
Lecture notes on Analysis and Geometry on Manifolds

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Chapter 0:

Manuel's notes

Warning

These are unofficial lecture notes written by a student. They are messy, will almost surely contain errors, typos and misunderstandings and may not be kept up to date! I do however try my best and use these notes to prepare for my exams. Feel free to email me any corrections to mh@mssh.dev or s6mlhinz@uni-bonn.de.
Happy learning!

General Information

- Basis: Basis
- Website: https://www.math.uni-bonn.de/~lcote/V3D3_2024.html
- Time slot(s): **Tuesday: 14-16** Nussallee Anatomie B and **Friday: 12-14** GHS
- Exams: Tuesday **11.02.2025, 9-11**, Großer Hörsaal, Wegelerstraße 10 and Friday **21.03.2025, 9-11**, Großer Hörsaal, Wegelerstraße 10
- Deadlines: **Friday before noon**

0.1 Organization

- Four exercise classes, in the break come to the front and sign up.
- First homework is due this Friday
- Exercise sheets are due on Fridays, every week electronically (groups, at most 2)
- No published lecture notes by him!
- 5 Minute break right before the full hour
- Friday after class for questions

Start of lecture 01
(08.10.2024)

0.2 Course overview

He assumes we already know about

- Analysis on \mathbb{R}^n
- Basic point set topology

For this class: smooth manifolds based on [2]

- Intersection between analysis and topology
- Exiting: Connections between those two point of views

Main topics:

Topic 00: Topological manifolds

Topic 01: Basic theory of smooth manifolds

Topic 02: Vector fields on smooth manifolds

Topic 03: Tensor calculus and Stokes' theorem

Topic 04: Lie groups, symplectic and Riemannian geometry

I would also recommend [4] and the notes of Gabriel Ong[other notes of F4D1], which are also based on this course

Chapter 1:

Topological manifolds

1.1 Some point set topology

Some (set theoretical) conventions for the whole course:

- $A \subset B$ means A subset (not necessarily proper!) of B , i.e. $\subset = \subseteq$
- A **neighborhood** of some point $p \in X$ means *an open set* $U \subset X$ containing p
- Given $p = (p_1, \dots, p_n) \in \mathbb{R}^n, r > 0$, $B_r^n(p) := \{(x_1, \dots, x_n) \mid \sum_{i=1}^n (x_i - p_i)^2 < r^2\}$. Often while $B_s = B_s^n(0) \subset \mathbb{R}^n$

1.1.1 Locally Euclidean spaces

Definition. A topological space X is called **locally Euclidean of dimension $n \geq 0$** , if every point of X is contained in a neighborhood homeomorphic to some open subset of \mathbb{R}^n .

Remark. When we speak of a topological space as being **locally Euclidean**. The dimension is fixed and implicit.

Definition. Assume that X is locally Euclidean. A **chart** is a pair U, ϕ , where $U \subset X$, $\phi : U \rightarrow \mathbb{R}^n$ is a homeomorphism into its image. Given $p \in X$, we say that U, ϕ is **centered at p** if $p \in U$ and $\phi(p) = 0 \in \mathbb{R}^n$



Figure 1.1: Sketch 1.01

Lemma 1.1. The following are equivalent (TFAE):

- X is locally Euclidean
- For any $p \in X$, there is a chart U, ϕ centered at p with image $\phi(U) = B_1$

- For any $p \in X$, there is a chart U, ϕ centered at p with image $\phi(U) = \mathbb{R}^n$

Proof. 2. and 3. are equivalent, since $B_1 \simeq \mathbb{R}^n$ are homeomorphic ($B_1^n \ni x \mapsto \frac{x}{1-\|x\|}$)

2. \implies 1. is tautological

1. \implies 2. given $p \in X$, since X is locally Euclidean, there exists **some** chart $U, \psi, p \in U$.

$\psi : U \rightarrow \mathbb{R}^n$, homeo onto its image $\psi(U) = O \subset \mathbb{R}^n$. By translativity $\mathbb{R}^n \ni x \mapsto x - \psi(p)$, one can assume $\psi(p) = 0 \in \mathbb{R}^n$. By scaling $\mathbb{R}^n(x \mapsto \lambda x, \lambda > 0)$, can assume $B_1 \subset \psi(U)$. Let $U' = \psi^{-1}(B_1)$, then (U, ψ) as claimed. \square

1.1.2 Hausdorff spaces

Definition. A topological space X is called Hausdorff, if given any $p_1 \neq p_2, p_1, p_2 \in X$, there exist neighborhoods $U_1 \ni p_1, U_2 \ni p_2$ s.t. $U_1 \cap U_2 = \emptyset$.



Figure 1.2: Sketch 1.02

Example. • \mathbb{R}^n

- CW complexes
- most reasonable spaces

Example (Not Hausdorff). $X = \{0, 1\}$, open subsets $\emptyset, \{0\}, \{0, 1\}$

Remark. X is homeomorphic to \mathbb{R}/\mathbb{R}^* (quotient topology), $\mathbb{R}^*, (s, x \mapsto sx)$

Lemma 1.2. Let X be Hausdorff.

- (a) point sets $\{x\}$ are closed
- (b) convergent sequences have unique limits. $(x_n \rightarrow p, x_n \rightarrow q \implies p = q)$
- (c) compact sets are closed

Proof. (c) \implies (a)

For (c): Let $K \subset X$ be compact. Want to show K^c is open. Pick $p \in K^c$. For each $q \in K$, we can choose $U_q \ni q, U_p \ni p : U_q \cap U_p = \emptyset$. Since K is compact, it can be covered by U_{q_1}, \dots, U_{q_l} . Then $\bigcap_{i=1}^l U_{q_i}$ is open and contains p , disjoint, then $\bigcup_{i=1}^l U_{q_i} \supset K$.

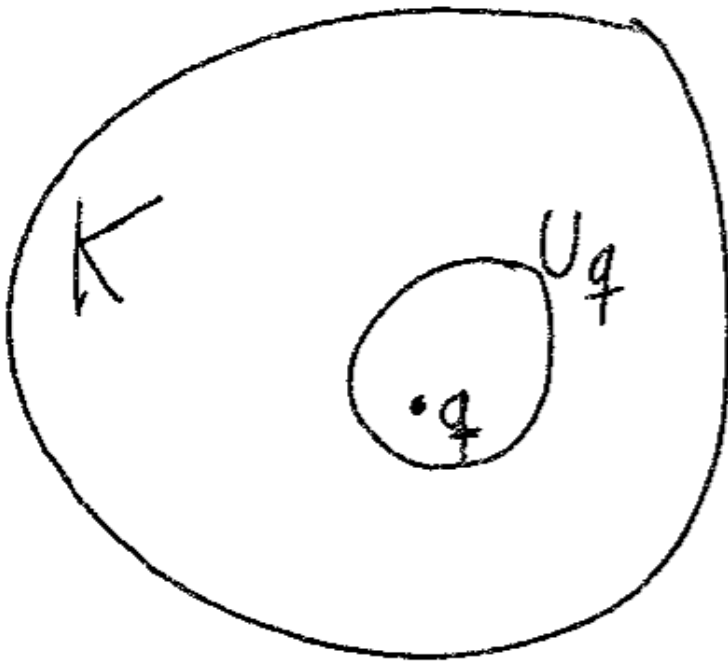


Figure 1.3: Sketch 1.03

(b) Suppose for contradiction that $x_i \rightarrow p, x_i \rightarrow q$ and $p \neq q$. Since X is Hausdorff, $\exists U \ni p, O \ni q, U \cap O = \emptyset$. But for $N \gg 0, x_i \in U, x_i \in O \forall i > N$

□

1.1.3 Basis and covers

Let X be a topological space.

Definition. A collection \mathcal{B} of subsets of X is called a **basis(base)** for X , if for any $p \in X$ and any neighborhood $U \ni p$, there exists an element $\mathcal{U} \in \mathcal{B}$ s.t. $p \in \mathcal{U} \subset U$.



Figure 1.4: Sketch 1.04

Lemma 1.3. \mathcal{B} is a basis for $X \iff$ every open set of X is a union of elements of \mathcal{B} .

Proof. Trivial. □

Definition. A topological space X is **second-countable** if it admits a countable basis.

Example. $\bullet \mathbb{R}^n, \mathcal{B} = \{B_s^n(p) \mid s \in \mathbb{Q}_+, p = (p_1, \dots, p_n) \in \mathbb{Q}^n \subset \mathbb{R}^n\}$

Lemma 1.4. The property of being second-countable is closed under

- (a) subspaces
- (b) countable disjoint unions
- (c) countable products

Remark. The property of being second-countable is not closed under arbitrary quotients $q : A \rightarrow A/B$. An obvious sufficient conditions is for q to be an open map. (Since it is a pushforward)

When constructing manifolds via quotients, check that it is still second-countable!

Lemma 1.5. If X is second countable, then any open cover of X admits a countable subcover.

Proof. Let \mathcal{B} be a countable basis for X . Let \mathcal{C} be an open cover. Let $\tilde{\mathcal{B}} \subset \mathcal{B}$ be the collection of basis elements U , which are contained in some $\mathcal{U} \in \mathcal{C}$. Observe (key!) $\tilde{\mathcal{B}}$ is a cover of X . For each $U \in \tilde{\mathcal{B}}$, choose $\mathcal{U}_U \in \mathcal{C}$ such that $U \subset \mathcal{U}_U$. Then $\{\mathcal{U}_U\}$ is a countable subcover of \mathcal{C} . □

Definition. Let X be a topological space. An **exhaustion of X by compact subsets** is a sequence $\{K_i\}_{i \in \mathbb{N}}$, where $K_i \subset X$ compact and $K_i \subset \text{int}(K_{i+1})$ and $\bigcup_{i=1}^{\infty} K_i = X$.

Recall given $A \subset X$. $\text{int}(A) := \{x \in A \mid x \text{ in a neighborhood } U \subset A\}$.

Lemma 1.6. *If X is locally Euclidean, Hausdorff^a and second countable. Then X admits an exhaustion by compact subsets.*

^anot needed

Proof. Since X is locally Euclidean, admits a basis \mathcal{B} of open subsets having compact closure.

That is take the close of $B_{\frac{1}{2}} \subset \mathbb{R}^n$

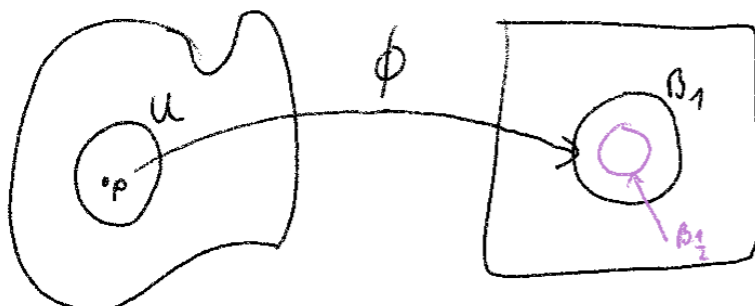


Figure 1.5: Sketch 1.05

By Lemma 1.5, one can extract a countable subcover $\{U_i\}_{i=1}^{\infty}$. Set $K_1 = \overline{U_1}$. Assume that we already constructed K_1, \dots, K_k such that $U_j \subset K_j$ and $K_{j-1} \subset \text{int}(K_j)$, $j \geq 2$. Since K_k is compact and $K_k \subset X = \bigcup_{i=1}^{\infty} U_i$, then there exists some m_k such that $K_k \subset \bigcup_{i=1}^{m_k} U_i$ by compactness. Might as well assume that $m_k \geq k$. Set

$$K_{k+1} = \overline{\bigcup_{i=1}^{m_k} U_i} = \bigcup_{i=1}^{m_k} \overline{U_i}.$$

By construction K_{k+1} is compact, $K_k \subset \text{int}(K_{k+1})$. We get $\{K_j\}_{j=1}^{\infty}$, $U_j \subset K_j$ (because $m_j \geq j$)
 $\Rightarrow \bigcup_{i=1}^{\infty} U_i = \bigcup_{i=1}^{\infty} K_i$ \square

Start of lecture 02
(11.10.2024)

Definition. Let X be a topological space. Let \mathcal{C} be a collection of subsets of X . We say that \mathcal{C} is **locally finite** if for every $x \in X$ there exists a neighborhood $U \ni x$ such that the intersection of U with all but finitely many elements of \mathcal{C} is empty.

Example (Example for local finiteness). Take $X = \mathbb{R}$, $\mathcal{C} = \{(i-1, i+1)\}_{i \in \mathbb{Z}}$.

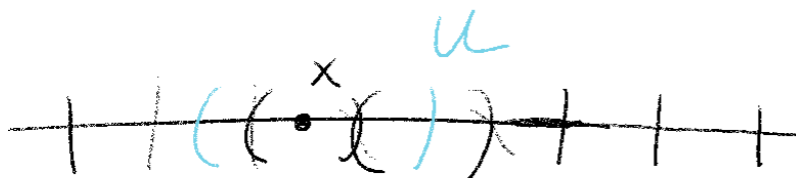


Figure 1.6: Sketch 1.06

Example (Non-example for local finiteness). $X = \mathbb{R}$, $\mathcal{C} = (q-1, q+1)_{q \in \mathbb{Q}}$

Definition. Let X be a topological space. Let \mathcal{C} be a cover of X . A cover \mathcal{C}' of X is called a **refinement** of \mathcal{C} , if for all elements $U \in \mathcal{C}'$, there exists such $V \in \mathcal{C}$: $U \subset V$.

Example (Example of Refinement). In the proof of lemma 1.5, we showed that any open cover admits a refinement by basis elements.

Definition. A topological space X is called paracompact if every open cover admits a locally finite refinement.

Whats up with the word **paracompact**? It's like compact, but weaker! It is necessary that it only admits a locally finite refinement!

Lemma 1.7. Let X be Hausdorff and suppose that X admits an exhaustion by compact subsets. Then X is paracompact. In fact, we will show that given any basis \mathcal{B} of X , any open cover admits a locally finite refinement by elements of \mathcal{B} .

Proof. By assumption, $\{K_i\}_{i \in \mathbb{N}}$, K_i compact, $K_i \subset \text{int}(K_{i+1})$, $\bigcup_{i=1}^{\infty} K_i = X$. Let, for $j \in \mathbb{Z}$: $V_j = K_{j+1} \setminus \text{int}(K_j)$ if $j \geq 0$; $K_j = \emptyset^1$.

Careful! There are many definitions of exhaustion by compact sets ...

$$V_0 = K_1 \dots \underbrace{V_{j-1} \quad V_j \quad V_{j+1}}_{\text{neighborhood}} \dots$$

Figure 1.7: Sketch 1.07

Notice:

- V_j is compact, since we take the intersection of a compact set and a closed set. ($\text{int}(K_j)^c$ is closed)
- $\bigcup_{j \in \mathbb{Z}} V_j = X$, since $\bigcup_{j \leq n} V_j = \bigcup_{j \leq n+1} K_j = K_{j+1}$
- The compact sets V_j are intersecting (along their boundary?)
 $V_j \cap V_{j-1} = \partial K_j := K_j \setminus \text{int}(K_j)$

Evidently $\{U_\alpha \cap \text{int}(K_{j+1}) \cap \text{int}(K_{j-1})^c\}_{\alpha \in \mathcal{A}}$ covers $V_j = K_{j+1} \setminus \text{int}(K_j)$, where the $\{U_\alpha\}_{\alpha \in \mathcal{A}}$ is an open cover. Since \mathcal{B} is a basis, we can find a refinement of this cover by basis elements. Since V_j are compact, we can extract a finite subcover $\{V_l^j\}_{l=1, \dots, k_j}$. Let's consider: $\{V_l^j\}_{j \in \mathbb{Z}, l=1, \dots, k_j}$. This subcover works, i.e.

