r\sin\theta d\theta) \wedge r\cos\theta d\theta \\ &= (\cos\theta dr \wedge \sin\theta dr) - (r\sin\theta d\theta \wedge \sin\theta dr) + (\cos\theta dr \wedge r\cos\theta d\theta) - (r\sin\theta d\theta \wedge r\cos\theta d\theta) \\ &= -(r\sin\theta d\theta \wedge \sin\theta dr) + (\cos\theta dr \wedge r\cos\theta d\theta) \\ &= r\sin^2\theta(dr \wedge d\theta) + r\cos^2\theta(dr \wedge d\theta) \\ &= r dr \wedge d\theta. \end{aligned}$$

5.5 Lecture 20

Definition 5.5.1. Let $\omega \in A^k(M)$ and write $\omega_I dx^I$ in local coordinates. The *exterior derivative* of ω is

$$d\omega \equiv d\omega_I \wedge dx^I.$$

We call the operation $d : A^k(M) \to A^{k+1}(M)$ *exterior differentiation.*

Note 5.5.2. $d\omega = \frac{\partial}{\partial x^j}\omega_I dx^j \wedge dx^I$.

Aside. If we view $\Omega^k : \mathbf{Diff}^{\mathrm{op}} \to \mathbf{Vec}_{\mathbb{R}}$ as the functor sending each smooth map f to the pullback f^*, then the exterior derivative becomes a natural transformation $\Omega^k \Rightarrow \Omega^{k+1}$.

Definition 5.5.3. Let $\omega \in A^k(M)$.

1. We say that ω is *closed* if $d\omega = 0$.
2. We say that ω is *exact* if $\omega = d\eta$ for some $\eta \in A^{k-1}(M)$.

Lemma 5.5.4. *Suppose $M = \mathbb{R}^n$.*

1. *d is linear over $\mathbb{R}$.*
2. *$d(\omega \wedge \eta) = d\omega \wedge \eta + (-1)^k \omega \wedge d\eta$.*
3. *$d \circ d \equiv 0$.*
4. *$d(F^*\omega) = F^*(d\omega)$.*

Proof. The first statement is obvious, and the last amounts to an easy computation. Now, write $\omega = udx^I$ and $\eta = vdx^J$. By linearity, it suffices to compute $d(udx^I \wedge vdx^J)$ in order to verify the second statement.

$$\begin{aligned}
d(\omega \wedge \eta) &= d(udx^I \wedge vdx^J) \\
&= d(uvdx^I \wedge dx^J) \\
&= (vdu + udv) \wedge dx^I \wedge dx^J \\
&= (du \wedge dx^I) \wedge (vdx^J) \wedge (dv \wedge udx^I) \wedge dx^J \\
&= (du \wedge dx^I) \wedge (vdx^J) \wedge (-1)^k (udx^I) \wedge (dv \wedge dx^J) \\
&= d(\omega \wedge \eta) = d\omega \wedge \eta + (-1)^k \omega \wedge d\eta.
\end{aligned}$$

To prove the third statement, first observe that if $k = 1$ and we write $\omega = \omega_j dx^j$, then

$$\begin{aligned}
d\omega &= \sum_{i,j} \frac{\partial \omega_j}{\partial x^i} dx^i \wedge dx^j \\
&= \sum_{i<j} \frac{\partial \omega_j}{\partial x^i} dx^i \wedge dx^j + \sum_{i>j} \frac{\partial \omega_j}{\partial x^i} dx^i \wedge dx^j \\
&= \sum_{i<j} \left(\frac{\partial \omega_j}{\partial x^i} - \frac{\partial \omega_i}{\partial x^j} \right) dx^i \wedge dx^j.
\end{aligned}$$

This together with Clairaut's theorem implies that

$$d(du) = \frac{\partial^2 u}{\partial x^i \partial x^j} dx^i \wedge dx^j = \sum_{i<j} \left(\frac{\partial^2 u}{\partial x^i \partial x^j} - \frac{\partial^2 u}{\partial x^j \partial x^i} \right) dx^i \wedge dx^j = 0.$$

Drop the assumption that $k = 1$. Then expanding $d(d\omega)$ yields a sum of two summations of wedge products. One of which contains the term $d(d\omega_J)$, and the other contains the term $d(dx^{j_i})$. These both equal zero, hence the entire expression $d(d\omega)$ vanishes. ☐

Corollary 5.5.5. *The exterior derivative is well-defined.*

Proof. Let (U, ϕ) be a chart for M. Notice that

$$d\omega = \phi^* d\left(\phi^{-1*}\omega\right).$$

Let (V, ψ) be another chart. Then

$$\left(\phi \circ \psi^{-1}\right)^* d\left(\phi^{-1^*}\omega\right) = d\left(\left(\phi \circ \psi^{-1}\right)^* \phi^{-1^*}\omega\right).$$

Since $\left(\phi \circ \psi^{-1}\right)^* = \psi^{-1^*} \circ \phi^*$ and $F^* \circ F^{-1^*} = \mathrm{id}$ for any diffeomorphism F, it follows that

$$\psi^{-1^*} \circ \phi^* d\left(\phi^{-1^*}\omega\right) = d\left(\psi^{-1^*}\omega\right).$$
$$\Downarrow$$
$$\phi^* d\left(\phi^{-1^*}\omega\right) = \psi^* d\left(\psi^{-1^*}\omega\right).$$

$\square$

Corollary 5.5.6. *Any exact form is closed.*

Remark 5.5.7. It is not the case, however, that any closed form is exact. Let $M \coloneqq \mathbb{R}^2 \setminus \{0\}$. Define the 1-form $\omega : M \to T^*M$ by $(x, y) \mapsto \frac{xdy - ydx}{x^2+y^2}$. On the one hand, a straightforward computation shows that $d\omega = 0$. On the other hand, recall from calculus that ω is exact on a connected open $\omega \subset M$ if and only if $\int_c \omega = 0$ for any closed curve $c \subset \omega$. But if $\gamma : [0, 2\pi] \to M$ is given by $(\cos\theta, \sin\theta)$, then

$$\int_\gamma \omega = \int_0^{2\pi} d\theta = 2\pi \neq 0,$$

hence ω is not exact.

