

# Notes on Lee's Manifolds

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Sunday 21<sup>st</sup> June, 2020

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## 1 Chapter 1

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### 1.1 Recommended Problems

**Exercise (Problem 1.6)** Show that if  $M^n \neq \emptyset$  is a topological manifold of dimension  $n \geq 1$  and  $M$  has a smooth structure, then it has uncountably many distinct ones.

Recommended problem

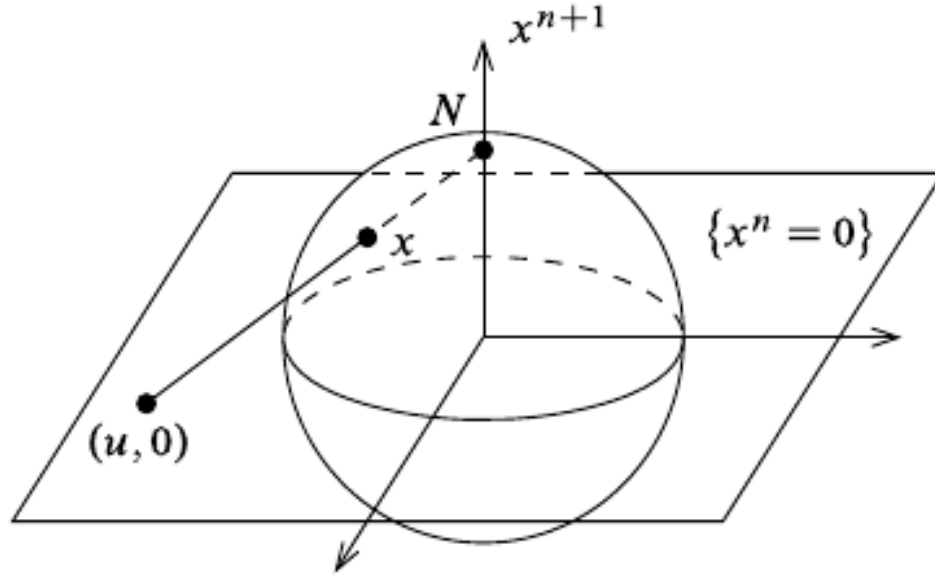
Hint: show that for any  $s > 0$  that  $F_s(x) := |x|^{s-1}x$  defines a homeomorphism  $F_x : \mathbb{D}^n \rightarrow \mathbb{D}^n$  which is a diffeomorphism iff  $s = 1$ .

**Exercise (Problem 1.7)** Let  $N := [0, \dots, 1] \in S^n$  and  $S := [0, \dots, -1]$  and define the stereographic projection

Recommended problem

$$\sigma : S^n \setminus N \rightarrow \mathbb{R}^n$$
$$\left[ x^1, \dots, x^{n+1} \right] \mapsto \frac{1}{1 - x^{n+1}} \left[ x^1, \dots, x^n \right]$$

and set  $\tilde{\sigma}(x) = -\sigma(-x)$  for  $x \in S^n \setminus S$  (projection from the South pole)

**Fig. 1.13** Stereographic projection

1. For any  $x \in S^n \setminus N$  show that  $\sigma(x) = \mathbf{u}$  where  $(\mathbf{u}, 0)$  is the point where the line through  $N$  and  $x$  intersects the linear subspace  $H_{n+1} := \{x^{n+1} = 0\}$ .

Similarly show that  $\tilde{\sigma}(x)$  is the point where the line through  $S$  and  $x$  intersects  $H_{n+1}$ .

2. Show that  $\sigma$  is bijective and

$$\sigma^{-1}(\mathbf{u}) = \sigma^{-1}\left([u^1, \dots, u^n]\right) = \frac{1}{\|\mathbf{u}\|^2 + 1} [2u^1, \dots, 2u^n, \|\mathbf{u}\|^2 - 1].$$

3. Compute the transition map  $\tilde{\sigma} \circ \sigma^{-1}$  and verify that the atlas

$$\mathcal{A} := \{(S^n \setminus N, \sigma), (S^n \setminus S, \tilde{\sigma})\}$$

define a smooth structure on  $S^n$ .

4. Show that this smooth structure is equivalent to the standard smooth structure: Put graph coordinates on  $S^n$  as outlined in 1.2 to obtain  $\{(U_i^\pm, \varphi_i^\pm)\}$ .