Here we use Hausdorffness

- obviously a cover, since the V_j cover X , obviously a refinement of $\{U_\alpha\}$
- locally finite: given $x \in X$, $x \in V_j$, hence $x \in \text{int}(K_{j+2}) \cap K_{j-1}^c =: U$. If $U \cap V_l^k$, then we must have $j-2 \leq k \leq j+2$. But $\{V_l^k\}_{j-2 \leq k \leq j+2}$ is finite. \square

Corollary 1.8. If X is locally Euclidean, Hausdorff and second countable $\implies X$ is paracompact.

Proof. By lemma 1.6 (exhaustion by compact subsets) and lemma 1.7 \implies paracompact. \square

Corollary 1.8'. Let X be Euclidean and Hausdorff. Then X is second countable iff X has countably many components and X is paracompact.

Remark. There are different definitions of manifolds. They differ in either forcing second countability or paracompactness. This lemma shows that there only is a difference if there are uncountably many components.

Proof. Corollary 1.8 and the bonus homework problem from sheet 01. \square

Remark. Basis elements are open.

1.2 Topological manifolds

¹He writes – for \setminus

Definition. A topological n -manifold M is a topological space with the following properties:

- (i) M is locally Euclidean (of dimension n)
- (ii) M is Hausdorff
- (iii) M is second countable

Morally we only really need condition (i). Why do we need the others? For (ii) you will not get a useful theory without it, while (iii) can be replaced by paracompactness (see corollary 1.8').

Definition. Let Man^0 be the category of topological manifolds with

- 1. objects: topological manifolds
- 2. morphisms: continuous functions

Remark. Man^0 full subcategory of Top .

Remark. By definition, $M, N \in \text{Man}^0$, then M, N are isomorphic iff M, N are homeomorphic.

1.2.1 Examples of topological manifolds

Example (Spaces isomorphic to \mathbb{R}^n). $\mathbb{R}^n, n \geq 0$ More generally, if V a finite dimensional \mathbb{R} -vector space, then V is a topological n -manifold.

Example. Any open subset of \mathbb{R}^n

Example (Graphs). Let $U \subseteq \mathbb{R}^n$ open, let $f : U \rightarrow \mathbb{R}^n$ be a continuous function. We set

$$M := \text{graph}(f) := \{(x, y) \in U \times \mathbb{R}^n \mid y = f(x)\}.$$

Then M is a manifold. The map $M \rightarrow U$ by $(x, y) \mapsto x$ gives a global chart.

Example (Spheres). Let $S^n := \{x_0^2 + \dots + x_n^2 = 1\} \subset \mathbb{R}^{n+1}$. Then S^n is a manifold. We define charts

$$\phi_i^\pm : U_i^\pm = \{(x_0, \dots, x_n) \in S^n \mid \pm x_i > 0\} \rightarrow B_1^n(0)$$

by $(x_0, \dots, x_n) \mapsto (x_0, \dots, \hat{x}_i, \dots, x_n) := (x_0, \dots, x_{i-1}, x_{i+1}, \dots, x_n)$

Here we no longer have a global chart (for topological reasons)



Figure 1.8: Sketch 1.08

Example (spheres'). Let $C^n := \partial([-1, 1]^{n+1}) = [-1, 1]^{n+1} \setminus \text{int}([-1, 1]^{n+1})$. Homework: $C^n \simeq S^n$ (homeomorphic)

Example (n -torus). Let $\Pi^n := \mathbb{R}^n / \mathbb{Z}^n$ with the quotient topology. Then this is a manifold (exercise).



Figure 1.9: Sketch 1.09

Example ($\mathbb{RP}^n := S^n / \{x \sim -x\}$). \mathbb{RP}^n are also manifolds (called the real projective spaces).



Figure 1.10: Sketch 1.10

Example (Klein bottle).

Remark. \mathbb{RP}^2 or generally \mathbb{RP}^{2n} and the Klein bottle are not orientable.

1.2.2 Brief interlude: Why do we need Hausdorffness?

- Back in the day (Riemann)
- There is no hope to classify even 1d locally Euclidean, second-countable NOT Hausdorff spaces (See the line with two origins)
- With Hausdorff: Only 1d manifolds are \mathbb{R}, S^1 (see website)

Why do we need second countability?

- Subspaces of \mathbb{R}^n are second countable
- We want partitions of unity (paracompactness suffices for that)

1.2.3 Manifolds with boundary

Let $\mathbb{H}^n := \{(x_1, \dots, x_n) \in \mathbb{R}^n \mid x_n \geq 0\}$.

Definition. A manifold with boundary is a topological space with the following properties:

- (i) Every point has a neighborhood homeomorphic to an open subset of \mathbb{H}^n
- (ii) Hausdorff
- (iii) second countable

Clearly every manifold is also a manifold with boundary.

Example. \mathbb{H}^n is a manifold with boundary, but not a manifold. Since for points on the boundary, there are no neighborhoods homeomorphic to Euclidean space.

Example. $S^n \cap \mathcal{H}^{n+1}, S^n \subset \mathbb{R}^{n+1}, [a, b], [0, \infty)$



Figure 1.11: Sketch 1.12

Definition. If M manifold with boundary, we say x is a **boundary point**, if $x \in M \setminus \text{int}(M)$ (i.e. it has no neighborhood homeomorphic to Euclidean space?), otherwise x is an interior point. We let $\partial M := \{\text{boundary points}\}$.

Remark. Most of what he says in the course can be generalized to manifolds with boundary (unless it makes no sense). Those results are only stated (and proved) for manifolds. it might be a good exercise to go through the notes and generalize the statements to manifolds with boundary.

Start of lecture 03
(15.10.2024)

1.2.4 Elementary topological properties of topological manifolds

- A manifold is connected iff it is path connected
- For manifolds, all forms of compactness (ordinary compactness (every open cover has a finite subcover), limit point compactness, sequential compactness) are equivalent
- All manifolds are metrizable (Urysohn metrization theorem + second countable \implies metrizable)
- Any manifold is homotopy equivalent to a countable CW complex (Milner?) $\pi_k(M)$ are countable

Not proved here, but we are welcome to use

The first two point were proven on the first sheet. The last two use countability

1.3 Classification of topological manifolds (proofs are not examinable)

1.3.1 Classification of 1-dimensional manifolds

Theorem 1.9. Any connected one dimensional manifold is homeomorphic to

- \mathbb{R}^1 or
- \mathbb{H}^1

Proof. See Course website: [1] in the form of a take-home exam

□

Remark. If you allow a boundary, then you also have $[0, 1], [0, 1)$.

1.3.2 Classification of 2-dimensional manifolds

2-dimensional manifolds are often called surfaces

- $S^2 = \{(x_0, x_1, x_2) \in \mathbb{R}^3 \mid \sum_{i=0}^2 x_i^2 = 1\}$
- $\Pi^2 := \mathbb{R}^2 / \mathbb{Z}^2$
- $\mathbb{RP}^2 = S^2 / \{x \sim -x\}$

Construction (Connected sum of surfaces):

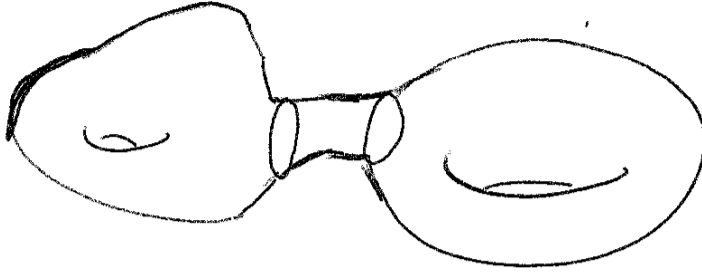


Figure 1.12: Sketch 1.14

Let M_1, M_2 be surfaces (i.e. 2-dimensional manifolds). Choose charts $M_i \supset U_i \xrightarrow{\phi_i} B_1 \subset \mathbb{R}^2$. Let $\mathring{M}_i = M_i \setminus \phi_i^{-1}(B_{\frac{1}{2}})$. Let $M_1 \# M_2 := \mathring{M}_1 \cup \mathring{M}_2 / \sim$, where $X \in \mathring{M}_1 \sim y \in \mathring{M}_2$ if $x \in \phi_1^{-1}(\partial B_{\frac{1}{2}})$ and $y = (\phi_2^{-1} \circ \phi_1)(x)$

Facts:

- If M_1, M_2 are connected, then $M_1 \# M_2$ is well defined up to homeomorphism.
- The operation of connected sum is also well defined for connected n -manifolds
- (for the future) The operation of connected sum also works in the smooth category.

Theorem 1.10 (Classification of surfaces). *Every compact, connected surface is homeomorphic to one of the following manifolds:*

- S^2
- $\underbrace{\Pi^2 \# \dots \# \Pi^2}_{k \text{ times}}$
- $\underbrace{\mathbb{RP}^2 \# \dots \# \mathbb{RP}^2}_{l \text{ times}} \text{ (non-orientable)}$



Figure 1.13: Sketch 1.15

Remark. Surfaces are classified by the following invariants:

- (a) orientability
- (b) Euler characteristic

For later: This classification also works in the smooth category.

1.3.3 Classification of high dimensional manifolds (not examinable at all)

Poincaré conjecture (now theorem of G. Perelman (2003), W. Thurston (1980s)): Any compact connected 3 dimensional manifold which is simply connected is homeomorphic to S^3 . This paper is all about PDEs and Ricci flows.

Generalized Poincaré conjecture: Any n -manifold, which is homotopy equivalent to S^n is homeomorphic to S^n . This is true in all dimensions. for $n \geq 5$ Smale in the 1960s, for $n = 4$ Freedman in the 1980s.

Unlike in dimension 1,2,3 the classification of $n \geq 3$ -dimensional manifolds is complicated and not complete.

Example. Any finitely presented group arises as the fundamental group of a compact connected 4-manifold (Which is provably too hard).

Chapter 2:

Smooth manifolds

2.1 Basic theory

2.1.1 Charts and atlases

Definition. Given $U \subset \mathbb{R}^n$ open, a function $f : U \rightarrow \mathbb{R}^m, f = (f_1, \dots, f_m)$ is called **smooth** (or \mathbb{C}^∞ or **infinitely differentiable**), if the **component functions** f_i admit all partial derivatives of all orders and all these partial derivatives are continuous.

In other words f smooth: $\iff \forall 1 \leq i \leq m, \alpha = (\alpha_1, \dots, \alpha_n) \in \mathbb{N}^n, \partial_\alpha f := \partial_{x_1}^{\alpha_1} \dots \partial_{x_n}^{\alpha_n} f$ exists.

Remark. Given $k \geq 0$, we can similarly say that f is **k -times continuously differentiable** and write $(f \in)$ and write $f \in C^k(U, \mathbb{R}^m)$, if for all $\alpha = (\alpha_1, \dots, \alpha_n) \in \mathbb{N}^n, \sum \alpha_i \leq k$ $\partial_x^\alpha f_i$ is continuous for all i .

Definition. Let M be a topological manifold. We say that two charts $(U_1, \phi_1), (U_2, \phi_2)$ are **smoothly compatible** if the map $\phi_2 \circ \phi_1^{-1} : \phi_1(U_1 \cap U_2) \rightarrow \phi_2(U_1 \cap U_2)$ is smooth. We call $\phi_2 \circ \phi_1^{-1}$ a **transition function**.

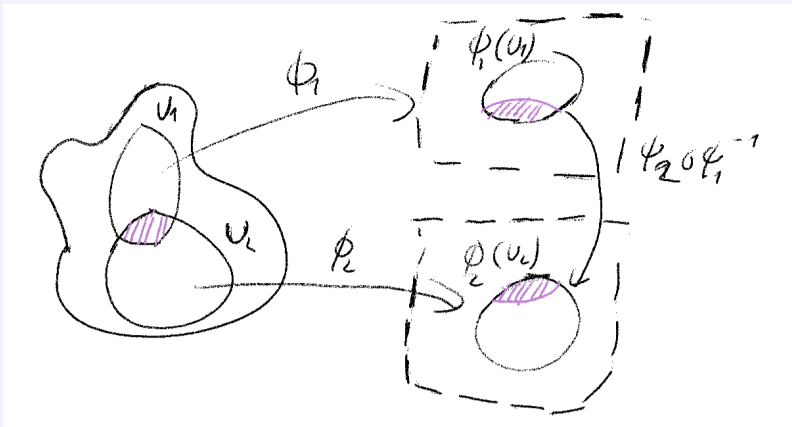


Figure 2.1: Sketch 2.01

Definition. Let M be a topological manifold. An **(smooth) atlas** \mathcal{A} of M is a collection of charts $\{U_\alpha, \phi_\alpha\}_{\alpha \in \mathcal{A}}$ such that

- the $\{U_\alpha\}$ cover M
- the charts are pairwise smoothly compatible (i.e. for all $\alpha, \beta \in \mathcal{A}$ $(U_\alpha, \phi_\alpha), (U_\beta, \phi_\beta)$ are smoothly compatible).

Definition. We say that two atlases $\mathcal{A}, \mathcal{A}'$ (on a fixed topological manifold) are equivalent, if their union $\mathcal{A} \cup \mathcal{A}'$ is still an atlas.

Fact(Sheet 03): This defines an equivalence relation.

Definition. A smooth manifold $M = (M, [\mathcal{A}])$ consists of the following data:

- (i) a topological manifold M
- (ii) an equivalence class of smooth atlases

Remark. • typically, we will designate smooth manifolds by a capital letter, e.g. M . But we always mean $(M, [\mathcal{A}])$. **Note** being a smooth manifold is extra structure on a topological space, while being a topological manifold is a property

- Using Zorn's lemma, it can be shown that any atlas is contained in a unique maximal atlas. Uniqueness here does not use Zorn's lemma, only existence needs that! Equally well define a smooth manifold to be a topological manifold and a maximal atlas.
- $\forall 0 \leq k \leq \infty$, we can define the notion of a C^k -atlas, simply by requiring that the transition functions are C^k functions. This yields the definition of C^k -Manifolds. Two extreme cases: C^0 -manifold (topological manifolds) and C^∞ -manifolds. Any $k \geq 1$ is not more interesting than C^∞ !

Typically we are given an atlas, since the maximal atlases have uncountably many charts, which is why we work with equivalence classes, rather than maximal atlases
Start of lecture 04
(18.10.2024)

2.1.2 First examples of smooth manifolds

Example (Example 1: The canonical smooth manifold). $\mathbb{R}^n, n \geq 0$ is canonically a smooth manifold. The canonical atlas is induced by the topological chart $U = \mathbb{R}^n, \phi : U \xrightarrow{id} \mathbb{R}^n$.

Example (Example 2: Another canonical smooth manifold). Let V be a finite dimensional real vector space. Then V is canonically a smooth manifold. Pick a vector space basis \mathcal{B} . This basis induces a homeomorphism $\phi_{\mathcal{B}} : V \rightarrow \mathbb{R}^n$. If we had picked another basis \mathcal{B}' , then then the transition map $\phi_{\mathcal{B}'} \circ \phi_{\mathcal{B}}^{-1} \in GL(n, \mathbb{R})$. Hence $\phi_{\mathcal{B}'} \circ \phi_{\mathcal{B}}^{-1}$ is smooth.

Example (Example 3: Spheres). We have $S_c^n := \{(x_0, \dots, x_n) \in \mathbb{R}^{n+1} \mid \sum_{i=0}^n x_i^2 = c^2\}$ for $c > 0$.