Theorem 5.5.8 (Unique differentiation theorem). *The exterior derivative is the unique operation $\bar{d} : A^k(M) \to A^{k+1}$ satisfying the three above properties along with the property that $\bar{d}f$ equals the differential of f for any $f \in C^\infty(M)$.*

Proposition 5.5.9 (Naturality of the exterior derivative). *If F is a smooth map, then $d(F^*\omega) = F^*(d\omega)$.*

Proof. This follows from the case where $M = \mathbb{R}^n$, which is stated in Lemma 5.5.4. $\square$

Definition 5.5.10. Let V be a finite-dimensional vector space. For each $v \in V$, define *interior multiplication* as the linear map $i_v : \bigwedge^k(V) \to \bigwedge^{k-1}(V)$ given by $i_v\omega(w_1, \ldots, w_{k-1}) = \omega(v, w_1, \ldots, w_{k-1})$. Let $v \lrcorner \omega \coloneqq i_v\omega$. Then we may extend interior multiplication as follows. For each $X \in \mathscr{X}(M)$ and $\omega \in A^k(M)$, define the $(k-1)$-form $X \lrcorner \omega$ by $p \mapsto X_p \lrcorner \omega_p$.

5.6 Lecture 21

Definition 5.6.1. Let V be a finite-dimensional vector space. Suppose that $\{e_1, \ldots, e_n\}$ and $\{f_1, \ldots, f_n\}$ are two bases for V. We say that they are *co-oriented* if the change-of-basis matrix has positive determinant.

This yields us two equivalence classes of bases for V, which we call the *orientations for* V. If $[E_1, \ldots, E_n]$ is a given orientation for V, then we call any basis in it *(positively) oriented* and any basis not in it *negatively oriented*.

Definition 5.6.2 (Orientation). An *orientation* on a manifold M is a continuous choice of orientation for each T_pM.

Equivalently, if $\{(U_\alpha, \phi_\alpha)\}$ denotes the smooth structure on M, we say that M is *orientable* if the Jacobian $D\left[\phi_\beta \circ \phi_\alpha^{-1}\right]$ has positive determinant on $\phi_\alpha(U_\alpha \cap U_\beta)$ for any α, β.

Example 5.6.3. $\mathbb{S}^n$ is orientable for any $n \geq 1$. For each $p \in \mathbb{S}^n$, say that $(v_1, \ldots, v_n)$ is positively oriented on $T_p\mathbb{S}^n$ if $(p, v_1, \ldots, v_n)$ is positively oriented on $\mathbb{R}^{n+1}$, i.e. is co-oriented with the standard basis for $\mathbb{R}^{n+1}$.

Lemma 5.6.4. *Let $\pi : E \to M$ be a smooth vector bundle and $V \subset E$ open. If V_p is a convex subspace of E_p for every $p \in M$, then there is some $\sigma \in \Gamma(E)$ such that $\sigma_p \in V_p$ for every p.*

Proof. Find a cover of E by local trivializations U_α over M along with smooth sections σ_α of them. We get some partition of unity ψ_α subordinate to (U_α). Define $\sigma : M \to E$ as $\sum_\alpha \psi_\alpha \sigma_\alpha$, so that $\sigma \in \Gamma(E)$. Then σ_p belongs to V_p by convexity. $\square$

Proposition 5.6.5. *Suppose that M is an n-manifold. Any nowhere vanishing n-form on M gives rise to a unique orientation on M. Conversely, any orientation on M gives rise to a nowhere vanishing n-form on M.*

Proof. First, let $\omega \in A^n(M)$ be nowhere vanishing. For each $p \in M$, we see that ω_p defines an orientation O_M^p on M by saying that $[e_1, \dots, e_n] \in O_M^p$ if and only if $\omega_p(e_1, \dots, e_n) > 0$. It remains to show that if $p \in M$, then we can find some chart U_p around p and some local frame $(E_1, \dots, E_n)_p$ on U_p such that $\omega_q(E_1\big|_q, \dots, E_n\big|_q) > 0$ for every $q \in U_p$. To see this, pick any U_p and local frame $(E_1, \dots, E_n)_p$ on U_p. Write $\omega = f dE^1 \wedge \cdots \wedge dE^n$ locally for some smooth $f : U_p \to \mathbb{R}$. Since ω is nowhere vanishing, it follows that

$$\omega(E_1, \dots, E_n) = f \neq 0.$$

Since f is continuous and M connected, we see that $f > 0$ or $f < 0$. We may assume that $f > 0$ as otherwise we choose $(-E_1, \dots, -E_n)_p$ instead.

Conversely, given $p \in M$ and an orientation O_M^p on T_pM, say that $w \in \bigwedge^n(T_pM)$ is positively oriented if $w(e_1, \dots, e_n) > 0$ for any $[e_1, \dots, e_n] \in O_M^p$. Then the subspace $\bigwedge_+^n(T_pM)$ is open and convex. By Lemma 5.6.4, we are done. $\square$

Definition 5.6.6. A diffeomorphism $F : M \to N$ between two oriented manifolds is *orientation-preserving* if the isomorphism dF_p maps positively oriented bases for T_pM to positively oriented bases for $T_{F(p)}N$ for each $p \in M$. It is called *orientation-reversing* if it maps positively oriented bases to negatively oriented ones.

Note 5.6.7. F is orientation-preserving $\iff$ $\det(dF_p) > 0$ for each $p \in M$ $\iff$ $F^*\omega$ is positively oriented for any positively oriented form ω.

Lemma 5.6.8. *The antipodal map $\alpha : \mathbb{S}^n \to \mathbb{S}^n$ is orientation-preserving if and only if n is odd.*

Proof. We have the commutative diagram

$$\begin{tikzcd} \mathbb{S}^n \arrow[r, "\alpha"] \arrow[d, hook] & \mathbb{S}^n \arrow[d, hook] \\ \mathbb{R}^{n+1} \arrow[r, "\hat{\alpha}"] & \mathbb{R}^{n+1} \end{tikzcd}$$

where $\hat{\alpha} : \vec{x} \mapsto -\vec{x}$. By inspecting $\det(I_{n+1})$, we see that $\hat{\alpha}$ is orientation-preserving if and only if n is odd. Thus, the restriction α has the same property. $\square$

Corollary 5.6.9. $\mathbb{RP}^n$ *is not orientable when n is even.*

Proof. Suppose, for contradiction, that $\mathbb{RP}^n$ admits some orientation. Apply Proposition 5.5.9 to obtain a nowhere vanishing n-form ω on $\mathbb{RP}^n$. If $\pi : \mathbb{S}^n \to \mathbb{RP}^n$ denotes the natural projection, then we also obtain the nowhere vanishing n-form $\pi^*\omega$ on $\mathbb{S}^n$. Applying the same proposition shows that this determines the usual orientation on $\mathbb{S}^n$. Note that $\pi \circ \alpha = \pi$, so that $\alpha^*\pi^*\mathbb{S}^n = \pi^*\mathbb{S}^n$. But this implies that α preserves the orientation of $\mathbb{S}^n$, contrary to Lemma 5.6.8. $\square$

The converse is also true, although we omit a proof of it.