For indices  $i < j$ , show that

$$\varphi_i^\pm \circ (\varphi_j^\pm)^{-1} [u^1, \dots, u^n] = [u^1, \dots, \hat{u}^i, \dots, \pm \sqrt{1 - \|\mathbf{u}\|^2}, \dots, u^n]$$

where the square root appears in the  $j$ th position. Find a similar formula for  $i > j$ . Show that if  $i = j$ , then

$$\varphi_i^\pm \circ (\varphi_j^\pm)^{-1} = \varphi_i^- \circ (\varphi_i^+)^{-1} = \text{id}_{\mathbb{D}^n}.$$

Show that these yield a smooth atlas.

**Exercise (Problem 1.8)** Define an *angle function* on  $U \subset S^1$  as any continuous function  $\theta : U \rightarrow \mathbb{R}$  such that  $e^{i\theta(z)} = z$  for all  $z \in U$ .

Recommended problem

Show that  $U$  admits an angle function iff  $U \neq S^1$ , and for any such function  $\theta$ ,  $(U, \theta)$  is a smooth coordinate chart for  $S^1$  with its standard smooth structure.

**Exercise (Problem 1.9)** Show that  $\mathbb{CP}^n$  is a compact  $2n$ -dimensional topological manifold, and show how to equip it with a smooth structure, using the correspondence

Recommended problem

$$\begin{aligned} \mathbb{R}^{2n} &\iff \mathbb{C}^n \\ [x^1, y^1, \dots, x^n, y^n] &\iff [x^1 + iy^1, \dots, x^n + iy^n]. \end{aligned}$$

## 1.2 Notes

**Definition 1.0.1** (Topological Manifold).

A topological space  $M$  that satisfies

1.  $M$  is Hausdorff, i.e. points can be separated by open sets
2.  $M$  is second-countable, i.e. has a countable basis
3.  $M$  is locally Euclidean, i.e. every point has a neighborhood homeomorphic to an open subset  $\hat{U}$  of  $\mathbb{R}^n$  for some fixed  $n$ .

The last property says  $p \in M \implies \exists U$  with  $p \in U \subseteq M$ ,  $\hat{U} \subseteq \mathbb{R}^n$ , and a homeomorphism  $\varphi : U \rightarrow \hat{U}$ .

Note that second countability is primarily needed for existence of partitions of unity.

**Exercise** Show that the in the last condition,  $\hat{U}$  can equivalently be required to be an open ball or  $\mathbb{R}^n$  itself.

**Theorem 1.1** (*Topological Invariance of Dimension*).

Two nonempty topological manifolds of different dimensions can not be homeomorphic.

**Exercise** Show that in a Hausdorff space, finite subsets are closed and limits of convergent sequences are unique.

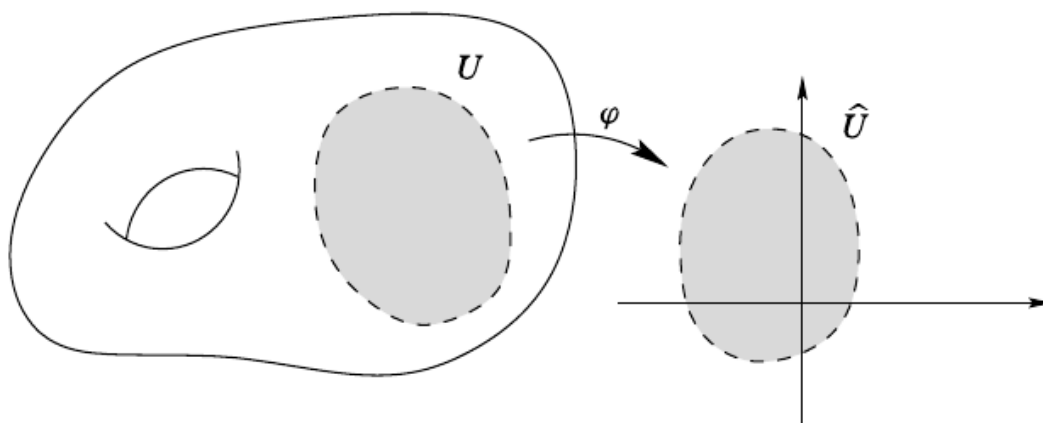
**Exercise** Show that subspaces and finite products of Hausdorff (resp. second countable) spaces are again Hausdorff (resp. second countable).