Let $\phi_i^\pm : \underbrace{U_i^\pm}_{:= \{(x_0, \dots, x_n) \in S_c^n \mid \pm x_i > 0\}} \rightarrow B_c^n$. Then

$\phi_j^\pm \circ (\phi_i^{pm})^{-1}(y_1, \dots, y_n) = \phi_j^\pm(y_1, \dots, \pm \sqrt{c^2 - \sum y_i}, \dots, y_n)$, where $(y_1, \dots, y_n) \in B_c^n$.

$$= \begin{cases} (y_1, \dots, y_n) & i = j \\ (y_1, \dots, \sqrt{c^2 - \sum y_k}, \dots, \hat{y}_j, \dots, y_n) & j > i \\ (y_1, \dots, y_{\hat{j}+1}, \dots, \sqrt{c^2 - \sum y_k}, \dots, y_n) & j < i \end{cases} \quad (1)$$

We conclude $\{U_i^\pm, \phi_i^\pm\}$ is a smooth atlas.

Example (Example 4: Level sets). Let $\Phi : \mathbb{R}^{n+1} \rightarrow \mathbb{R}$ be a smooth function. Fix $c \in \mathbb{R}$. Recall that the set $\Phi^{-1}(c) = \{x \in \mathbb{R}^{n+1} \mid \Phi(x) = c\}$ is called a level set of value c . **Suppose** that, $\forall p \in \Phi^{-1}(c) : D \underbrace{\Phi(p)}_{=(\partial_{x_0} \Phi(p), \dots, \partial_{x_n} \Phi(p))} \neq 0$. This means that $\exists 0 \leq i \leq n$ s.t. $\partial_{x_i} \Phi(c) \neq 0$. By the

implicit function theorem (Lee, Theorem C.40, Course website), there exists a neighborhood U of p such that $U \cap \Phi^{-1}(p) = \{(x_0, \dots, f(x_0, \dots, \hat{x}_i, \dots, x_n), x_n)\}$.

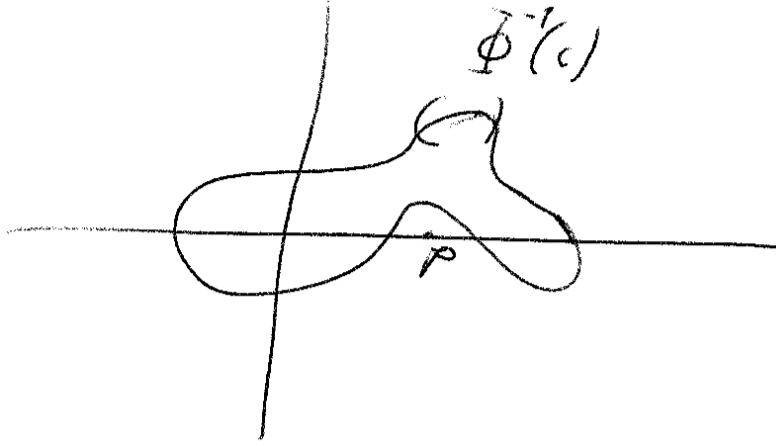


Figure 2.2: Sketch 2.02

Let $M = \phi^{-1}(c)$. We define $\hat{\pi}_i : \mathbb{R}^{n+1} \rightarrow \mathbb{R}^n, (x_0, \dots, x_n) \mapsto (x_0, \dots, \hat{x}_i, \dots, x_n)$.

$$\{(U, \hat{\pi}_i) \mid U \subset M, \hat{\pi}_i|_U \text{ homeomorphism, } \partial_{x_i} \Phi \neq 0 \text{ on } U\}$$

Remains to check the formula:

$$\pi_j \circ \hat{\pi}_i^{-1}(y_1, \dots, y_n) = \begin{cases} (y_1, \dots, f, \dots, y_j, \dots, y_n) & j > i \\ (y_1, \dots, y_{j+1}, \dots, f, \dots, y_n) & i < j \\ (y_1, \dots, y_n) & i = j \end{cases}$$

Remark. The condition $D\Phi \neq 0$ is very explicit! It is very easy to generate lots of manifolds. For example: $\Phi(x) = \sum \lambda_i x_i^2$

Example (Example 5: Subset of smooth manifold). Let M be a smooth manifold. Then $U \subset M$ open, is also a smooth manifold. (Take charts of M and intersect / restrict each chart)

Example (Example 6: Product of manifolds). Let M, N be smooth manifolds. Then $M \times N$ is also a smooth manifold. Take as charts

$$\{(U \times V, (\phi, \psi)) \mid (U, \phi), (V, \psi) \text{ charts of } M, N \text{ respectively}\}$$

Example (Example 7:). Let's consider \mathbb{R} . We define a chart $\mathbb{R} \rightarrow \mathbb{R}, x \mapsto x^3$. Observe that

$$M = (U = \mathbb{R}, U \xrightarrow{id} \mathbb{R})$$

and

$$N = (U = \mathbb{R}, U \xrightarrow{x \mapsto x^3} \mathbb{R})$$

are smooth manifolds, which are different! Since the transition functions between them are not smooth:

Indeed $id \circ (x \mapsto x^3)^{-1} = (x \mapsto x^{\frac{1}{3}})$, which is not smooth!

This takes care of the torus!

This is one to pay attention to!

2.1.3 Smooth maps

Definition. Let M be a smooth manifold. A map $f : M \rightarrow \mathbb{R}^m$ is said to be smooth, if for all $p \in M$, there exists a chart (U, ϕ) containing p , such that

$$f \circ \phi^{-1} : \underbrace{\phi(U)}_{\subset \mathbb{R}^n} \rightarrow \mathbb{R}^m$$

is smooth.

Definition. Let M, N be manifolds. We say $f : M \rightarrow N$ is **smooth** if, for all $p \in M$ there exists charts (U, ϕ) with $p \in U \subset M$ and (V, ψ) with $V \subset N$ such that:

- $V \supset f(U)$
- $\psi \circ f \circ \phi^{-1} : \underbrace{\phi(U)}_{\subset \mathbb{R}^n} \rightarrow \mathbb{R}^m$ is smooth

manifolds = smooth manifolds as always (unless otherwise stated)

Reality check.

Lemma 2.1. Smooth maps are continuous.

Proof. Enough to show that $\forall p \in M$, there exists a neighborhood of p on which $f : M \rightarrow N$ is continuous, for f smooth. By definition $\exists (U, \phi), p \in U, (V, \psi), V \subset N$ s.t.

$\psi \circ f \circ \phi^{-1} : \phi(U) \rightarrow \mathbb{R}^m$ smooth.

Observe $f = \psi^{-1} \circ (\psi \circ f \circ \phi^{-1}) \circ \phi$ on U . □

Lemma 2.2. $f : M \rightarrow N$ is smooth if and only if each $p \in M$ has a neighborhood U such that $f|_U$ is smooth.

Proof. Sheet 03. □

Lemma 2.3 (Properties of smooth maps). (i) Any constant map $c : M \rightarrow N$ is smooth^a

(ii) The identity map $id : M \rightarrow M$ is smooth

(iii) If $U \subset M$ open, then the inclusion $i : U \hookrightarrow M$ is smooth

(iv) Compositions of smooth functions are smooth

^aSince it sends M to a point in N

Proof. Sheet 03. □

Definition. Let M, N be manifolds. A **diffeomorphism** $f : M \rightarrow N$ is a smooth map, which is bijective and admits a smooth inverse.

In particular, diffeomorphisms are homeomorphism!

Example. $f : \mathbb{R} \rightarrow \mathbb{R}, x \mapsto x + 3$ is a diffeomorphism with inverse $x \mapsto x - 3$.

Example. Let $A \in GL(n, \mathbb{R})$. Define a map

$$f_A : \mathbb{R}^n \rightarrow \mathbb{R}^n, x \mapsto Ax.$$

This is a diffeomorphism (smooth, since linear) with inverse $f_A^{-1} = f_{A^{-1}}$.

Example. Let $S_c^n := \{(x_0, \dots, x_n) \mid \sum_{i=0}^n x_i^2 = c^2\} \subset \mathbb{R}^{n+1}$. Given $d > c > 0$, we define a diffeomorphism.

$$S_c^n \rightarrow S_d^n, (x_0, \dots, x_n) \mapsto \frac{d}{c}(x_0, \dots, x_n).$$

Example. $M = (\mathbb{R}, id), N = (\mathbb{R}, x \mapsto x^3)$. The map $M \rightarrow N, x \mapsto x^{\frac{1}{3}}$ is a diffeomorphism. Indeed,

$$(x \mapsto x^3) \circ (x \mapsto x^{\frac{1}{3}}) \circ id^{-1} = id$$

2.1.4 The category of smooth manifolds

Definition. Let Man^∞ be the category of smooth manifolds. The objects are the smooth manifolds. The morphisms are the smooth maps.

Exercise: M, N objects in Man^∞ are isomorphic if and only if they are diffeomorphic.

Observe that there is a forgetful functor: $\text{Man}^\infty \rightarrow \text{Man}^0$ by $(M, [\mathcal{A}]) \rightarrow M$ and $f : M \rightarrow N \mapsto f$. In general:

- not full
- not essentially surjective

Remark (Hierarchy of categories). • for $k = 0, \dots, \infty$, we can consider the category Man^k with objects C^k -Manifolds, and morphisms C^k -maps. for $k \leq l$ there is a forgetful functor $\text{Man}^l \rightarrow \text{Man}^k$

- if $k \geq 1$, then the forgetful functor $\text{Man}^\infty \rightarrow \text{Man}^k$ is essentially surjective. This is different from the C^0 case. For this reason, we mainly focus on $\text{Man}^0, \text{Man}^\infty$. This is a theorem by Whitney
- there are other interesting categories: $\text{Man}^{\text{Real-analytic}}, \text{Man}^{\text{Cplx-analytic}}, \dots$, which both come with a forgetful functor to Man^∞

Remark (Classification of manifolds (not examinable)). • all topological manifolds of dimension ≤ 3 admit a unique smooth structure

- S^7 , as a topological manifold, admits 15 pairwise non-diffeomorphic smooth structures. These are called exotic spheres. They also exist in higher dimensions (Milan-Kervaire?)
- \mathbb{R}^4 admits uncountably many pairwise non-diffeomorphic smooth structures (Taubes 1980s)
- Open problem (**Smooth 4 dimensional Poincaré conjecture**): Prove or disprove: any smooth 4-manifold, which is homeomorphic to S^4 is diffeomorphic to S^4 . Most experts believe this is false!

Start of lecture 05
(22.10.2024)

2.1.5 Smooth manifolds with boundary

Definition. A function $f : \mathbb{H}^n \supset U \rightarrow \mathbb{R}^k$ is smooth if every $p \in U$ admits an open neighborhood $p \in U_p \subset \mathbb{R}^n$ on which f extends to a smooth function. (i.e. there exists $\tilde{f}_p : U_p \rightarrow \mathbb{R}^k, \tilde{f}_p$ smooth and $\tilde{f}_p|_{\mathbb{H}^n \cap U} = f$)

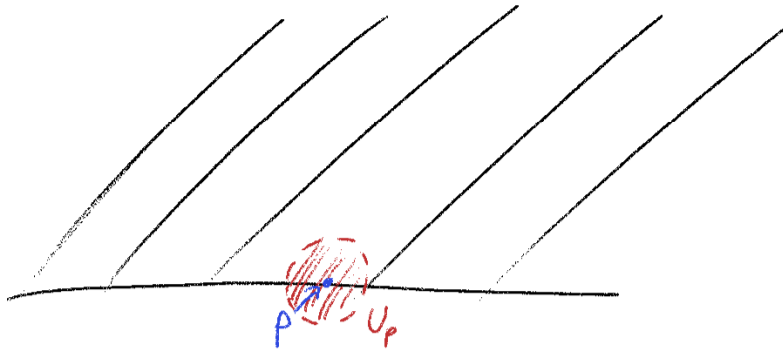


Figure 2.3: Sketch 2.03

Example. $n = 1, \mathbb{H}^1 = [0, \infty), f(x) = x^2$

Example (Non-Example). $n = 1, \mathbb{H}^1 = [0, \infty), f(x) = \sqrt{x}$ has no smooth extension to 0, since the derivative goes to ∞ .

Give a topological manifold with boundary, we can define unproblematically the notions of

- smoothly compatible charts: $(U, \phi) : M \rightarrow \mathbb{H}^n, \phi_\alpha \circ \phi_\beta^{-1} : \phi_\beta(U_\alpha \cap U_\beta) \rightarrow \mathbb{H}^n$
- smooth atlases

Definition. A smooth manifold with boundary $M = (M, [\mathcal{A}])$ is the data of

- a topological manifold with boundary

- an equivalence class of atlases

Remark. Every smooth manifold is a smooth manifold with boundary. This is an enlargement of Man^∞ .

Similarly we can generalise even more to manifolds with corners ...

2.2 Partitions of unity

2.2.1 Preparatory lemmas

Lemma 2.4. The function $f : \mathbb{R} \rightarrow \mathbb{R}$,

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

is smooth.

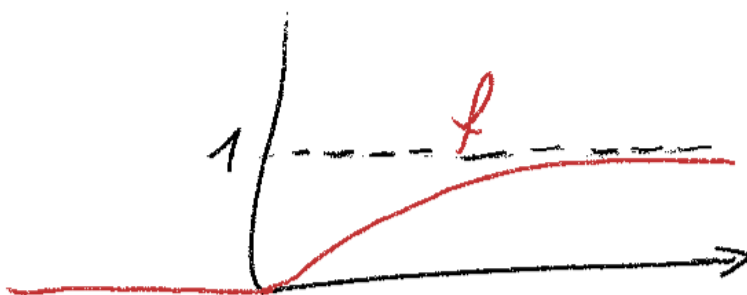


Figure 2.4: Sketch 2.04

Proof. It is enough to prove, that f has well defined derivatives of all orders, since f is a function on \mathbb{R} .

$f^0 = f$, for $k \geq 1$, assume

1. $f^{(k-1)}$ exists
2. $f^{(k-1)}|_{(-\infty, 0]} = 0$
3. $f^{(k-1)}|_{(0, \infty)}(t) = P_{k-1}(\frac{1}{t})e^{-\frac{1}{t}}$ for some polynomial $P_{(k-1)}$.

Clearly this holds for $k = 1$.

We have

$$\begin{aligned} \lim_{t \rightarrow 0^+} \frac{f^{(k-1)}(t) - f^{(k-1)}(0)}{t} &= \lim_{t \rightarrow 0^+} \frac{f^{(k-1)}(t)}{t} \\ &= \lim_{t \rightarrow 0^+} P_{(k-1)}\left(\frac{1}{t}\right) \frac{1}{t} e^{-\frac{1}{t}} \\ &= \lim_{x \rightarrow \infty} P_{(k-1)}(x) \cdot x \cdot e^{-x} = 0 \end{aligned}$$

Therefore $f^{(k-1)}$ is differentiable at the origin, the derivative $f^{(k-1)'}(0) = 0$. and $f^{(k-1)}|_{(-\infty, 0]} = 0$. Therefore $f^{(k-1)}$ is differentiable. Therefore we only have to check 3., which only takes place on \mathbb{R}_+ !