Proposition 5.6.10. $\mathbb{RP}^n$ *is orientable only if n is even.*

Definition 5.6.11 (Manifold with boundary). Let $\mathbb{H}^n \coloneqq \left\{(x^1, \dots, x^n) \in \mathbb{R}^n : x^n \geq 0\right\}$.

1. An *n-dimensional manifold with boundary M* is a second-countable Hausdorff space that is locally homeomorphic to either an open Euclidean ball or an open subset in $\mathbb{H}^n$.

2. Any point $p \in M$ is called an *interior point* if it belongs to a chart homeomorphic to an open ball.

3. The point p is called a *boundary point* if it belongs to a boundary chart that maps p into $\partial\mathbb{H}^n$.

Note 5.6.12. Every point in M is either an interior or a boundary point, but not both.

Proposition 5.6.13. *The set of boundary points ∂M is an $(n-1)$-dimensional embedded submanifold of M.*

Moreover, ∂M inherits an orientation from M when M is oriented. This is called the *induced* or *Stokes orientation*. Indeed, we may construct a smooth outward-pointing vector field N along ∂M, which is nowhere tangent to ∂M. Therefore, if ω denotes the orientation form for M, then the form $i^*_{\partial M}(N \lrcorner \omega)$ is an orientation form ∂M.

Example 5.6.14. $\mathbb{S}^n$ is orientable as the boundary of the closed unit ball.

6 Integration

6.1 Lecture 22

Definition 6.1.1. A *singular k-cell on M^n* is a smooth map $\sigma : [0,1]^k \to M$.

Remark 6.1.2. Note that 0-cells are precisely points in M and 1-cells are precisely smooth curves in M.

Definition 6.1.3. Let $A^k_0\left(\mathbb{R}^k\right)$ denote the space of k-forms with compact support. Let $\omega \in A^k_0(\mathbb{R}^k)$ and write $\omega = f dx^1 \wedge \cdots \wedge dx^k$. Define

$$\int_{\mathbb{R}^k} \omega = \int_{\mathbb{R}^k} f(x^1, \dots, x^k) dx^1 \cdots dx^k.$$

Exercise 6.1.4. *Given another coordinate representation $\omega = g y^1 \wedge \cdots \wedge y^k$ with $\det\left(\frac{\partial x}{\partial y}\right) > 0$, show that $\int_{\mathbb{R}^k} f(x^1, \dots, x^k) dx^1 \cdots dx^k = \int_{\mathbb{R}^k} g(x^1, \dots, x^k) dy^1 \cdots dy^k$. Thus, Definition 6.1.3 makes sense.*

Definition 6.1.5. Let $\omega \in A^k(M)$ and σ be a singular k-cell on M. Define

$$\int_\sigma \omega = \int_{[0,1]^k} \sigma^* \omega.$$

Proposition 6.1.6. *Let $p : [0,1]^k \to [0,1]^k$ be a diffeomorphism. If p is orientation-preserving, then $\int_\sigma \omega = \int_{\sigma \circ p} \omega$. If p is orientation-reversing, then $\int_\sigma \omega = -\int_{\sigma \circ p} \omega$.*

Definition 6.1.7.

1. A *singular k-chain on M* is a formal finite $\mathbb{R}$-combination $\sigma = \sum_{i=1}^N a_i \sigma_i$ of singular k-cells on M. Define
$$\int_\sigma \omega = \sum_{i=1}^N a_i \int_{\sigma_i} \omega.$$

2. Let σ be a singular k-cell on M. Let $i = 1, \dots, 2k$ and $\alpha = 0, 1$. Define the *(i,α)-face of σ* as the smooth map $\sigma_{(i,\alpha)}$ given by
$$\sigma_{(i,\alpha)}(x^1, \dots, x^k) = \sigma(x^1, \dots, x^{i-1}, \alpha, x^i, \dots, x^k).$$
Moreover, define the *boundary of σ* as the $(k-1)$-chain
$$\partial\sigma \equiv \sum_{i=1}^k (-1)^{i+1} (\sigma_{(i,1)} - \sigma_{(i,0)}).$$

3. If $\sigma \coloneqq \sum_{i=1}^{N} a_i\sigma_i$ is a singular k-chain, then define the *boundary of* σ as the $(k-1)$-chain

$$\partial\sigma \equiv \sum_{i=1}^{N} a_i \partial\sigma_i.$$

Note that $\int_{\partial\sigma}\omega = \sum_{i=1}^{N} a_i \int_{\partial\sigma_i}\omega$.

Definition 6.1.8. A singular k-chain σ is a *closed* if $\partial\sigma = 0$.

Exercise 6.1.9. *Show that if σ is any singular k-chain, then $\partial\sigma$ is closed.*

Theorem 6.1.10 (Stokes' theorem for chains). *Let σ be a k-chain and $\omega \in A^{k-1}(M)$. Then*

$$\int_\sigma d\omega = \int_{\partial\sigma} \omega.$$

Proof. For now, assume that $M = \mathbb{R}^k$ and $\sigma = I^k$. As the smooth structure on $\mathbb{R}^k$ is global, we may write $\omega = f dx^1 \wedge \cdots \wedge \widehat{dx^i} \wedge \cdots \wedge dx^k$ for some distinguished $1 \le i \le k$ and some smooth $f : \mathbb{R}^k \to \mathbb{R}$. We compute

$$\begin{aligned}
d\omega &= df \wedge dx^1 \wedge \cdots \wedge \widehat{dx^i} \wedge \cdots \wedge dx^k \\
&= \left(\sum_{j=1}^{k} \frac{\partial f}{\partial x^j} dx^j\right) \wedge dx^1 \wedge \cdots \wedge \widehat{dx^i} \wedge \cdots \wedge dx^k \\
&= (-1)^{i-1}\frac{\partial f}{\partial x^i} dx^1 \wedge \cdots \wedge dx^k.
\end{aligned}$$