Thus any open subset of a topological manifold with the subspace topology is again a topological manifold.

**Exercise** Give an example of a connected, locally Euclidean Hausdorff space that is not second countable.

**Definition 1.1.1** (Charts).

A chart on  $M$  is a pair  $(U, \varphi)$  where  $U \subseteq M$  is open and  $\varphi : U \rightarrow \hat{U}$  is a homeomorphism from  $U$  to  $\hat{U} = \varphi(U) \subseteq \mathbb{R}^n$ . If  $p \in M$  and  $\varphi(p) = 0 \in \hat{U}$ , then the chart is said to be *centered* at  $p$ . Note that any chart about  $p$  can be modified to a chart  $(\varphi_1, \hat{U}_1)$  that is centered at  $p$  by defining  $\varphi_1(x) = x - \varphi(p)$ .



**Fig. 1.2** A coordinate chart

$U$  is the *coordinate domain* and  $\varphi$  is the *coordinate map*.

Note that we can write  $\varphi$  in components as  $\varphi(p) = [x^1(p), \dots, x^n(p)]$  where each  $x^i$  is a map  $x^i : U \rightarrow \mathbb{R}$ . The component functions  $x^i$  are the *local coordinates* on  $U$ .

Shorthand notation:  $[x^i] := [x^1, \dots, x^n]$ .

**Example 1.1** (Graphs of Continuous Functions).

Define

$$\Gamma(f) = \left\{ (x, y) \in \mathbb{R}^n \times \mathbb{R}^k \mid x \in U, y = f(x) \in \hat{U} \right\}.$$

This is a topological manifold since we can take  $\varphi : \Gamma(f) \rightarrow U$  by restricting  $\pi_1 : \mathbb{R}^n \times \mathbb{R}^k \rightarrow \mathbb{R}^n$  to the subspace  $\Gamma(f)$ . Projections are continuous, restrictions of continuous functions are continuous.

This is a homeomorphism because the map  $g : x \mapsto (x, f(x))$  is continuous and  $g \circ \pi_1 = \text{id}_{\mathbb{R}^n}$  is continuous with  $\pi_1 \circ g = \text{id}_{\Gamma(f)}$ . Note that  $U \cong \Gamma(f)$ , and thus  $(U, \varphi) = (\Gamma(f), \varphi)$  is a single *global* coordinate chart, called the *graph coordinates* of  $f$ .

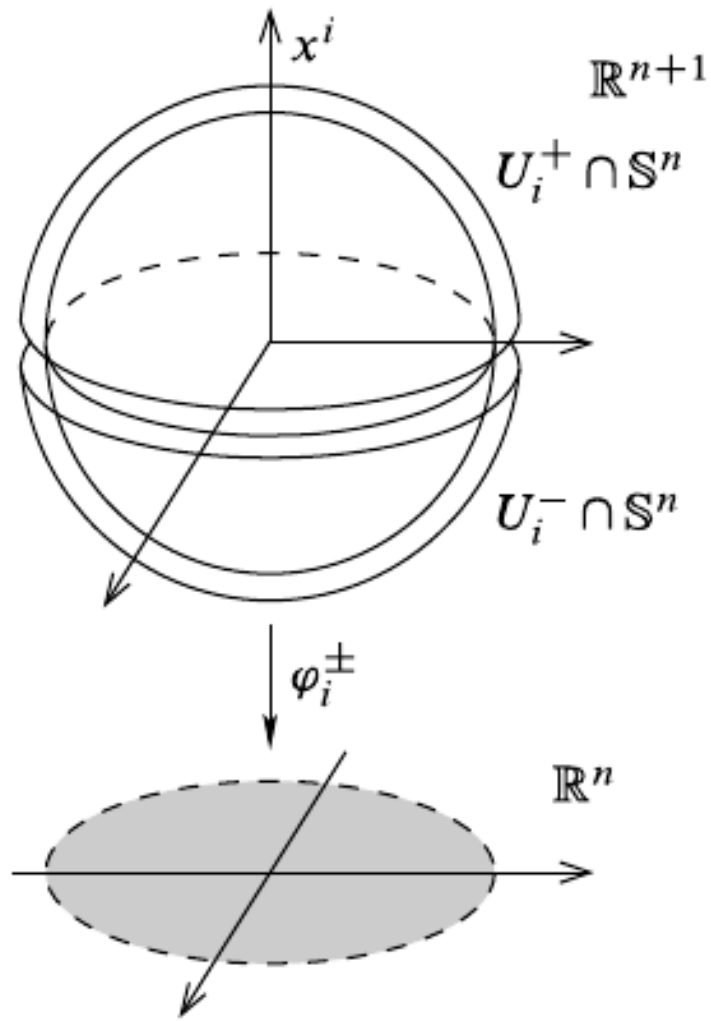
Thus graphs of continuous functions  $f : \mathbb{R}^n \rightarrow \mathbb{R}^k$  are locally Euclidean?