Finally

$$f^{(k-1)}|_{(0, \infty)}(t) = P_{(k-1)}\left(\frac{1}{t}\right)e^{-\frac{1}{t}} \implies P'_{(k-1)}\left(\frac{1}{t}\right)\left(-\frac{1}{t^2}e^{-\frac{1}{t}} + P_{(k-1)}\left(\frac{1}{t}\right)e^{-\frac{1}{t}}\right) =: P_{(k)}\left(\frac{1}{t}\right)e^{-\frac{1}{t}}. \quad \square$$

Lemma 2.5. Fix real numbers $r_1 < r_2$. Then there exists a smooth function $h : \mathbb{R} \rightarrow \mathbb{R}$ such that

1. $h \equiv 1$ on $(-\infty, r_1]$

2. $0 < h < 1$ on r_1, r_2
3. $h \equiv 0$ on $[r_2, \infty)$

Proof. $h(t) := \frac{f(s_2-t)}{f(s_2-t)+f(t-s_1)}$, since the denominator never goes to 0. \square

Lemma 2.6 (Existence of cutoff functions). *Given $0 < r_1 < r_2$, there exists a smooth function $H : \mathbb{R}^n \rightarrow \mathbb{R}$ such that*

1. $H \equiv 1$ on $\overline{B_{r_1}}$
2. $0 < H < 1$ on $B_{r_2} \setminus \overline{B_{r_1}}$
3. $H \equiv 0$ on $\mathbb{R}^n \setminus B_{r_2}$

Proof. Set $H(x) := h(|x|)$, where h is defined as in lemma 2.5. (Recall: $|x| := \sqrt{x_1^2 + \dots + x_n^2}$). Then H is smooth, since it is a composition of smooth functions on $\mathbb{R}^n \setminus \overline{B_{r_1}}$ and constant on $\overline{B_{r_1}}$. \square

2.2.2 Partitions of unity

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

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

Example. *If $f : \mathbb{R} \rightarrow \mathbb{R}$ has the form $f(x) = a_0 + a_1x + \dots, a_nx^n \implies \text{supp}(f) = \mathbb{R}$. In fact, by Taylor's theorem, if f analytic, then $\text{supp}(f)$ either \mathbb{R} or \emptyset . In contrast, the function $h : \mathbb{R} \rightarrow \mathbb{R}$ defined in lemma 2.5 has support $(-\infty, r_2] \subsetneq \mathbb{R}$.*

Definition. *Let M be a smooth manifold. Let $\{U_\alpha\}_{\alpha \in A}$ be an open cover. A partition of unity subordinate to the cover is the data of a collection of smooth functions $\{\psi_\alpha\}_{\alpha \in A}, \psi_\alpha : M \rightarrow \mathbb{R}$ such that*

- (1) $0 < \psi_\alpha < 1$
- (2) $\text{supp}(\psi_\alpha) \subset U_\alpha$
- (3) $\{\text{supp}(\psi_\alpha)\}_{\alpha \in A}$ is locally finite
- (4) $\sum_{\alpha \in A} \psi_\alpha \equiv 1$

Remark. *There is an analogous notion in the category $\text{Top}, \text{Man}^0, \text{Man}^k$, etc.,...*

Example. $M = \mathbb{R}, U_1 = (-\infty, r_2 + 1), U_2 = (r_1 - 1, \infty)$, where $r_1 < r_2$ as in lemma 2.5. Similarly let h as in lemma 2.5. and set $\psi_1 = h, \psi_2 = 1 - h$



Figure 2.5: Sketch 2.05

Theorem 2.7 (Existence of partitions of unity). *Let M be a smooth manifold. Let $\{U_\alpha\}_{\alpha \in A}$ be an open cover. Then there exists a partition of unity subordinate to this cover.*

Remark. The same theorem works in Top , Man^0 , Man^k . It will not work in $Man^{Analytic}$, $Man^{Cplx-Analytic}$, $Varieties/\mathbb{C}$.

Proof. **Step 1: Construction of the V_i** An open subset $U \subset M$ is called a **regular coordinate ball** if there exists $\tilde{U} \subset \tilde{U}$, $(\tilde{U}, \tilde{\phi})$ a chart such that $\tilde{\phi}(U) = B_{r_1}$, $\tilde{\phi}(\tilde{U}) = B_{r_2}$.



Figure 2.6: Sketch 2.06

By lemma 1.6 M admits an exhaustion by compact sets. By lemma 1.7, given any basis, any open cover, one can find a locally finite, countable basis refinement of this cover by basis elements.

Claim: $\{\text{regular coordinate balls whose closure is contained in some } U_\alpha\}$ basis of M

These two points imply that $\{U_\alpha\}_{\alpha \in \mathcal{A}}$ admits a countable, locally finite refinement by regular coordinate balls $\{V_i\}_{i \in I}$.

By sheet 2, exercise 1 (a) $\{\bar{V}_i\}$ is still locally finite.

Step 2: Construction of the f_i For each $V_i \exists \tilde{V}_i \supset \tilde{V}_i$, $\tilde{\phi}_i : \tilde{V}_i \rightarrow \mathbb{R}^n$ such that

$\tilde{\phi}_i(V_i) = B_{r_1^i}$, $\tilde{\phi}_i(\tilde{V}_i) = B_{r_2^i}$ with $0 < r_1^i < r_2^i$, $\tilde{V}_i \subset U_\alpha$ for some α . Using lemma 2.6, let

$H_i : \mathbb{R}^n \rightarrow \mathbb{R}$ be a cutoff function, i.e. $H_i|_{B_{r_1^i}} > 0$, $H_i = 0$ on $\mathbb{R}^n \setminus B_{r_2^i}$. Let us set

$$f_i : M \rightarrow \mathbb{R}, f_i = \begin{cases} H_i \circ \tilde{\phi}_i & \text{on } \tilde{V}_i \\ 0 & M \setminus \bar{V}_i \end{cases}$$

Step 3: Construction of the g_i Let us set $f = \sum_{i \in I} f_i$. This is well defined by local finiteness of the \bar{V}_i . Note also that $f > 0$. We set $g_i = f_i/f$. Then clearly we have $0 \leq g_i \leq 1$, $\sum_{i \in I} g_i \equiv 1$

Step 4: Reindexing and conformation Since $\tilde{V}_i \subset U_\alpha$, for some α , we can choose for each $i \in I$, $\alpha(i) \in \mathcal{A}$ s.t. $V_i \in U_{\alpha(i)}$. Let us set

$$\psi_\alpha := \sum_{i | \alpha = \alpha(i)} g_i$$

Observe for (2):

$$\text{supp}(\psi_\alpha) = \overline{\bigcup_{\alpha(i)=\alpha} V_i} \stackrel{\text{Exercise 2.1}}{=} \bigcup_{\alpha(i)=\alpha} \bar{V}_i \subset U_\alpha$$

We still have $0 \leq \psi_\alpha \leq 1$, which is (1)

and $\text{supp}(\psi_\alpha)$ are locally finite: for each $p \in M$, since $\{\bar{V}_i\}$ locally finite, there exists a neighborhood U_p of p which only intersects finitely many of the $\{\bar{V}_i\}$, call them V_1, \dots, V_k . Then the only ψ_α which have a chance of being non-zero must satisfy $\alpha \in \{\alpha(1), \dots, \alpha(k)\}$ (this is (3)). Lastly

$$\sum_{\alpha \in \mathcal{A}} \psi_\alpha = \sum_{\alpha} \left(\sum_{i: \alpha = \alpha(i)} g_i \right) = \sum_{i \in I} g_i \equiv 1,$$

which confirms (4). □

The claim is easy to verify

Finding \tilde{V}_i s.t. $\tilde{V}_i \subset U_\alpha$ is the reason we considered regular coordinate balls whose **closure is contained in some U_α**

Here the empty sum is 0

2.2.3 Applications of partitions of unity

Definition. Let X be a topological space. Let $A \subset X$ be closed, $U \subset X$, $A \subset U$ be open. A **bump function for A supported in U** is a function

$$\phi : X \rightarrow \mathbb{R}$$

such that $\phi|_A \equiv 1$, $\text{supp}(\phi) \subset U$.

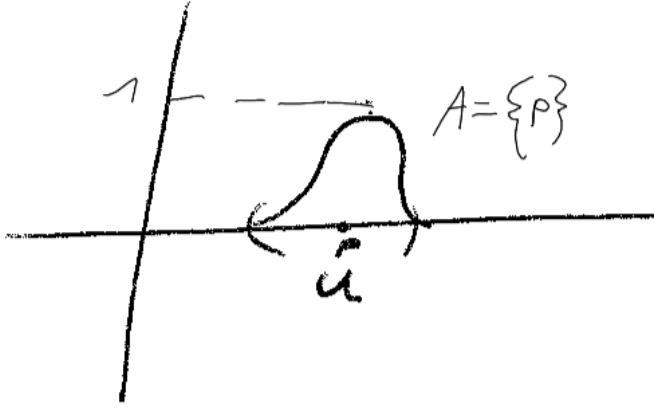


Figure 2.7: Sketch 2.07

Proposition 2.8. Let M be a smooth manifold. Fix $A \subset M$ closed, $U \subset M$, $A \subset U \subset M$ open. Then there exists a smooth bump function for A supported in U

Proof. Let $V = M \setminus A$. Then $\{U, V\}$ is a covering and by theorem 2.7, there exist $\{\Psi_U, \Psi_V\}$ partitions of unity subordinate to this cover. Now Ψ_U does the job. \square

Definition. Let M, N be smooth manifolds. Let $A \subset M$ be closed. We say that $f : A \rightarrow N$ is smooth if it admits a smooth extension in a neighborhood of each point $p \in A$.

I.e. for any $p \in A$ there exists $U_p \ni p$, a smooth function $\tilde{f}_p : U_p \rightarrow N$ s.t. $\tilde{f}_p|_{U_p \cap A} = f|_{U_p \cap A}$

Proposition 2.9. Let M be a smooth manifold. Let $A \subset M$ be closed and $f : A \rightarrow \mathbb{R}^k$, $k \geq 0$ be smooth. Then for any open $U \subset M$, $A \subset U$, there exists $\tilde{f} : M \rightarrow \mathbb{R}^k$, such that $\tilde{f}|_A = f$ and $\text{supp}(\tilde{f}) \subset U$

Remark. This would be **false** if we replaced \mathbb{R}^k by an arbitrary smooth manifold N . E.g. take $\mathbb{R}^2 \hookrightarrow A = S^1 \xrightarrow{f=id} S^1$

Proof. For each $p \in A$, choose a neighborhood $p \in W_p \subset U$, $\tilde{f}_p : W_p \rightarrow \mathbb{R}^k$ smooth extension of $f|_{A \cap W_p}$. Then observe that $\{W_p\}_{p \in A} \cup (M - A)$ forms an open cover of M . $\{\psi_p\}_{p \in A} \cup \psi_0$ be a partition of unity subordinate to the cover. Now we set $\tilde{f} = \sum_{p \in A} \psi_p \tilde{f}_p$. By local finiteness \tilde{f} is smooth. Also

We maybe need $\overline{W_p} \subset U$? Prob. not?

$$\begin{aligned} \tilde{f}|_A &= \sum_{p \in A} \psi_p|_A \underbrace{\tilde{f}_p|_A}_{=f} \\ &= f \sum_{p \in A} \psi_p|_A = f|_A \cdot 1 = f|_A. \end{aligned} \quad \square$$

Definition. Let X be a topological space. An **exhaustion function** $f : X \rightarrow \mathbb{R}$ is a continuous function such that $\forall C \in \mathbb{R}$, $f^{-1}(-\infty, C]$ is compact.

If X is compact every f is an exhaustion function
...

Example. $X = \mathbb{R}$, $f : \mathbb{R} \rightarrow \mathbb{R}$, $x \mapsto x^2$

Example (NON-EXAMPLE). $X = \mathbb{R}$, $f(x) = x$

Proposition 2.10. *Every smooth manifold admits a smooth exhaustion function.*

Proof. Pick a countable partition of unity $\{U_i\}_{i \in \mathbb{N}_+}$ by open subsets having compact closure¹. Let $\{\Psi_i\}_{i \in \mathbb{N}_+}$ be a subordinate partition of unity. Let $f := \sum_{i \in \mathbb{N}_+} i\psi_i$. Observe that for any $c \in \mathbb{R}$, $c < N \in \mathbb{N}$ that

$$f^{-1}(-\infty, c] \subset f^{-1}(-\infty, c] \subset \bigcup_{i=1}^N \overline{U_i}$$

Why $f^{-1}(-\infty, c] \subset \bigcup_{i=1}^N \overline{U_i}$? Let $q \notin \bigcup_{i=1}^N \overline{U_i}$. Then

$$\begin{aligned} f(q) &= \underbrace{\sum_{i=1}^N i\psi_i(q)}_{=0} + \sum_{i=N+1}^{\infty} i\psi_i(q) \\ &\geq (N+1) \sum_{i=N+1}^{\infty} \psi_i(q) = (N+1) \underbrace{\sum_{i=1}^{\infty} \psi_i(q)}_{=1} \\ &= N+1 \end{aligned}$$

□

Proposition 2.11. *Let M be a smooth manifold. Let $A \subset M$ be a closed subset. Then there exists a smooth function*

$$f : M \rightarrow \mathbb{R}, f^{-1}(0) = A$$

In fact, the prove shows one can assume $f \geq 0$

E.g. take $M = \mathbb{R}$, $A = \text{Cantor set}$, shows that this is non-trivial.

Proof. Assume $M = \mathbb{R}^n$ (general case: Sheet 04).

Choose a countable cover of $\mathbb{R}^n \setminus A$ by balls $\{B_{r_i}(x_i)\}_{i=1}^{\infty}$ with $r_i < 1$. By Lemma 2.6 there exists a cutoff function

$$H : \mathbb{R}^n \rightarrow \mathbb{R}$$

s.t. $H \equiv 1$ on $\overline{B_{\frac{1}{2}}(0)}$ and $0 < H < 1$ on $B_1(0) \setminus \overline{B_{\frac{1}{2}}(0)}$ and $H \equiv 0$ on $\mathbb{R}^n \setminus B_1(0)$. For each $i \geq 1$ let $C_i \gg 1$ be large enough so that

$$C_i > \sup\{\partial_x^\alpha H \mid \alpha = \overbrace{(\alpha_1, \dots, \alpha_n)}^{\in \mathbb{N}^n}, |\alpha| \leq i\}$$

Let

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

We need to argue that f is smooth. Observe that, since $r_i < 1$, $\frac{r_i}{2^i C_i} H\left(\frac{x - x_i}{r_i}\right) \leq \frac{1}{2^i}$. It follows from Analysis 2 that f is continuous. To prove that f is smooth assume for $k \geq 1$ that all partial of order $k < 1$ exist and are continuous. If $|\alpha| = k$, then

$$\partial^\alpha \frac{r_i^i}{2^i C_i} H\left(\frac{x - x_i}{r_i}\right) = \frac{r_i^{i-k}}{2^i C_i} \partial^\alpha H\left(\frac{x - x_i}{r_i}\right)$$

If $i > k$, then

$$\left| \frac{r_i^{i-k}}{2^i C_i} \partial^\alpha H\left(\frac{x - x_i}{r_i}\right) \right| < \frac{1}{2^i}$$

Again follows by Analysis 2 that $\partial^\alpha f$ exists and equals $\sum \partial^\alpha \left(\frac{r_i^i}{2^i C_i} H\left(\frac{x - x_i}{r_i}\right) \right)$. □

¹Like in the proof of 2.7

Chapter 3:

Tangent Vectors

3.1 Motivation

Consider the following pictures

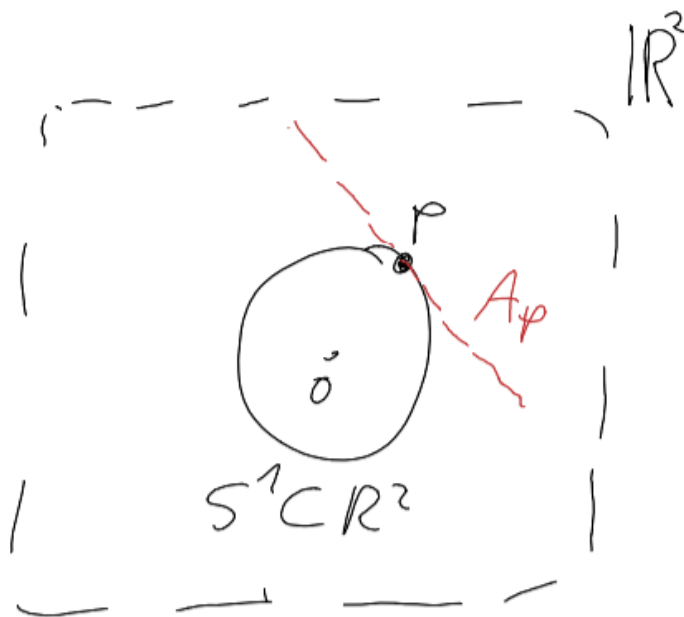


Figure 3.1: Sketch 3.01

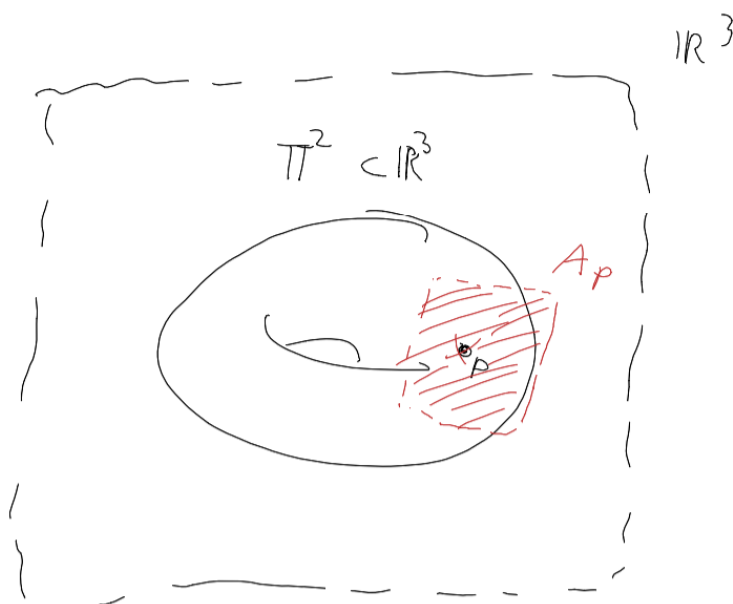


Figure 3.2: Sketch 3.02

A_p the affine hyperplane tangent to $S^1(\Pi^2)$ at the point p . Let $T_p M := A_p - p \subset \mathbb{R}^{n+1}$. This is a vector subspace of \mathbb{R}^{n+1} . It is called the **tangent space of M at p** . Consider

$$TM = \coprod_{p \in M} T_p M,$$

called the **tangent bundle**. Observe that there is a map

$$\pi : TM \rightarrow M$$

by

$$x \in T_p M \mapsto p$$

the data $TM \xrightarrow{\pi}$ forms a **vector bundle**.