Now, apply Fubini and the fundamental theorem of calculus (FTC) to obtain

$$\begin{aligned}
\int_\sigma d\omega &= (-1)^{i-1}\int_{[0,1]^k} \frac{\partial f}{\partial x^i} dx^1 \wedge \cdots \wedge dx^k \\
&= (-1)^{i-1}\int_0^1 \cdots \int_0^1 \left(\int_0^1 \frac{\partial f}{\partial x^i} dx^i\right) dx^1 \cdots \widehat{dx^i} \cdots dx^k \\
&= (-1)^{i-1}\int_0^1 \cdots \int_0^1 (f(x^1, \ldots, \underbrace{1}_{i\text{-th position}}, \ldots, x^k) - f(x^1, \ldots, \underbrace{0}_{i\text{-th position}}, \ldots, x^k)) dx^1 \cdots \widehat{dx^i} \cdots dx^k \\
&= (-1)^{i-1}\left(\int_{[0,1]^{k-1}} f(x^1, \ldots, 1, \ldots, x^k) dx^1 \cdots \widehat{dx^i} \cdots dx^k - \int_{[0,1]^{k-1}} f(x^1, \ldots, 0, \ldots, x^k) dx^1 \cdots \widehat{dx^i} \cdots dx^k\right) \\
&= (-1)^{i-1}\left(\int_{\sigma_{(i,1)}} \omega - \int_{\sigma_{(i,0)}} \omega\right).
\end{aligned}$$

Moreover, we compute

$$\int_{\partial\sigma}\omega = \sum_{j=1}^{k} (-1)^{j-1}\left(\int_{\sigma_{(j,1)}} \omega - \int_{\sigma_{(j,0)}} \omega\right).$$

Since x^j is constant along the (j, α)-face for each $\alpha = 0, 1$, it follows that $dx^j = 0$. Therefore,

$$\int_{\partial\sigma}\omega = (-1)^{i-1}\left(\int_{\sigma_{(i,1)}} \omega - \int_{\sigma_{(i,0)}} \omega\right) = \int_\sigma d\omega.$$

Finally, assume that M is arbitrary and σ is an arbitrary k-cell on M. By the special case just proved, we have that

$$\int_\sigma d\omega = \int_{[0,1]^k} \sigma^*(d\omega) = \int_{[0,1]^k} d(\sigma^*\omega) = \int_{\partial[0,1]^k} \sigma^*\omega = \int_{\partial\sigma} \omega.$$

This clearly remains true if σ is a k-chain on M. ∎

Corollary 6.1.11. *The FTC occurs precisely when $\sigma = I^1$ and $\omega = f$. This shows that Stokes' theorem for chains is equivalent to the FTC.*

6.2 Lecture 23

Lemma 6.2.1. *Let M be an oriented manifold. Let $\omega \in A^n(M)$. Let σ_1 and σ_2 be singular n-cells on M that can be extended to diffeomorphisms on (open) neighborhoods of $[0,1]^n$. Suppose that both are orientation-preserving. If $\operatorname{supp}\omega \subset \sigma_1([0,1]^n) \cap \sigma_2([0,1]^n)$, then $\int_{\sigma_1} \omega = \int_{\sigma_2} \omega$.*

Proof. Since $\operatorname{supp}\omega \subset \sigma_1([0,1]^n) \cap \sigma_2([0,1]^n)$, Proposition 6.1.6 implies that

$$\int_{\sigma_1} \omega = \int_{\sigma_2 \circ (\sigma_2^{-1} \circ \sigma_1)} \omega = \int_{\sigma_2} \omega.$$

$\square$

Definition 6.2.2 (Integral).

1. Let $\omega \in A^n(M)$. Let σ be an orientation-preserving singular n-cell on M. If $\operatorname{supp}\omega \subset \sigma([0,1]^n)$, then, by Lemma 6.2.1, we may define
$$\int_M \omega = \int_\sigma \omega.$$

2. In general, there exists an open cover (U_α) of M such that each $U_\alpha \subset \sigma_\alpha([0,1]^n)$ where σ_α is some orientation-preserving singular n-cell on M. Find a partition of unity (ϕ_α) subordinate to this cover. Note that each $\phi_\alpha \omega$ belongs to $A^n(M)$ and is supported in U_α. If ω is compactly supported, then $\operatorname{supp}\omega$ intersects at most finitely many $\operatorname{supp}\phi_\alpha$. In this case, we define
$$\int_M \omega = \sum_\alpha \int_M \phi_\alpha \omega$$
as this sum if finite.

Lemma 6.2.3. *If (V_β, ψ_β) is another such partition of unity, then $\sum_\beta \int_M \psi_\beta \omega = \sum_\alpha \int_M \phi_\alpha \omega$. Hence Definition 6.2.2 makes sense.*

Proof.

$$\begin{aligned}
\sum_\alpha \int_M \phi_\alpha \omega &= \sum_\alpha \int_M \phi_\alpha \sum_\beta \psi_\beta \omega \\
&= \sum_\alpha \sum_\beta \int_M \phi_\alpha \psi_\beta \omega = \sum_\beta \sum_\alpha \int_M \psi_\beta \phi_\alpha \omega \\
&= \sum_\beta \int_M \psi_\beta \sum_\alpha \phi_\alpha \omega = \sum_\beta \int_M \psi_\beta \omega.
\end{aligned}$$

$\square$

Note 6.2.4. If ω is not assumed to be compact, then $\int_M \omega$ may be infinite but is still well-defined.

Theorem 6.2.5 (Stokes). *Let M be an oriented compact n-manifold with boundary. If $\omega \in A^{n-1}(M)$, then*

$$\int_M d\omega = \int_{\partial M} \omega.$$

Proof. There are three cases to consider.

<u>Case 1:</u> Suppose that there is some orientation-preserving n-cell σ on M such that $\operatorname{supp}\omega \subset \operatorname{Int}(\operatorname{im}\sigma)$ and $\operatorname{im}\sigma \cap \partial M = \emptyset$. By Stokes' theorem for chains, it follows that

$$\int_M d\omega = \int_\sigma d\omega = \int_{\partial\sigma} \omega = 0 = \int_{\partial M} \omega.$$

Case 2: Suppose that there is some orientation-preserving n-cell σ on M such that $\operatorname{supp}\omega \subset \operatorname{im}\sigma$, $\operatorname{im}\sigma \cap \partial M = \sigma_{(n,0)}([0,1]^{n-1})$, and $\operatorname{supp}\omega \cap \operatorname{im}\partial\sigma \subset \sigma_{(n,0)}$. By Stokes' theorem for chains, it follows that

$$\int_M d\omega = \int_\sigma d\omega = \int_{\partial\sigma} \omega = (-1)^n \int_{\sigma_{(n,0)}} \omega.$$

Note that if μ is the usual orientation on $\mathbb{H}^n$, then the induced orientation on the boundary $\partial\mathbb{H}^n$ is equal to $(-1)^n\mu$. Therefore, $\sigma_{(n,0)} : [0,1]^{n-1} \to \partial M$ is orientation-preserving if and only if n is even. In either case, we have that

$$(-1)^n \int_{\sigma_{(n,0)}} \omega = \int_{\partial M} \omega,$$

which completes this case.

Case 3: In general, there exist an open cover (U_α) of M and a partition of unity (ϕ_α) subordinate to it such that each $\phi_\alpha\omega$ is an $(n-1)$-form of the kind in Case 1 or Case 2. Since $\sum_\alpha \phi_\alpha$ is constant, we see that $0 = d\left(\sum_\alpha \phi_\alpha\right) = \sum_\alpha d\phi_\alpha$. Hence $\sum_\alpha d\phi_\alpha \wedge \omega = 0$, so that $\sum_\alpha \int_M d\phi_\alpha \wedge \omega = 0$. From this we compute

$$\begin{aligned}
\int_M d\omega &= \int_M \sum_\alpha \phi_\alpha d\omega \\
&= \sum_\alpha \int_M \phi_\alpha d\omega \\
&= \sum_\alpha \int_M d\phi_\alpha \wedge \omega + \phi_\alpha d\omega \\
&= \sum_\alpha \int_M d(\phi_\alpha\omega) \\
&= \sum_\alpha \int_{\partial M} \phi_\alpha\omega \\
&= \int_{\partial M} \omega.
\end{aligned}$$

□

7 De Rham cohomology

7.1 Lecture 24

Definition 7.1.1. Given a manifold M^n and integer $k \geq 1$, define the real vector spaces

$$\begin{aligned}
Z^k(M) &= \{\omega \in A^k(M) : d\omega = 0\} \\
B^k(M) &= \{d\eta : \eta \in A^{k-1}(M)\}.
\end{aligned}$$

Since $B^k(M) \subset Z^k(M)$, we may form the quotient space

$$H^k_{\mathrm{dR}}(M) := {}^{Z^k(M)}\!\big/_{B^k(M)},$$

called the *k-th de Rham cohomology group of M.*

Remark 7.1.2. This is the same as the singular cohomology group over $\mathbb{R}$.

$H^k_{\mathrm{dR}}(M)$ can be thought of as a quantitative measure of the number of holes in M.

Theorem 7.1.3. *If M and N are continuously homotopy equivalent, then $H^k_{\mathrm{dR}}(M) \cong H^k_{\mathrm{dR}}(N)$ for each $k \geq 1$.*

Lemma 7.1.4 (Poincaré). *If M is (smoothly) contractible, then $H^k_{\mathrm{dR}}(M) = 0$ for each $k \geq 1$.*

Proof. Assume that $k = 1$. For each $t \in [0,1]$, define $\iota_t : M \to M \times [0,1]$ by $p \mapsto (p,t)$.

Claim. *If ω is any closed 1-form on $M \times [0,1]$, then $\iota_1^*\omega - \iota_0^*\omega$ is exact.*

Proof. If $\pi_M : M \times [0,1] \to M$ denotes the projection and (U, x^i) denotes local coordinates on M, then $(\pi_M^{-1}(U), (\bar{x}^i, t))$ is a coordinate chart on $M \times [0,1]$ where $\bar{x}^i \coloneqq x^i \circ \pi_M$. We thus have that $\omega = w_i d\bar{x}^i + f dt$. For each $\alpha = 0, 1$, we see that

$$\iota_\alpha^*\omega = \iota_\alpha^*(w_i d\bar{x}^i + f dt) = w_i(-,\alpha) dx^i + 0.$$

Moreover,

$$\begin{aligned} 0 &= d\omega \\ &= dw_i \wedge d\bar{x}^i + df \wedge dt \\ &= (\text{terms not involving } dt) + \frac{\partial w_i}{\partial t} dt \wedge d\bar{x}^i \\ &+ \frac{\partial f}{\partial \bar{x}^i} d\bar{x}^i \wedge dt. \end{aligned}$$

This implies that $\frac{\partial w_i}{\partial t} = \frac{\partial f}{\partial \bar{x}^i}$ for each i. For each $p \in U$, we compute the sum

$$w_i(p,1) - w_i(p,0) = \int_0^1 \frac{\partial w_i}{\partial t}(p,t) dt = \int_0^1 \frac{\partial f}{\partial \bar{x}^i}(p,t) dt.$$

As a result,

$$\iota_1^*\omega - \iota_0^*\omega = \left(\int_0^1 \frac{\partial f}{\partial \bar{x}^i}(p,t) dt \right) dx^i.$$

Define $g : U \to \mathbb{R}$ by $\int_0^1 f(p,t) dt$, so that $\frac{\partial g}{\partial x^i} = \int_0^1 \frac{\partial f}{\partial \bar{x}^i}(p,t) dt$. It follows that $\iota_1^*\omega - \iota_0^*\omega = \frac{\partial g}{\partial x^i} dx^i = dg$.

Since the pullback is coordinate-independent, g is as well. ☐

By assumption, there is some smooth map $H : M \times [0,1] \to M$ such that $H \circ \iota_1 = \mathrm{id}_M$ and $H \circ \iota_0 = e_{p_0}$ where $p_0 \in M$. Let ω be a closed 1-form on M. Then $H^*\omega$ is closed since pullbacks commute with exterior derivatives. Recall that the pullback is a contravariant functor. By our claim, it follows that $\iota_1^* H^*\omega - \iota_0^* H^*\omega = \omega - 0 = \omega$ is closed.