Problems with this approach:

- not very intrinsic (depends on $\mathbb{R}^{n+1} \dots$)
- need to prove that manifolds can always be embedded into \mathbb{R}^N

This is really the picture / intuition we should have, but we will construct it in a different way.

3.2 Two (equivalent) theories of tangent vectors

3.2.1 Definition via equivalence classes of smooth curves

Let M be a smooth manifold. Fix $p \in M$.

Definition. The **tangent space** of M at p denoted by $T_p M$ is the set of equivalence classes of smooth curves $\gamma : [-\epsilon, \epsilon] \rightarrow M, \gamma(0) = p$ with $\gamma_1 \sim \gamma_2 \iff$ for any smooth function f defined near^a p , we have $(f \circ \gamma_1)'(0) = (f \circ \gamma_2)'(0)$. Here the $\epsilon > 0$ is any positive real number, which depends on γ .

^ain a neighborhood of

Think of π as a map of $p, T_p M$

I could not quite make out what he called this chapter, so I named it according to [3]

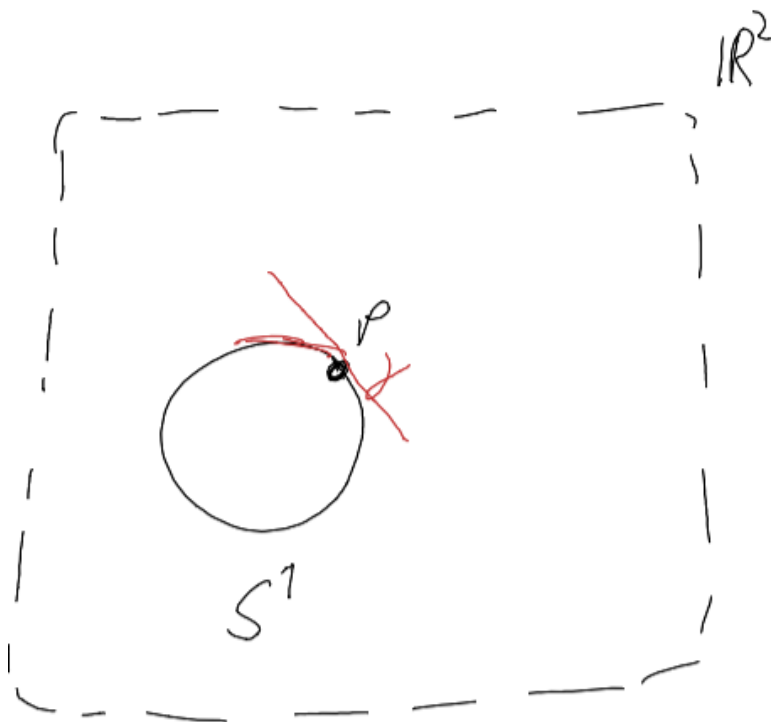


Figure 3.3: Sketch 3.03

Definition. Given a smooth map $F : M \rightarrow N$, let

$$dF_p : T_p M \rightarrow T_{F(p)} N$$

be given by

$$[\gamma] \mapsto [F \circ \gamma].$$

This map dF_p is called the **differential of F at p** .

This is clearly well defined

Remark. The map is also called the **tangent map of M at p** and the **total derivative**. It is also denoted by

$$DF_p, TF_p, \nabla F_p, F'_p, DF(p), TF(p), \dots$$

Lemma 3.1 (Fundamentality of the differential). Let $F^1 : M_1 \rightarrow M_2$, $F^2 : M_2 \rightarrow M_3$ smooth. Then:

$$(i) \quad dF_{F^1(p)}^2 \circ dF_p^1 = d(F^2 \circ F^1)_p$$

$$(ii) \quad \text{If } F : M \rightarrow M \text{ is the identity, then } dF_p = id$$

Proof. Exercise. □

Lemma 3.2. Let $\gamma : [-\epsilon, \epsilon] \rightarrow \mathbb{R}^n$ and $\sigma : (-\delta, \delta) \rightarrow \mathbb{R}^n$ with $\gamma(0) = \sigma(0) = p \in \mathbb{R}^n$. Then $\gamma \sim \sigma \iff \underbrace{\gamma'(0)}_{(\gamma'_1(0), \dots, \gamma'_n(0)) \in \mathbb{R}^n} = \sigma'(0)$

Proof. By abusive notation, we denote by x_i the map $\mathbb{R}^n \rightarrow \mathbb{R}, (x_1, \dots, x_n) \mapsto x_i$. If $\gamma \sim \sigma$, then $\gamma^{i'}(0) = (x_i \circ \gamma)'(0) \stackrel{\text{Def.}}{=} (x_i \circ \sigma)'(0) = \sigma^{i'}(0) \implies \gamma'(0) = \sigma'(0)$.

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x^i might be better (in the sense of the dual space), but x_i is used in practice

Conversely, suppose $\sigma'(0) = \gamma'(0)$. Given any f smooth defined near p , we have

$$\begin{aligned} (f \circ \gamma)'(0) &= (\partial_{x_1} f(p), \dots, \partial_{x_n} f(p)) \cdot (\gamma^{1'}(0), \dots, \gamma^{n'}(0)) \\ &= (\partial_{x_1} f(p), \dots, \partial_{x_n} f(p)) \cdot (\sigma^{1'}(0), \dots, \sigma^{n'}(0)) \\ &= (f \circ \sigma)'(0). \end{aligned}$$

□

Corollary 3.3. *Let V be a finite dimensional \mathbb{R} vector space. Then, for any $p \in V$, the canonical map*

$$\begin{aligned} V &\rightarrow T_p V \\ w &\mapsto [t \mapsto p + tw] \end{aligned}$$

is a bijection.

Proof. If $V = \mathbb{R}^n$, then this is immediate from lemma 3.2. In general pick a basis to define an isomorphism¹ $F : V \rightarrow \mathbb{R}^n$. Then the following diagram commutes:

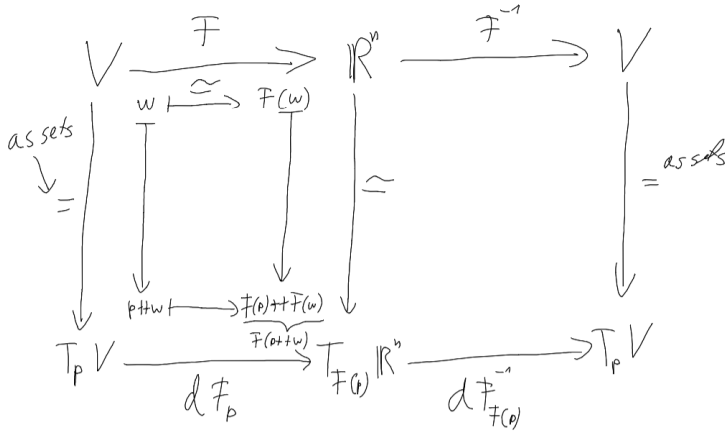


Figure 3.4: Sketch 3.04

using lemma 3.1.

□

3.2.2 Definition via derivations

Definition. Let M be a smooth manifold. A derivation at $p \in M$ is a linear map

$$\nu : C^\infty(M) \rightarrow \mathbb{R}$$

satisfying the property

$$\nu(fg) = f(p)\nu(g) + \nu(f)g(p), \quad (1)$$

which is also called the Leibniz rule.

Remark. Here $C^\infty(M)$ is the set of smooth functions from $f : M \rightarrow \mathbb{R}$. It is naturally an \mathbb{R} -vector space. Similarly we have $C^0(M)$ the space of continuous functions $f : M \rightarrow \mathbb{R}$ and $C^k(M)$ the space of k -times differentiable function $f : M \rightarrow \mathbb{R}$.

Definition. The set of derivations at p shall be also called the tangent space of M at p , denoted by $T_p M$.

Lemma 3.4. $T_p M$ is naturally a vector subspace of $C^\infty(M)^\vee$

$C^\infty(M)^\vee$ denotes the dual space of $C^\infty(M)$

¹In particular a diffeomorphism

Proof. Given derivations $\nu_1, \nu_2 \in T_p M$ we must show that $a\nu_1 + \nu_2$ is still an element of $T_p M \forall a \in \mathbb{R}$. We compute we compute

$$\begin{aligned} (a\nu_1 + \nu_2)(fg) &= a\nu_1(fg) + \nu_2(fg) = a[\nu_1(f)g(p) + f(p)\nu_1(g)] + [\nu_2(f)g(p) + f(p)\nu_2(g)] \\ &= f(p)[a\nu_1 + \nu_2] + [a\nu_1 + \nu_2](f)g(p) \end{aligned} \quad \square$$

Definition. Given a smooth map $F : M \rightarrow N$, we let $dF_p : T_p M \rightarrow T_{F(p)} N$ be the map

$$\nu \mapsto dF_p(\nu) := C^\infty(N) \ni f \mapsto \nu(f \circ F)$$

Lemma 3.5. (i) the previous definition gives a derivation

$$(ii) \quad dF_{F^{-1}(p)}^2 \circ dF_p^1 = d(F^2 \circ F^1)_p$$

(iii) If $F : M \rightarrow M$ is the identity, then $dF_p = id$

By (ii) and (iii) d is a Functor

Lemma 3.6. Let ν be a derivation at $p \in M$. Then

(a) $f \equiv C$, then $\nu(f) = 0$. That is ν annihilates constant functions.

(b) if $f(p) = g(p) = 0$, then $\nu(fg) = 0$

Proof. (a): Since ν is linear, it is enough to prove $\nu(f) = 0$ for $f \equiv 1$. But then

$$\nu(f) = \nu(f^2) = f(p)\nu(f) + \nu(f)f(p) = 2\nu(f).$$

(b) is obvious by the Leibniz rule (1). \square

Lemma 3.7. Let V be a finite dimensional vector space over \mathbb{R} . A derivation $\nu \in T_p V$ is entirely determined by its action on any dual basis $\{\xi^1, \dots, \xi^n\}$.

This should remind us of lemma 3.2

Proof. Fix a basis $\{e_1, \dots, e_n\}$ to identify $V \equiv \mathbb{R}^n$. It is enough to show that $\nu(f) = 0$ if $\{\partial_{x_1} f(p), \dots, \partial_{x_n} f(p)\}$ all vanish (Indeed, consider $f \rightarrow f - \sum_{k=1}^n \partial_{x_k} f(p) \xi_k$). By Taylor's formula (Appendix C.15, Lee), we have

with $\xi_i : \mathbb{R}^n \rightarrow \mathbb{R}$ as before

$$f(x) = \underbrace{f(p)}_{\text{constant}} + \underbrace{\sum_{i=1}^n \partial_{x_i} f(p)(x_i - p_i)}_{=0} + \sum_{i,j=1}^n \underbrace{\left(\underbrace{x_i - p_i}_{\text{constant at } p} \right) \left(\underbrace{x_j - p_j}_{\text{constant at } p} \right)}_{\text{constant at } p} \int_0^1 (1-t) \partial_{x_i x_j} f(p + t(x-p)) dt.$$

Then by lemma 3.6 $\nu(f) = 0$. \square

Corollary 3.8. The canonical map $V \rightarrow T_p V$, $p \in V$ defined by

$$w \mapsto (C^\infty(V) \ni f \mapsto \frac{d}{dt} \Big|_{t=0} f(p + tw))$$

is an isomorphism of vector spaces.

This should remind us of corollary 3.3
These are really canonically equal! No choice needed

Proof. We define

$$\begin{aligned} T_p V &\rightarrow V \\ \nu &\mapsto \sum_{i=1}^n \nu(\xi^i) e_i, \xi^i : V \rightarrow \mathbb{R} \end{aligned}$$

By lemma 3.7 this map is injective and hence $\dim T_p V \leq \dim V$. So it is enough to show that $V \mapsto T_p V$ is also injective. Suppose for contradiction that $V \ni w \neq 0$, that maps to the zero derivation.

$$\begin{aligned} 0 &= \frac{d}{dt} \Big|_{t=0} f(p + tw) \forall f \\ \implies 0 &= \frac{d}{dt} w^\vee(p + tw) = \frac{d}{dt} \Big|_{t=0} t = 1 \end{aligned} \quad \square$$

3.2.3 Both definitions agree

Temporary notation: Let $T_p M^{(1)}, dF_p^{(1)}, \dots$, be those objects defined in section 3.2.1 and $T_p M^{(2)}, dF_p^{(2)}, \dots$, the analogous objects defined in 3.2.2

Key observation: There is a **canonical** map, for any $p \in M$,

$$K_p : T_p M^{(1)} \rightarrow T_p M^{(2)}$$

$$\gamma \mapsto (C^\infty(M) \ni f \mapsto (f \circ \gamma)'(0)).$$

Note that this commutes with $dF^{(i)}$, i.e. $dF^{(2)} \circ K_p = K_{F^{(1)}(p)} \circ dF_p^{(1)}$ (exercise).

Proposition 3.9. K_p is a bijection.

Proof. Choose a chart $(U, \varphi), p \in U$. Then we have a map

$$U \rightarrow \varphi(U) \subset \mathbb{R}^n$$

Figure 3.5: Sketch 3.05

Finally, we have

Figure 3.6: Sketch 3.06

□

3.3 Coordinates

Definition. (1) Given a point $p \in \mathbb{R}^n$ let $(\partial_{x_i})_p \in T_p \mathbb{R}^n$ be the vector represented by the curve $t \mapsto p + t \underbrace{(0, \dots, 1, \dots, 0)}_{e_i}$.