The generalization of this result to any positive integer k proceeds as follows.

We have the decomposition $T_{(p,t)} M \times [0,1] = \ker d\pi\big|_{(p,t)} \oplus \ker d\pi_M\big|_{(p,t)}$ where $\pi : M \times [0,1] \to [0,1]$ denotes projection. Then any 1-form ω on $M \times [0,1]$ may be written uniquely as $\omega = \omega_1 + \omega_2$ such that $\omega_i(v_1 + v_2) = \omega(v_i)$ for each $i = 1, 2$. Hence there is some unique $f : M \times [0,1] \to \mathbb{R}$ such that $\omega_2 = f dt$. In general, one can show that if ω is a k-form on $M \times [0,1]$, then we can write ω uniquely as

$$\omega = \omega_1 + (dt \wedge \eta)$$

where $\omega_1(v_1, \ldots, v_k) = 0$ if some $v_i \in \ker d\pi_M\big|_{(p,t)}$ and η is a $(k-1)$-form with the analogous property.

Lemma 7.1.5. *Define the $(k-1)$-form $I\omega$ on M by*

$$I\omega\big|_p(v_1, \ldots, v_{k-1}) = \int_0^1 \eta(p,t)(d\iota_t\big|_{(p,t)}(v_1), \ldots, d\iota_t\big|_{(p,t)}(v_{k-1})) dt.$$

Then $\iota_1^*\omega - \iota_0^*\omega = d(I\omega) + I(d\omega)$. In particular, $\iota_1^*\omega - \iota_0^*\omega$ is exact whenever $d\omega = 0$.

Proof. For an argument similar to our $k = 1$ case, see *Spivak*, Theorem 7.17. In particular, $I\omega$ and η correspond to our g and f, respectively. ☐

☐

Corollary 7.1.6. *By Remark 5.5.7, $\mathbb{R}^2 \setminus \{0\}$ is not contractible.*

7.2 Lecture 25

Corollary 7.2.1. *If M is closed (i.e., compact without boundary) and orientable, then M is not contractible.*

Proof. There is some positively oriented orientation form ω on M. Then $d\omega = 0$, and $\int_M \omega > 0$. But if $\omega = d\eta$ for some form η, then $\underbrace{\int_M \omega = \int_{\partial M} \eta}_{\text{Stokes}} = 0$, a contradiction. Hence $H^n(M) \neq 0$. $\square$

Example 7.2.2. $\mathbb{S}^n$ is not contractible.

Theorem 7.2.3. *If M is a (connected) orientable n-manifold, then there is an isomorphism*

$$\underbrace{H^n_c(M)}_{\textit{compactly supported}} \xrightarrow{\cong} \mathbb{R}, \quad [\omega] \mapsto \int_M \omega.$$

Proof. Take for granted that the statement holds when $M = \mathbb{R}^n$. There is some compactly supported orientation form ω on M such that $\int_M \omega \neq 0$ and $\operatorname{supp} \omega \subset \underset{\text{open}}{U} \subset M$. Let ω' be a compactly supported n-form on M. Find any partition of unity (ϕ_α) on M. Then $\omega' = \phi_1\omega' + \cdots + \phi_k\omega'$, Thus, we may assume that $\operatorname{supp} \omega' \subset V$ where $V \approx \mathbb{R}^n$. We want to show that $\omega' = c\omega + d\eta$ for some $c \in \mathbb{R}$ and some $\eta \in A^{n-1}(M)$. Since M is connected, there is some sequence $U = V_1, V_2, \ldots, V_r = V$ of open sets such that $V_i \approx \mathbb{R}^n$ and $V_i \cap V_{i+1} \neq \emptyset$ for each $i = 1, \ldots, r-1$. For each $i = 1, \ldots, r-1$, find forms ω_i on M such $\int_M \omega_i \neq 0$ and $\operatorname{supp} \omega_i \subset V_i \cap V_{i+1}$. It follows that

$$\begin{aligned}
\omega_1 =& c_1\omega + d\eta_1 \\
\omega_2 =& c_2\omega_1 + d\eta_2 \\
&\vdots \\
\omega' =& c_r\omega_{r-1} + d\eta_r,
\end{aligned}$$

as desired. $\square$

If M and N are closed orientable n-manifolds and $f : M \to N$ is smooth, then the pullback f^* induces a linear map $f^* : H^n_{\mathrm{dR}}(N) \to H^n_{\mathrm{dR}}(M)$. We thus get a linear map $f^* : \mathbb{R} \to \mathbb{R}$, which shows that there is some real number a such that

$$\int_M f^*\omega = a \int_N \omega$$

for every $\omega \in H^n_{\mathrm{dR}}(N)$. Such a scalar a is called the *degree of f*.

7.3 Lecture 26

Theorem 7.3.1. *Let M and N be closed orientable n-manifolds and $f : M \to N$ be smooth. By Sard's theorem, find some regular value q of f. For each $p \in f^{-1}(q)$, define* $\operatorname{sgn}_p f = \begin{cases} 1 & df_p \textit{ orientation-preserving} \\ -1 & df_p \textit{ orientation-reversing} \end{cases}$. *Then*

$$\deg f = \sum_{p \in f^{-1}(q)} \operatorname{sgn}_p f$$

where we set $\deg f = 0$ *if* $f^{-1}(q) = \emptyset$. *In particular,* $\deg f$ *is always an integer.*

Proof. Since f has constant rank n and $\{q\}$ is closed, we see that $f^{-1}(q)$ is a compact 0-dimensional submanifold of M and thus must be finite. Write $f^{-1}(q) = \{p_1, \ldots, p_k\}$. Find respective charts $U_1, \ldots, U_k$ which are pairwise disjoint so that each $u_i \in U_i$ is a regular point of f. Find a chart (V, y^i) around q such that the components of $f^{-1}(V)$ are precisely the U_i. Set $\omega = g dy^1 \wedge \cdots \wedge dy^n$ where g is nonnegative and compactly supported in V. This implies that $f^*\omega \subset f^{-1}(V) = U_1 \sqcup \cdots \sqcup U_k$. Therefore,

$$\int_M f^*\omega = \sum_{i=1}^{k} \int_{U_i} f^*\omega.$$

Since each $f \restriction_{U_i} : U_i \to V$ is a diffeomorphism, we have that

$$\int_{U_i} f^*\omega = \begin{cases} \int_V \omega & f \restriction_{U_i} \text{ orientation-preserving} \\ -\int_V \omega & f \restriction_{U_i} \text{ orientation-reversing} \end{cases}.$$

As a result,

$$\int_M f^*\omega = \left(\sum_{p \in f^{-1}(q)} \operatorname{sgn}_p f \right) \int_V \omega = \left(\sum_{p \in f^{-1}(q)} \operatorname{sgn}_p f \right) \int_M \omega.$$

□

Example 7.3.2. Let $A_n : \mathbb{S}^n \to \mathbb{S}^n$ denote the antipodal map. Choose $p_0 \in \mathbb{S}^n$, which is a regular value of A_n. Hence $\deg A_n = (-1)^{n-1}$.

Theorem 7.3.3. *Suppose that $f, g : M \to N$ are (smoothly) homotopic maps. Then $f^* = g^*$ as linear maps. If M and N are compact orientable n-manifolds, it follows that $\deg f = \deg g$.*

Proof. By assumption, there exists a smooth map $H : M \times [0,1] \to M$ such that $H \circ \iota_0 = f$ and $H \circ \iota_1 = g$. Let $\omega \in Z^k(N)$. We apply Lemma 7.1.5 (including its notation) to compute

$$\begin{aligned} &g^*\omega - f^*\omega \\ &= (H \circ \iota_1)^*\omega - (H \circ \iota_0)^*\omega \\ &= \iota_1^*(H^*\omega) - \iota_0^*(H^*\omega) \\ &= d(IH^*\omega) + I(dH^*\omega) = d(IH^*\omega). \end{aligned}$$

This implies that $f^*([\omega]) = g^*([\omega])$, as required. □

Corollary 7.3.4 (Hairy ball theorem). *If n is even, then there is no non-vanishing vector field on $\mathbb{S}^n$.*

Proof. The identity $\mathrm{id}_{\mathbb{S}^n}$ has degree 1 and thus is not homotopic to the antipodal map A_n. Suppose, for contradiction, that there is some non-vanishing $X \in \mathscr{X}(\mathbb{S}^n)$. For each $p \in \mathbb{S}^n$, there is a unique great semicircle γ_p traveling from $\underset{t=0}{p}$ to $\underset{t=1}{A(p)}$ whose tangent vector at p equals cX_p for some $c \in \mathbb{R}$. The smooth map $H(p,t) = \gamma_p(t)$ defines a homotopy between $\mathrm{id}_{\mathbb{S}^n}$ and A_n, a contradiction. □

8 Integral curves and flows

8.1 Lecture 27

Definition 8.1.1. Let M be a manifold and $X \in \mathscr{X}(M)$. We say that a differentiable curve $\gamma : J \to M$ is an *integral curve for X* if $\gamma'(t) = X_{\gamma(t)}$ for any $t \in J$.

Terminology. If $0 \in J$, then $\gamma(0)$ is called the *starting point of γ*.

Example 8.1.2. Set $M = \mathbb{R}^2$, $X = x\frac{\partial}{\partial x} + y\frac{\partial}{\partial y}$, and $\gamma(t) = (x(t), y(t))$. Then $\gamma'(t) = x'(t)\frac{\partial}{\partial x} + y'(t)\frac{\partial}{\partial y}$. The system

$$\begin{cases} x(t) = x'(t) \\ y(t) = y'(t) \end{cases}$$

determines that $\gamma(t) = e^t(x(0), y(0))$.

Remark 8.1.3. In general, define the vector field $x^i \frac{\partial}{\partial x^i}$ on a chart (U, x^i) for the n-manifold M. Then given an integral curve $\gamma(t) = \big(\gamma^1(t), \dots, \gamma^n(t)\big)$ for X where $\gamma^i = \gamma \circ x^i$, we obtain the system

$$\gamma'^i(t) = X^i\left(\gamma^1(t), \dots, \gamma^n(t)\right).$$

Given that $\gamma(0) = p$, we have an initial value problem, to which we can always find a local solution.

Theorem 8.1.4 (Fundamental theorem for autonomous ODEs). *Let $U \subset \mathbb{R}^n$ be open and $X : U \to \mathbb{R}^n$ is a smooth vector field. Consider the initial value problem*

$$\begin{cases} \gamma'^i(t) = X^i\left(\gamma^1(t), \dots, \gamma^n(t)\right) \\ \gamma(t_0) = (c^1, \dots, c^n) \end{cases}. \tag{1}$$

1. *(Existence) Let $t_0 \in \mathbb{R}$ and $x_0 \in U$. There exist some interval $J_0 \ni t_0$ and open subset $U_0 \subset U$ such that for each $c \in U_0$, there is some C^1 curve $\gamma : J_0 \to U_0$ that solves Eq. (1).*
2. *(Uniqueness) Any two differentiable solutions to Eq. (1) agree on the common domain.*
3. *(Smoothness) Let J_0 and U_0 be as before. Define $\theta : J_0 \times U_0 \to U$ by $(t, x) \mapsto \gamma_x(t)$ where $\gamma_x : J_0 \to U$ uniquely solves Eq. (1) with initial condition $\gamma(t_0) = x$. Then θ is smooth.*

Example 8.1.5. For any compact manifold M, we may stipulate that the U_0 form a finite cover $\{U_1, \dots, U_k\}$ of M. Make J_0 smaller than any of the corresponding intervals $J_1, \dots, J_k$. This yields a smooth map $\theta : J \times \mathbb{S}^n \to \mathbb{S}^n$ defined by $(t, p) \mapsto \gamma_p^i(t)$.

Corollary 8.1.6. *Let X be a smooth vector field on M and $p \in M$. There is some $\epsilon > 0$ and a smooth curve $\gamma : (-\epsilon, \epsilon) \to M$ such that $\gamma(0) = p$ and γ is an integral curve for X.*

Definition 8.1.7. Let $\theta : \mathbb{R} \times M \to M$ be a group action on M.

1. We call θ a *global flow on M* if it is smooth, i.e., $\theta^p(t) \coloneqq \theta(t, p) : \mathbb{R} \to M$ is smooth for every $p \in M$.
2. We call the vector field $p \mapsto (\theta^p)'(0)$ the *infinitesimal generator of θ*.