(2) Given $p \in M$, we shall abuse notation by writing $(\partial_{x_i})_p := d\varphi_p^{-1}(\partial_{x_i})_p$ for some chart $((U, \phi))$

Remark. 1. Various authors also write $\partial_{x_i}(p)$

2. $\{(\partial_{x_1})_p, \dots, (\partial_{x_n})_p\}$ form a basis for $T_p M$, by construction

3. $\{\partial_{x_1}, \dots, \partial_{x_n}\}$ very much depend on the chart (U, φ)

Suppose now that $F : M \rightarrow N$ smooth map. Let $(U, \varphi), (V, \psi)$ be charts, $F(U) \subset V$. Let $\hat{p} := \phi(p) \in \mathbb{R}^m$. Then we have

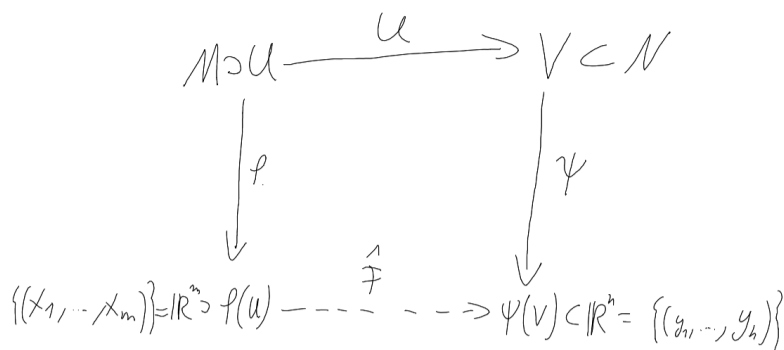


Figure 3.7: Sketch 3.07

where $\hat{F} = \psi \circ F \circ \varphi^{-1}$.

Note that $d\hat{F}_{\hat{p}} : T_{\hat{p}} \mathbb{R}^m \rightarrow T_{\hat{F}(\hat{p})} \mathbb{R}^n$ is a linear map. We want to find an expression of the matrix $d\hat{F}_{\hat{p}}$ w.r.t the basis $\{\partial_{x_1}, \dots, \partial_{x_m}\}$ and $\{\partial_{y_1}, \dots, \partial_{y_h}\}$.

Well, by definition

$$\begin{aligned} d\hat{F}_{\hat{p}}((\partial_{x_i})_{\hat{p}}) &:= [\hat{F}(\hat{p} + (0, \dots, 1, 0, \dots, 0))] \\ &= \sum_{j=1}^n \partial_{x_i} F^j(\hat{p}) (\partial_{y_j})_{\hat{F}(\hat{p})} \end{aligned}$$

and therefore

$$d\hat{F}_{\hat{p}} = \begin{pmatrix} \partial_{x_1} \hat{F}^1(\hat{p}) & \dots & \partial_{x_m} \hat{F}^1(\hat{p}) \\ \vdots & & \vdots \\ \partial_{x_1} \hat{F}^n(\hat{p}) & \dots & \partial_{x_m} \hat{F}^n(\hat{p}) \end{pmatrix}.$$

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Remark. By abuse of notation we often write $F \equiv \hat{F}, p \equiv \hat{p}, \partial_{x_i} f \equiv \partial_{x_i} \hat{F}, dF_p \equiv d\hat{F}_{\hat{p}}$

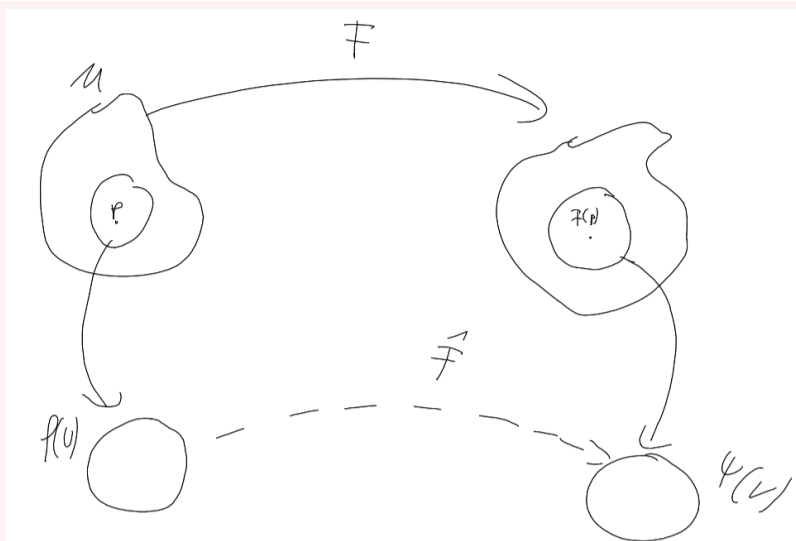


Figure 3.8: Sketch 3.08

Remark. $d\hat{F} : \underbrace{x}_{\in \phi(U) \subset \mathbb{R}^m} \mapsto d\hat{F}_x \in \text{Mat}(n \times m) \equiv \mathbb{R}^{n \times m}$. This is clearly a smooth map.

3.4 The tangent bundle

Definition. Given a smooth manifold M , let $TM := \coprod_{p \in M} T_p M$. We write elements of TM as pairs (p, v) , where $v \in T_p M$. Note that we have a map

$$\pi : TM \rightarrow M, (p, v) \mapsto p.$$

Remark (Added by Manuel, was an answer to my question). For $p \in M$ the preimage of p under π is called a **fiber**. He also highlighted, the condition that $\pi^{-1}(p)$ is a vector space (namely $T_p M$), which seems to be important in our context, but not generally required for fibers.

A priori, TM is just a set. We will exhibit natural smooth manifold structure.

Special case: $M \subset U \subset \mathbb{R}^n$. Then

$$TU := \coprod_{p \in U} T_p U \equiv U \times \mathbb{R}^n$$

$$(t \mapsto p + tv) \mapsto (p, v)$$

General construction Given a smooth chart (U, ϕ) for a smooth manifold M , we have a map $d\phi$

Remember that this is a canonical identification!

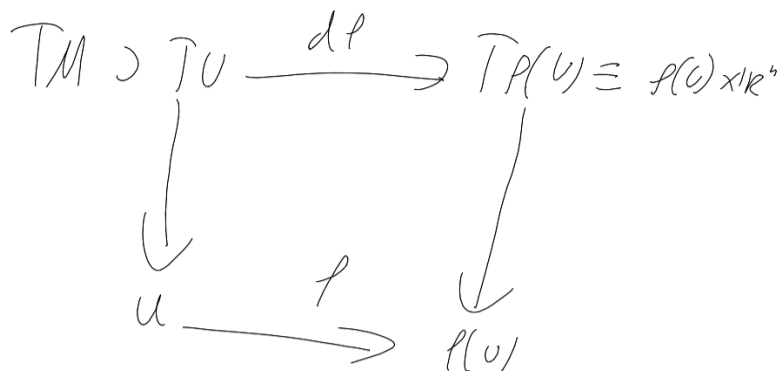


Figure 3.9: Sketch 3.09

where

$$d\phi(p, v) := (\phi(p), d\phi_p(v)).$$

Define a subset $S \subset TM$ to be open, if, for any chart U, ϕ , $d\phi(S \cap TU)$ open in $T\phi(U) \equiv \phi(U) \times \mathbb{R}^n$.

This is a pullback

Lemma 3.10. *This prescription defines a topological space on TM . Moreover, TM is a topological manifold.*

Proof. Omitted. Check transition maps

$$d\psi \circ d\phi^{-1} : \phi(U \cap V) \times \mathbb{R}^n \rightarrow \psi(U \cap V) \times \mathbb{R}^n$$

is it an elementary, but tedious proof. \square

Remark. *Alternatively define the same topology on TM by taking the basis the union over all charts (U, ϕ) in your atlas of $\{d\phi^{-1}(V) \mid V \subset T(\psi(U)) \text{ open}\}$.*

To make TM into a **smooth** manifold, we take as our atlas the set $\{(TU, d\phi)\}_{(U, \phi)}$, where (U, ϕ) runs over the smooth charts of M .

Lemma 3.11. *this is a smooth atlas.*

Proof. Fix charts $(U, \phi), (V, \psi)$. Then the transition functions take the form

$$\begin{array}{ccc} (x, v) & \xrightarrow{\quad} & (\psi \circ \phi^{-1}(x), d(\psi \circ \phi^{-1})_x(v)) \\ \downarrow & & \downarrow \\ \phi(U \cap V) & \xrightarrow{\psi \circ \phi^{-1}} & \psi(U \cap V) \end{array}$$

Figure 3.10: Sketch 3.11

Check if both components are smooth:

- The first component $x \mapsto \psi \circ \phi^{-1}(x)$ is smooth, since M is a smooth manifold and $(U, \phi), (V, \psi)$ are smooth
- For the second component can be fractured as follows:

$$(x, v) \mapsto (d(\underbrace{\psi \circ \phi^{-1}}_{\in \text{Man}(n \times n) \cong \mathbb{R}^{2n}}, v)) \mapsto d(\psi \circ \phi^{-1})_x v$$

Exercise: the map $\text{Mat}(m \times n) \times \text{Mat}(n \times p) \rightarrow \text{Mat}(m \times p)$ by $A, B \mapsto AB$ is smooth. \square

Remark. *We will see later that $(\phi : TM \rightarrow M)$ forms a vector bundle. It can be shown that given $F : M \rightarrow N$ the map $dF : TM \rightarrow TN, (p, v) \mapsto (F(p), dF_p(v))$ is smooth.. In fact, we have*

Since we can write the second component as a concatenation of maps, it is smooth

This is the exact same computation as in the proof of lemma 3.11



Figure 3.11: Sketch 3.12

commutes. This can be restated as follows: There is a functor $\text{Man}^\infty \rightarrow \text{Smooth vector bundles}$ by

$$M \mapsto (\pi : TM \rightarrow M)$$

$$F : M \rightarrow N \mapsto dF : TM \rightarrow TN$$

Chapter 4:

Submersions, immersions and embeddings

4.1 Basic definitions

Definition. Let $F : M \rightarrow N$ be smooth. The rank of F at $p \in M$ is the rank of the linear map $dF_p : T_p M \rightarrow T_{F(p)} N$.

Smooth maps, which have full rank (highest possible rank, i.e. $\text{rank} F = \max(m, n)$) are particularly important:

Definition. Let $F : M^m \rightarrow N^n$ be smooth. We say

- F is a submersion if dF_p is surjective, for all $p \in M$ ($m \geq n$)
- F is an immersion if dF_p is injective, for all $p \in M$ ($m \leq n$)

M^m, N^n means M, N are m, n dimensional manifolds

Lemma 4.1. Given $(m, n) \in \mathbb{N}_+ \times \mathbb{N}_+$, let $\text{Mat}(m \times n) \equiv \mathbb{R}^{m \times n}$. The subset $\text{Mat}(m \times n)^{\text{full rank}} := \{A \in \text{Mat}(m \times n) \mid A \text{ has full rank}\}$ is open in $\text{Mat}(m \times n)$.

Proof. Fix $M \in \text{Mat}(m \times n)^{\text{full rank}}$. Without loss of generality $m \leq n$, otherwise apply $\text{Mat}(m \times n) \rightarrow \text{Mat}(n \times m), A \mapsto A^T$. By definition there exists a submatrix M' , obtained by deleting $n - m$ columns, which is invertible. Now the map

$$\text{Mat}(m \times n) \xrightarrow{F: M \mapsto M'} \text{Mat}(m \times m) \xrightarrow{\det(\cdot)} \mathbb{R}$$

is continuous, since both the forgetful F and \det is smooth.

$$M \in (\det \circ F)^{-1}(\underbrace{\mathbb{R} \setminus \{0\}}_{\text{open}}) \subset \text{Mat}(m \times n)^{\text{full rank}}$$

since M was arbitrary this completes the proof.

M is fixed and F depends on M , but it does not matter here!

4.00

$$\underbrace{\begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 0 \end{pmatrix}}_M \xrightarrow{F: M \mapsto M'} \underbrace{\begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}}_{M'} \xrightarrow{\det(\cdot)} 1 \in \mathbb{R}$$

Figure 4.1: Sketch 4.00

□

Lemma 4.2. Fix $F : M^m \rightarrow N^n, p \in M$.

1. If dF_p is injective, then there exists a neighborhood of p on which dF is injective.
2. If dF_p is surjective, then there exists a neighborhood of p on which dF is surjective.

The property of full rank is stable under small perturbation!

Proof. This is a local statement. We can therefore assume that M, N are open subsets of $\mathbb{R}^m, \mathbb{R}^n$ respectively. Then

$$dF_{(\cdot)} : M \rightarrow \text{Mat}(n \times m)$$

is smooth, hence continuous. By assumption $dF_p \in \text{Mat}(n \times m)^{\text{full rank}}$. But $\text{Mat}(n \times m)^{\text{full rank}}$, so the preimage is open (by lemma 4.1) and contains p . □

Remark.

1. If $F : M \rightarrow N$ is both an immersion and a submersion, then we say that F is a **local diffeomorphism**. We will see (by the rank theorem 4.3) that F is a local diffeomorphism $\iff \forall p \in M \exists p \in U : F|_U$ is a diffeomorphism.
2. be warned. local diffeomorphism need not be global:

important: contains both a definition and a counterexample!

$$\begin{aligned} \mathbb{R}^2 \equiv \mathbb{C} \supset S^1 = \{|z| = 1\} &\rightarrow S^1 \\ (x, y) \mapsto x + iy & \quad z \longmapsto z^2 \end{aligned}$$

Definition. An immersion is an **embedding** if it is a homeomorphism onto its image with the subspace topology.



Figure 4.2: Sketch 4.01

Example. Another example:

$$S^n = \{(x_0, \dots, x_n) \in \mathbb{R}^{1+n} \mid \sum x_i^2 = 1\} \subset \mathbb{R}^{1+n}$$

with

$$i : S^n \hookrightarrow \mathbb{R}^{1+n}$$

Non-examples

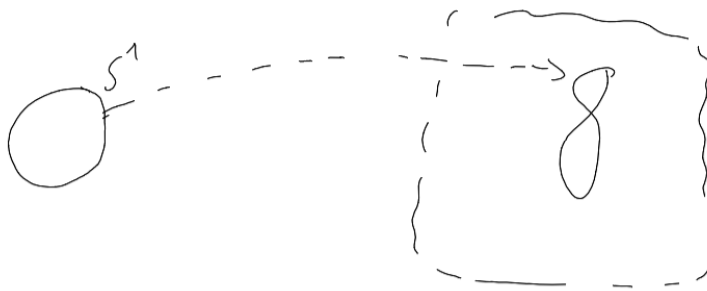


Figure 4.3: Sketch 4.02

parametrized by

$$t \mapsto (\sin t, \sin 2t)$$

and

$$\begin{aligned} \mathbb{R} &\mapsto \mathbb{R}^2/\mathbb{Z}^2 = S^1 \times S^1 \\ t &\mapsto (t, \alpha t), \quad \alpha \in \mathbb{R} \setminus \mathbb{Q} \end{aligned}$$

Can show¹ that the image is dense. It is an immersion, but not a homeomorphism!

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4.2 The rank theorem

Theorem 4.3 (rank theorem). *Let $F : M^m \rightarrow N^n$ be a smooth map of constant rank r . For each $p \in M$, there exist charts $(U, \varphi) : p \in U$ and $(V, \psi) : F(U) \subset V$, such that*

$$\hat{F} := \psi \circ F \circ \varphi^{-1} :$$

Figure 4.4: Sketch 4.03
 \hat{F} takes the form

$$\hat{F}(x_1, \dots, x_r, x_{r+1}, \dots, x_m) = (x_1, \dots, x_r, 0, \dots, 0)$$

This is arguably the most important result of the first half of the course. There is a lot of results in [2], what is actually useful? Implied answer: Rank theorem

Remark. By lemma 4.2, if F has full rank at $p \in M$, then

- if $m = r \geq n$, then F is an submersion near p and

$$\hat{F}(x_1, \dots, x_n, x_{n+1}, \dots, x_m) = (x_1, \dots, x_n)$$

- $m = r \leq n$, then F is an immersion near p , and

$$\hat{F}(x_1, \dots, x_m) = (x_1, \dots, x_m, 0, \dots, 0)$$

- $m = n \implies$ up to the diffeomorphism, \hat{F} is just the identity

Up to diffeomorphism there is only one map of constant, full, rank

Remark. This theorem is a non-linear generalization of the following linear algebra fact: $L : V^m \rightarrow W^n$, then there are linear maps $\varphi : V^m \xrightarrow{\sim} \mathbb{R}^m, \psi : W^n \xrightarrow{\sim} \mathbb{R}^n$, such that $\hat{L} := \psi \circ L \circ \varphi^{-1}$ takes the form

$$\hat{L}(x_1, \dots, x_r, x_{r+1}, \dots, x_m) = (x_1, \dots, x_r, 0, \dots, 0),$$

where $r = \text{rank}(L)$.

¹not obvious, non-examable

Proof of theorem 4.3. Step 0: We might as well assume that $M = U \subset \mathbb{R}^m, N = V \subset \mathbb{R}^n$, since we only make a local statement up to diffeomorphism. We may also assume, up to reordering the coordinates, that the matrix $(\partial_{x_i} F^j(p))_{1 \leq i, j \leq r}$ is invertible for $p \in U$. We label our coordinates:

$$(x_1, \dots, x_r, y_1, \dots, y_{m-r})$$

see [2]

source coordinates in U

$$(v_1, \dots, v_r, \dots, w_1, \dots, w_{n-r})$$

Target coordinates

and wlog $F(0, 0) = (0, 0)$.

We write $F(x, y) = \underbrace{Q(x, y)}_{v\text{-coordinates}}, \underbrace{R(x, y)}_{w\text{-coordinates}}$. Notice that $(\partial_{x_i} Q^j)$ is non-singular.

Step 1: Define $\varphi : U \rightarrow \mathbb{R}^m, \varphi(x, y) = (Q(x, y), y)$. Then

$$d\varphi_{(0,0)} = \begin{pmatrix} \underbrace{\partial_{x_i} Q^j}_{\in \text{Mat}(r \times r)} & \partial_{y_i} Q^j \\ 0 & \underbrace{1}_{\in \text{Mat}((n-r) \times (n-r))} \end{pmatrix}$$

\Rightarrow by the inverse function theorem, there exist connected neighborhoods $U_0 \subset U, \tilde{U}_0 \subset \text{Mat}((n-r) \times (n-r)) \cap \varphi(U)$, such that $\varphi|_{U_0} : U_0 \rightarrow \tilde{U}_0$. We may as well assume that \tilde{U}_0 is a cube, i.e. $(-\epsilon, \epsilon)^n$.

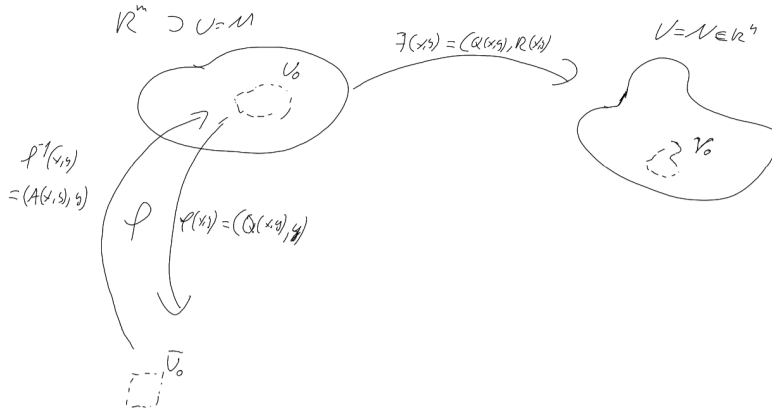


Figure 4.5: Sketch 4.04

While $\varphi^{-1}(x, y) = (A(x, y), B(x, y))$, for some $A : \tilde{U}_0 \rightarrow \mathbb{R}^r, B : \tilde{U}_0 \rightarrow \mathbb{R}^{m-r}$. We compute

$$(x, y) = \varphi \circ \varphi^{-1}(x, y) = \varphi(A(x, y), B(x, y)) = (Q(A(x, y), B(x, y)), B(x, y)) \Rightarrow \begin{matrix} x = Q(A(x, y), B(x, y)) \\ y = B(x, y) \end{matrix}$$

Hence $\varphi^{-1}(x, y) = (A(x, y), y)$.

Step 2: Observe that

$$F \circ \varphi^{-1}(x, y) = (Q(\varphi^{-1}(x, y)), R(\varphi^{-1}(x, y))) = (x, \tilde{R}(x, y)),$$

where

$$\tilde{R}(x, y) = R(\varphi^{-1}(x, y)).$$

Then

$$d(F \circ \varphi^{-1}) = \begin{pmatrix} \underbrace{\partial_{x_i} \tilde{R}^j}_{\in \text{Mat}(r \times r)} & 0 \\ \partial_{y_i} \tilde{R}^j & \end{pmatrix}$$

But the rank of $d(F \circ \varphi^{-1})$ is r , because φ^{-1} is a diffeomorphism and F has rank r

- Since $1_{r \times r}$ has rank r , we must have $\partial_{y_i} \tilde{R} \equiv 0$

We write $S(x) := \tilde{R}(x, y)$, we now have

$$F \circ \varphi^{-1}(x, y) = (x, S(x)) \quad (1)$$

Step 3: Recall

$$\begin{aligned} F : U &\rightarrow V \subset \mathbb{R}^n \\ F(0, 0) &= (0, 0) \end{aligned}$$

Let $V_0 \subset V$ be defined as follows:

$$V_0 := \{(v, w) \in V \mid (v, 0) \in \tilde{U}_0\}$$

By (1), $F \circ \varphi^{-1}(\tilde{U}_0) \subset V_0$. Hence $F(U_0) \subset V_0$. Set $\psi : V_0 \rightarrow \mathbb{R}^n$, $\psi(v, w) = (v, w - S(v))$. Clearly ψ is a diffeomorphism, since

$$(v, w) \mapsto (v, w + S(v))$$

is an inverse. $\implies (V_0, \psi)$ is a smooth chart.

$$\hat{F} := \psi \circ F \circ \phi^{-1} = \Psi(x, S(x)) = (x, S(x) - S(x)) = (x, 0) \quad \square$$

Remark. *This is one theorem you should really not forget! If you continue to think about Manifolds in your life, this is really useful! Do not remember the proof, remember the statement!*

to make clear \tilde{R} does not really depend on y

$S(v)$ makes perfect sense, since both x, v have r entries

Chapter 5:

Submanifolds

5.1 Basic definitions

Definition. Let M be a topological manifold. A subset $S \subset M$ is a topological submanifold, if S is a topological manifold with the subspace topology.

Example. $S^n = \{(x_0, \dots, x_n) \mid \sum x_i^2 = 1\} \subset \mathbb{R}^{1+n}$

Example (Non-example). $\{(x, y) \mid x = 0 \vee y = 0\} \subset \mathbb{R}^2$, since this is not a manifold (see sheet 01).

Definition. Let M be a smooth manifold. A topological submanifold $S \subset M$ is a smooth submanifold, if it is equipped with a smooth structure, s.t. the embedding $i : S \hookrightarrow M$ is smooth.

Example. If M is a smooth manifold and $U \subset M$ open, then $U \subset M$ is a smooth manifold.

With the restricted smooth structure of M

Remark. Some authors (including Lee's textbook) use the term embedded submanifold to distinguish from immersed submanifolds. For use “submanifolds” \equiv “embedded submanifold”.

Lemma 5.1. Suppose that $f : M \rightarrow N$ smooth embedding. Let $S := f(M) \subset N$. Then S admits a unique smooth structure making it a smooth submanifold, with the property that f is a diffeomorphism onto its image.

Proof. By definition of f being an embedding, f is a homeomorphism onto its image, with the subspace topology. $\implies S$ is a topological manifold.

We define a smooth atlas on S by taking $\{(f(U), \varphi \circ f^{-1})\}$, as (U, φ) ranges over the set of charts for M .

Clearly f is a diffeomorphism, since $\varphi \circ f \circ f^{-1} \circ \psi^{-1}$, for $(U, \varphi), (V, \psi)$ smooth charts, this follows from the fact that $(U, \varphi), (V, \psi)$ are smoothly compatible on M .

This is the only smooth atlas with the property that f is a diffeomorphism, if \mathcal{B} is another such atlas, then the fact that f is a diffeomorphism for $(S, \mathcal{B}) \iff (S, \mathcal{A})$ compatible.

Finally

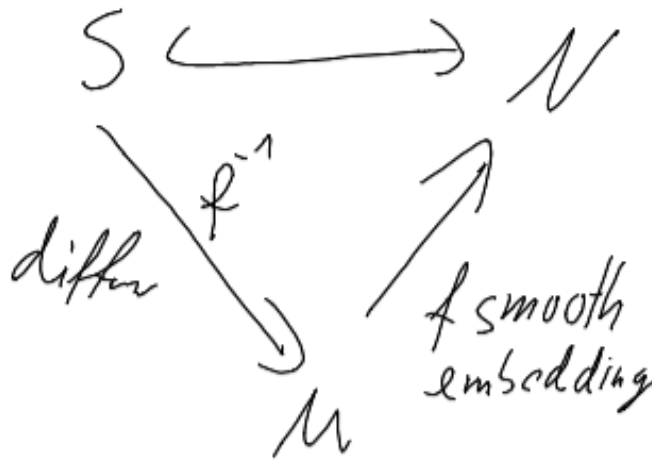


Figure 5.1: Sketch 5.01

so i is a smooth embedding. □

Definition. A embedded submanifold S is called properly embedded, if the inclusion map $i \hookrightarrow N$ is proper (i.e. the preimage of a compact set is compact).

Example. $S^n \hookrightarrow \mathbb{R}^{n+1}$ properly embedded.

Example (Non-example). $S^n \setminus \{pt\} \subset \mathbb{R}^{n+1}$

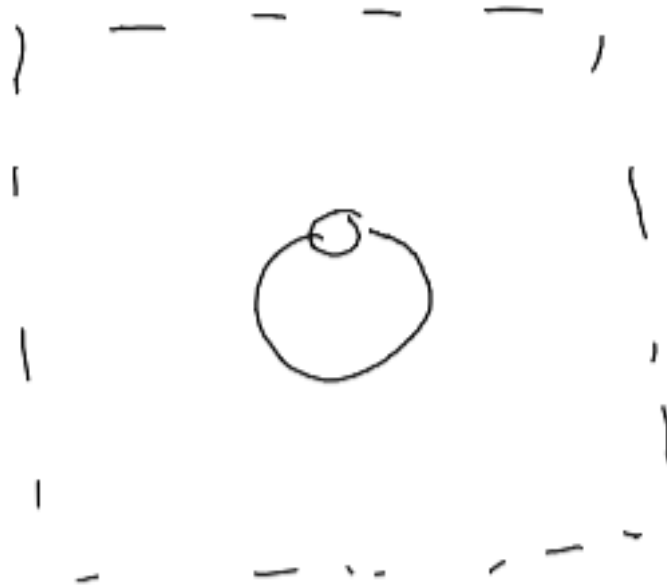


Figure 5.2: Sketch 5.02

Lemma 5.2. A topological submanifold $S \subset N$ is properly embedded iff S is closed.

Proof. Exercise.

□ Elementary exercise in point set topology

5.2 The “slice lemma”

Theorem 5.3 (Slice lemma^a). (a) Suppose $S^k \subset M^n$ is a submanifold of codimension $n - k$. Then, for all $p \in S$, there exists a chart $(V, \psi), p \in U \subset N$, such that

$$\psi(V \cap S) = \{(x_1, \dots, x_k, x_{k+1}, \dots, x_n) \in \psi(V) \mid x_{k+1} = c_{k+1}, \dots, x_n = c_n\}.$$

this is also a definition of codimension:
 $\dim M - \dim S$



Figure 5.3: Sketch 5.03

(b) Suppose that $S \subset N$ is a subset with the property that, for all $p \in S$, there exists a slice chart $(V, \psi), p \in V \subset N$, such that

$$\psi(V \cap S) = \{(x_1, \dots, x_k, x_{k+1}, \dots, x_n) \in \psi(V) \mid x_{k+1} = c_{k+1}, \dots, x_n = c_n\},$$

then S admits a smooth manifold structure making it a smooth submanifold of N .

^aLee [2] calls it a theorem

Start of lecture 10
 (12.11.2024)
 The converse of (a)

Remark. • We get an equivalent theorem by requiring $c_{k+1} = \dots = c_n = 0$

- Part (b) of theorem 5.3 tells us, that being a smooth submanifold $S \subset N$ of ambient smooth manifold N is a property property of the subset. It suffices to check, pointwise, the local property described above!

Proof. (a): By assumption $S \hookrightarrow N$ is an immersion. By theorem 4.3 (rank theorem), there exists charts $(\bar{U}, \varphi), (V, \psi)$ such that $i(U) \subset V$ and

$$\begin{aligned} \hat{i} &= \psi \circ i \circ \varphi^{-1} : \varphi(U) \rightarrow \psi(V) \\ (x_1, \dots, x_k) &\mapsto (x_1, \dots, x_k, 0, \dots, 0) \end{aligned}$$

Up to shrinking ψ (restricting the image of φ), we find that

$$\psi(V \cap S) = \{(x_1, \dots, x_k, x_{k+1}, \dots, x_n) \mid x_{k+1} = \dots = x_n = 0\}$$

Warning: What can go wrong here? Consider

Locally, all immersions look the same

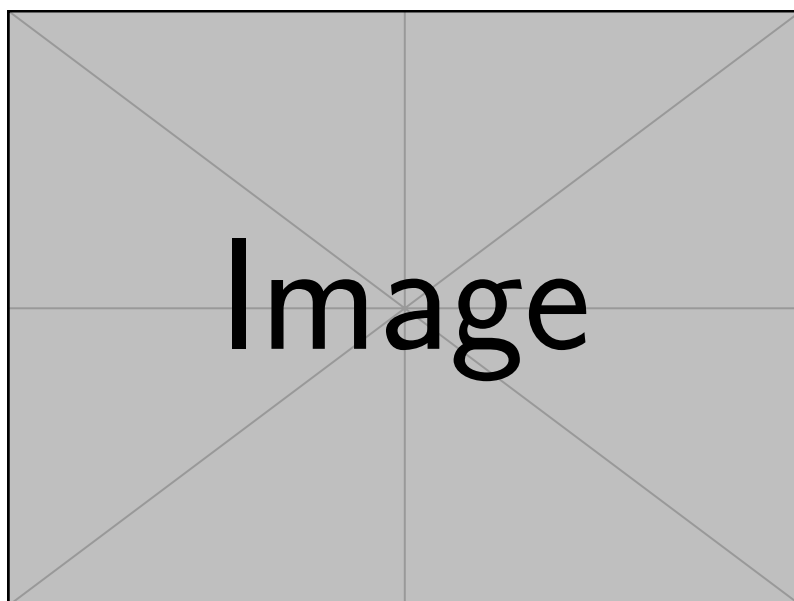


Figure 5.4: Sketch 5.04

Show that there is no more stuff in the set!

(b): We have to check that the local charts given form an atlas. Which is almost a tautology and quite tedious, as we can use $\{S \cap V, \psi|_S\}$ as the atlas. \square

Remark (+Exercise). In section 2.1.2, example 4, we considered $\Phi : \mathbb{R}^{1+n} \rightarrow \mathbb{R}$. We assumed $d\Phi$ is nonzero on the set $\Phi^{-1}(0) \subset \mathbb{R}^{1+n}$. Under this assumption, we proved that $\Phi^{-1}(0)$ is a naturally smooth manifold. Using theorem 5.3 (or by hand) $\Phi^{-1}(0)$ is a smooth submanifold.