Question. When is a vector field an infinitesimal generator of a global flow?

Example 8.1.8. Define $X = x^3 \frac{\partial}{\partial x}$ on $\mathbb{R}^2$. Then any integral curve $\gamma(t) = (x(t), y(t))$ for X must satisfy

$$\begin{aligned} \frac{dx}{dt} = x^3 &\implies dx = x^3 dt \\ &\implies -\frac{1}{2x^2} = t + c \\ &\implies x(t) = \frac{1}{\sqrt{c - 2t}}, \end{aligned}$$

which is not smooth on $\mathbb{R}$. Hence X does not generate global flow.

Lemma 8.1.9 (Escape lemma). *Let $X \in \mathscr{X}(M)$ and γ be an integral curve for X. If the domain of γ does not equal $\mathbb{R}$, then $\operatorname{im}\gamma$ is not contained in any compact set.*

Remark 8.1.10. If M is compact, then every smooth vector field on M generates a global flow.

Definition 8.1.11. A *flow domain* for M is an open subset $D \subset \mathbb{R} \times M$ such that for every $p \in M$, the set $\{t \in \mathbb{R} \mid (t, p) \in D\}$ is an open interval containing 0

Theorem 8.1.12 (Fundamental theorem on flows). *Let M be a manifold and $X \in \mathscr{X}(M)$. There exist some unique maximal flow domain $\mathcal{D} \subset \mathbb{R} \times M$ and unique flow $\phi : \mathcal{D} \to M$ such that X generates ϕ.*

Terminology. We call ϕ the *flow of X*.

Corollary 8.1.13. *If M is a closed manifold, then $\mathcal{D} = \mathbb{R} \times M$.*

8.2 Lecture 28

Definition 8.2.1 (Lie derivative). Let M be a manifold without boundary. Let $V \in \mathscr{X}(M)$. Let θ denote the flow of V. For any $W \in \mathscr{X}(M)$. Define the rough vector field

$$(\mathcal{L}_V W)_p = \lim_{t\to 0} \frac{d(\theta_{-t})_{\theta_t(p)}\left(W_{\theta_t(p)}\right) - W_p}{t}.$$

This is called the *Lie derivative of W with respect to V.*

Note 8.2.2. If $p \in M$, then $(\mathcal{L}_V W)_p$ exists and $\mathcal{L}_V W \in \mathscr{X}(M)$.

Theorem 8.2.3. *If $V, W \in \mathscr{X}(M)$, then $\mathcal{L}_V W = [V, W]$.*

Proof. Define $\mathcal{R}(M)$ as the set of points $p \in M$ such that $V_p \neq 0$. Note that $\mathrm{cl}\,(\mathcal{R}(M)) = \operatorname{supp} V$. Let $p \in M$. We consider three cases.

1. Suppose $p \in \mathcal{R}(M)$. Then it's a fact that we can find smooth coordinates (U, u^i) near p such that $V = \frac{\partial}{\partial u^1}$. In these coordinates we thus have that $\theta_t(u) = (u^1 + t, u^2, \ldots, u^n)$. The Jacobian of θ_{-t} at each t equals the identity. If $u \in U$, it follows that

$$\begin{aligned}
&d(\theta_{-t})_{\theta_t(u)}(W_{\theta_{t(u)}}) \\
&= d(\theta_{-t})_{\theta_t(x)}\left(W^j(u^1+t, u^2, \ldots, u^n)\frac{\partial}{\partial u^j}\Big|_{\theta_t(u)}\right) \\
&= W^j(u^1+t, u^2, \ldots, u^n)\frac{\partial}{\partial u^j}\Big|_u.
\end{aligned}$$

   From this we compute

$$\begin{aligned}
(\mathcal{L}_V W)_p &= \frac{d}{dt}\Big|_{t=0} W^j(u^1+t, u^2, \ldots, u^n)\frac{\partial}{\partial u^j}\Big|_u \\
&= \frac{\partial}{\partial u^1} W^j(u^1, u^2, \ldots, u^n)\frac{\partial}{\partial u^j}\Big|_u \\
&= [V, W]_u.
\end{aligned}$$

2. Suppose that $p \in \operatorname{supp} V \setminus \mathcal{R}(M)$. Since $\operatorname{supp} V$ is dense in M and TM is Hausdorff, it follows that $(\mathcal{L}_V W)_p = [V, W]_p$.

3. If $p \in M \setminus \operatorname{supp} V$, then V vanishes on some neighborhood H of p. This implies that $\theta_t = \mathrm{id}_H$, so that $d(\theta_{-t})_{\theta_t(p)}(W_{\theta_{t(p)}}) = W_p$. Hence $(\mathcal{L}_V W)_p = 0 = [V, W]_p$.

□

Definition 8.2.4. Let M be an n-manifold. A smooth local frame $(X_1, \ldots X_n)$ is called a *commuting* or *holonomic frame* if $[X_i, X_j] = 0$ for any $1 \leq i, j \leq n$.

Theorem 8.2.5. *Let $(X_1, \ldots, X_k)$ be a linearly independent k-tuple of smooth commuting vector fields defined on an open set $W \subset M$. For any $p \in W$, there is some chart (U, x^i) around p such that the equation*

$$X_i = \frac{\partial}{\partial x^i}$$

holds locally for each $i = 1, \ldots, k$.

Proof. See *Lee*, Theorem 9.46. □

9 Distributions

Definition 9.0.1. Let M be a manifold. A *k-distribution on M* is a rank-k smooth subbundle of TM.

In particular, 1-distributions are precisely vector fields.

Definition 9.0.2. Let $N \subset M$ be a nonempty submanifold and

$$D \coloneqq \coprod_{p \in M} D_p$$

be a distribution on M. Then N is called an *integral manifold of* D if $D_p = T_pN$ for each $p \in N$. Moreover, we say that D is *integrable* if each $p \in M$ is contained in an integrable manifold of D.

Definition 9.0.3. We say that a distribution D is *involutive* if $[X, Y] \in D$ whenever $X, Y \in D$.

Proposition 9.0.4. *If D is integrable, then it is involutive.*

Theorem 9.0.5 (Frobenius). *If D is involutive, then it is integrable.*