A priori, $S \subset N$ could admit multiple smooth structures making it a submanifold. We now seek to show that this is not the case.

Lemma 5.4. Let $S \subset N$ be a submanifold. If $F : M \rightarrow N$ is a smooth map which factors through $S \hookrightarrow N$ as a continuous map, then F is smooth as a map $M \rightarrow S$.

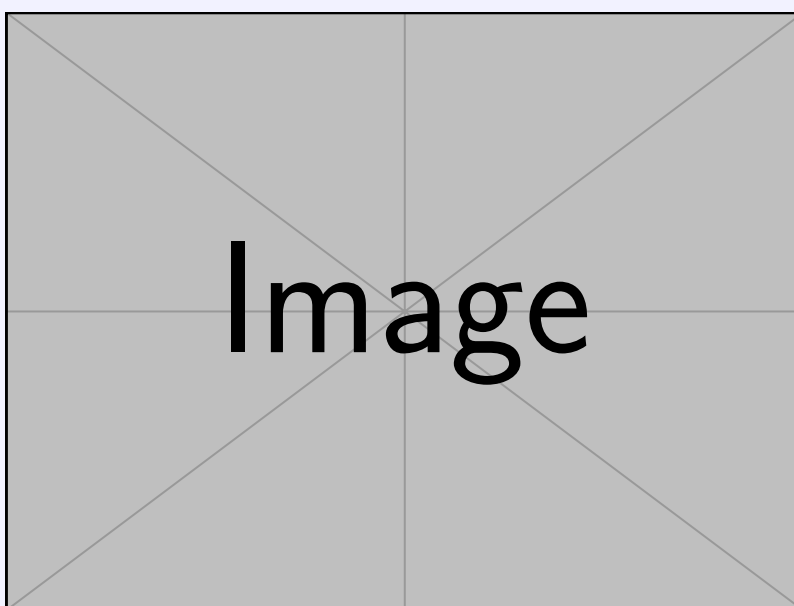
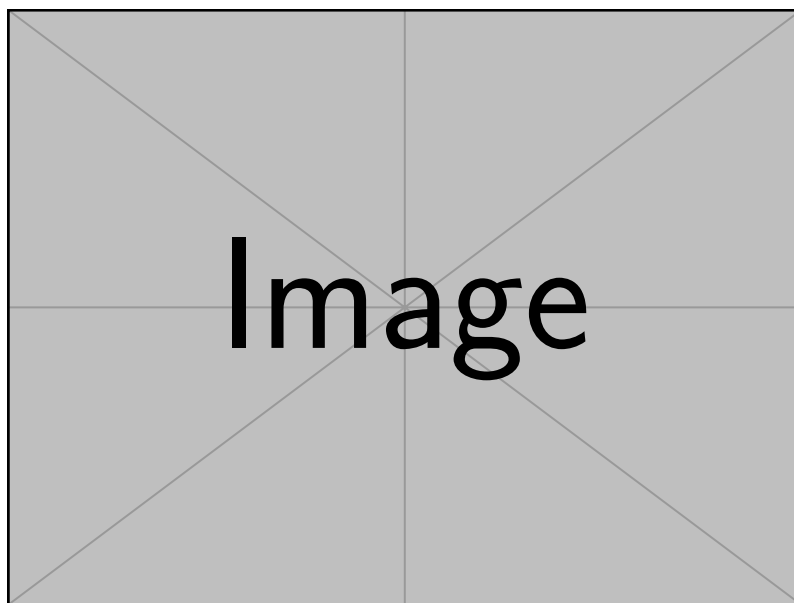


Figure 5.5: Sketch 5.05

Proof. By theorem 5.3, there exists $U \subset S \hookrightarrow N \supset V$



More by the proof of the theorem ...

Figure 5.6: Sketch 5.06

Let us call $\check{F}: M \rightarrow S, \check{F}(x) = F(x)$. Since \check{F} is continuous, $\check{F}^{-1}(U) \subset M$ open. So, we can write, for $(W, u), W \subset \check{F}^{-1}(U)$

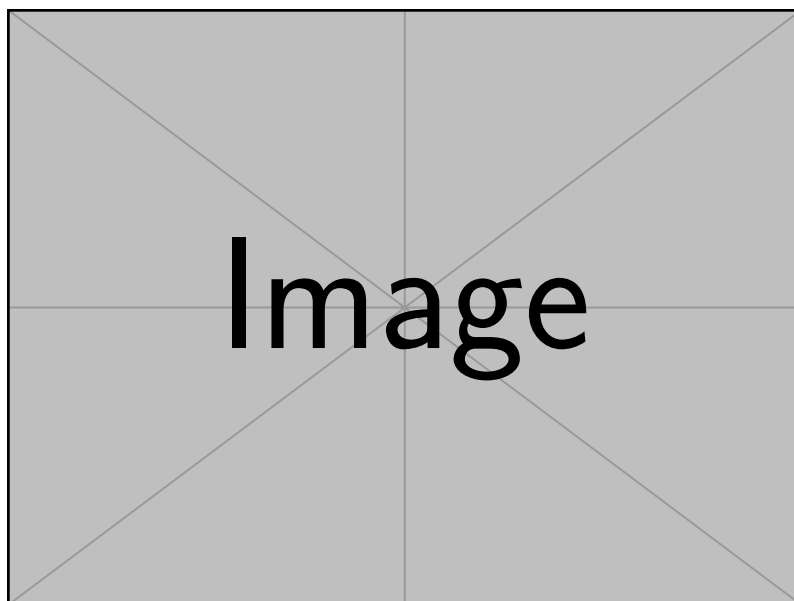


Figure 5.7: Sketch 5.07

were, a priori, \check{F}^i are continuous.

Concatenating the two diagrams, we find that

$F(x_1, \dots, x_m) = i \circ \check{F}(x_1, \dots, x_m) = (\check{F}^1(x_1, \dots, x_m), \dots, \check{F}^k(x_1, \dots, x_m), 0, \dots, 0)$. But then each \check{F}^i has to be smooth and therefore \check{F} is smooth. \square

Lemma 5.5. *Let $S \subset M$ be a subset satisfying the conditions of theorem 5.3 (b), then the smooth structure produced by the theorem is the unique smooth structure, such that $S \hookrightarrow M$ is a smooth submanifold.*

Proof. Let \tilde{S} be a copy of S , but endowed with some possibly different smooth structure s.t. $\tilde{S} \hookrightarrow M$ is an embedding.

$\tilde{S} \hookrightarrow M$ factors through S , so $\tilde{S} \xrightarrow{\text{id}} S$ smooth. Similarly $S \xrightarrow{\text{id}} \tilde{S}$ smooth.

Ergo it is a smooth submanifold of M . This uses lemma 5.4

5.3 The (weak) Whitney embedding theorem

Theorem 5.6 (Whitney). *Every compact n -dimensional smooth manifold admits an embedding into \mathbb{R}^N for $N \gg 1$ large enough.*

Remark. *Later (probably this month), we will remove the compactness assumption and also argue that one can take $N = 2n + 1$.*

Whitney proved that one can take $N = 2n$.

Don't sue him, if he is off by one :)

Added remark. *This is a very philosophically pleasing statement, since we recover our intuition of embedded manifold from the abstract theory. It is also true, that there is only one embedding (up to isotopy).*

Proof of theorem 5.6. Fix a finite cover of M $\{B_1, \dots, B_k\}$, $B_i \subset M$ open. We may as well assume that there exist charts (B'_i, ϕ_i) , $\overline{B'_i} \subset B'_i$, $\phi_i(B'_i) = B_1(0) \subset \mathbb{R}^m$.

Let $\rho_i : M \rightarrow \mathbb{R}$ be a cutoff function for $(\overline{B'_i} \subset B'_i)$, i.e. $\rho_i|_{B_i} \equiv 1$, $\text{supp}(\rho_i) \subset B'_i$, $0 \leq \rho_i \leq 1$. The existence of the ρ_i follows from proposition 2.8.

We now define

$$F : M \rightarrow \mathbb{R}^{mk+k} \\ p \mapsto (\rho_1(p) \underbrace{\varphi_1(p)}_{\in \mathbb{R}^m}, \dots, \rho_k(p) \varphi_k(p), \rho_1(p), \dots, \rho_k(p))$$

Notice the k comes from compactness, i.e. we have no control over it, as it its non-constructive

We will now see that F is an embedding. First, we will argue F is an injective immersion.

If $F(p) = F(q) \implies \rho_i(p) = \rho_i(q) \forall i = 1, \dots, k$. Let i_0 be such that $p \in B_{i_0}$. Then

$\rho_{i_0}(p) = 1 = \rho_{i_0}(q) \implies q \in \text{supp}(\rho_{i_0}) \subset B'_{i_0}$. But now

$\underbrace{\varphi_{i_0}(p)}_{\in \mathbb{R}^m} = \rho_{i_0}(p) \varphi_{i_0}(p) = \rho_{i_0}(q) \varphi_{i_0}(q) = \varphi_{i_0}(q)$. Hence $p, q \in B'_{i_0} \implies p = q$.

F is an immersion: Choose $p \in M$. Then $p \in B_{i_0}$, for some i_0 . Hence $\rho_{i_0} \equiv 1$ for some neighborhood of p .

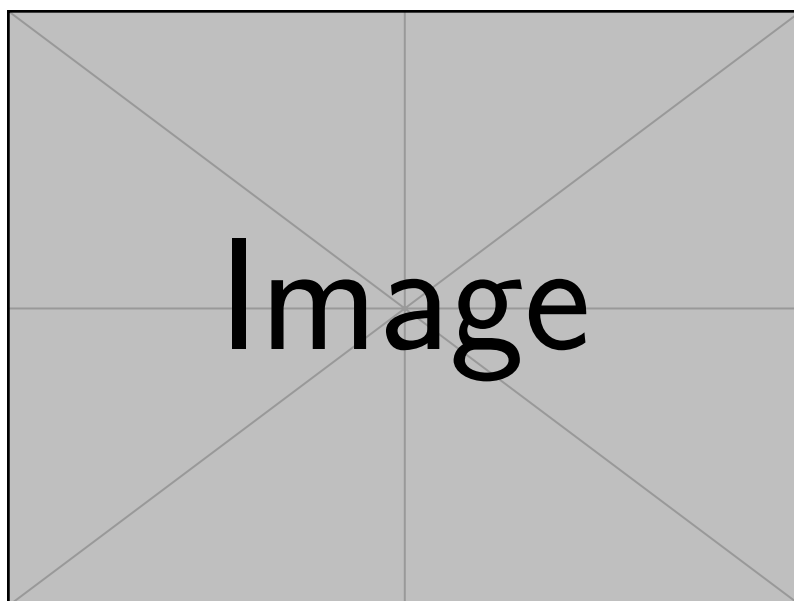


Figure 5.8: Sketch 5.08

Hence $d(\rho_{i_0}\varphi_{i_0}) = \underbrace{d\rho_{i_0}}_{\text{invertible } m \times m}$ near $p \implies dF$ is injective near p , but p was arbitrary.

Finally, since M is compact, the theorem follows from the following lemma 5.7.

Kind of cheating ...

I.e. it is enough to show that $F^{-1} : F(M) \rightarrow M$ is continuous, i.e. $F : M \rightarrow F(M)$ is a closed map. But since M is compact, F is proper $\xRightarrow{\text{lemma 5.7}}$ F closed.

□

Lemma 5.7 (Lee Appendix A: 57). *Let X be a topological space. Let Y be locally compact (e.g. a topological manifold), then any proper continuous map is closed.*

Chapter 6:

Transversality

6.1 Basic definition

6.1.1 Motivation

Let $l_1, l_2 \subset \mathbb{R}^2$ be (linear) lines. We will say that l_1, l_2 are **transverse**, if $\underbrace{T_0 l_1}_{l_1} \oplus \underbrace{T_1 l_2}_{l_2} = T_0 \mathbb{R}^2 \equiv \mathbb{R}^2$

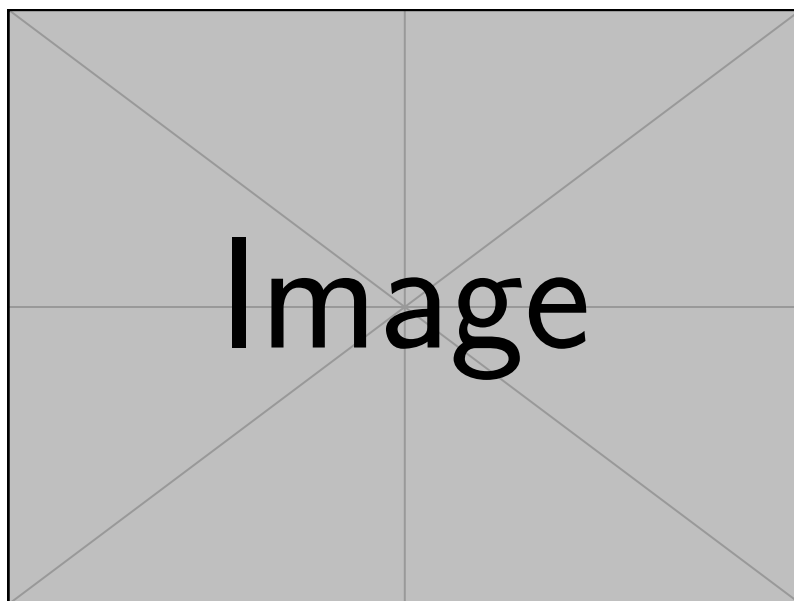


Figure 6.1: Sketch 6.01

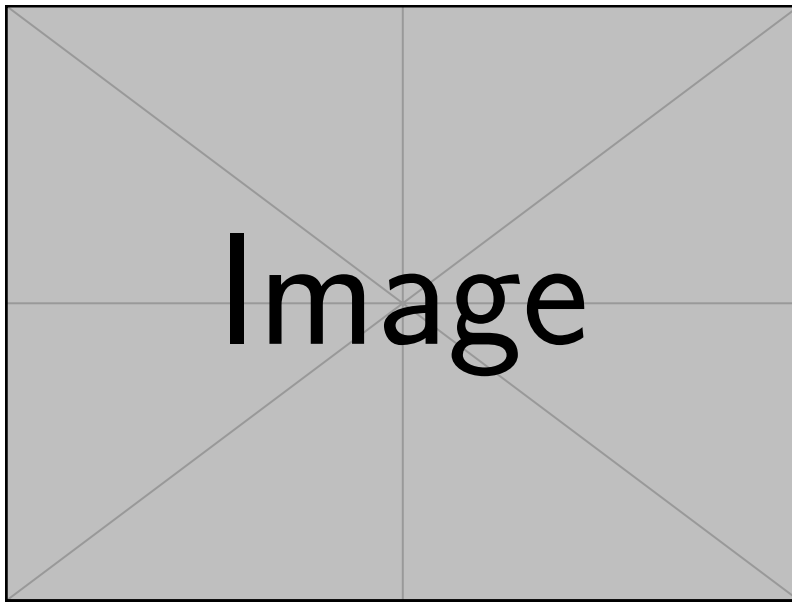


Figure 6.2: Sketch 6.02

Observations:

1. transversality is stable (slight changes to the lines don't change transversality)
2. transversality is generic (for pretty much any lines l_1, l_2 they are transverse)

Similarly to being full rank

One goal: Develop non-linear theory of transversality. I.e. replace $l_1, l_2 \subset \mathbb{R}^2$ by manifolds. Both of the above observations will still be true.

Journal

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¹Lee [2] calls it a theorem

- Lecture 10: Covering:

.
Starting in ‘Slice lemma²’ on page 44 and ending in ‘Motivation’ on page 50. Spanning 6 pages

²Lee [2] calls it a theorem

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