Note that this works in greater generality:: “The same observation applies to any subset of  $\mathbb{R}^{n+k}$  by setting *any*  $k$  of the coordinates equal to some continuous function of the other  $n$ .”

Coordinates as numbers vs functions?

**Example 1.2** (Spheres).

$S^n$  is a subspace of  $\mathbb{R}^{n+1}$  and is thus Hausdorff and second-countable by exercise 1.2.

**Fig. 1.3** Charts for  $S^n$ 

To see that it's locally Euclidean, take

$$U_i^+ := \left\{ [x^1, \dots, x^n] \in \mathbb{R}^{n+1} \mid x^i > 0 \right\} \quad \text{for } 1 \leq i \leq n+1$$

$$U_i^- := \left\{ [x^1, \dots, x^n] \in \mathbb{R}^{n+1} \mid x^i < 0 \right\} \quad \text{for } 1 \leq i \leq n+1.$$

Define

$$f : \mathbb{R}^n \longrightarrow \mathbb{R}^{\geq 0}$$

$$\mathbf{x} \mapsto \sqrt{1 - \|\mathbf{x}\|^2}.$$

Note that we immediately need to restrict the domain to  $\mathbb{D}^n \subset \mathbb{R}^n$ , where  $\|x\|^2 \leq 1 \implies 1 - \|x\|^2 \geq 0$ , to have a well-defined real function  $f : \mathbb{D}^n \longrightarrow \mathbb{R}^{\geq 0}$ .

Then (claim)

$$\begin{aligned} U_i^+ \cap S^n & \text{ is the graph of } x^i = f(x^1, \dots, \widehat{x^i}, \dots, x^{n+1}) \\ U_i^- \cap S^n & \text{ is the graph of } x^i = -f(x^1, \dots, \widehat{x^i}, \dots, x^{n+1}). \end{aligned}$$

This is because

$$\begin{aligned} \Gamma(x^i) &:= \{(\mathbf{x}, f(\mathbf{x})) \subseteq \mathbb{R}^n \times \mathbb{R}\} \\ &= \left\{ [x_1, \dots, \widehat{x^i}, \dots, x^{n+1}], f([x_1, \dots, \widehat{x^i}, \dots, x^{n+1}]) \subseteq \mathbb{R}^n \times \mathbb{R} \right\} \\ &= \left\{ [x_1, \dots, \widehat{x^i}, \dots, x^{n+1}], \left( 1 - \sum_{\substack{j=1 \\ j \neq i}}^{n+1} (x^j)^2 \right)^{\frac{1}{2}} \subseteq \mathbb{R}^n \times \mathbb{R} \right\} \end{aligned}$$

and any vector in this set has norm satisfying

$$\|(\mathbf{x}, y)\|^2 = \sum_{\substack{j=1 \\ j \neq i}}^{n+1} (x^j)^2 + \left( 1 - \sum_{\substack{j=1 \\ j \neq i}}^{n+1} (x^j)^2 \right) = 1$$

and is thus in  $S^n$ .

To see that any such point also has positive  $i$  coordinate and is thus in  $U_i^+$ , we can rearrange (?) coordinates to put the value of  $f$  in the  $i$ th coordinate to obtain

$$\Gamma(x_i) = \left\{ [x^1, \dots, f(x^1, \dots, \widehat{x^i}, \dots, x^n), \dots, x^n] \right\}$$

Seems like  $f$  is always the \*last\* coordinate in the graph

and note that the square root only takes on positive values.

Thus each  $U_i^\pm \cap S^n$  is the graph of a continuous function and thus locally Euclidean, and we can define chart maps

$$\begin{aligned} \varphi_i^\pm : U_i^\pm \cap S^n &\longrightarrow \mathbb{D}^n \\ [x^1, \dots, x^n] &\mapsto [x^1, \dots, \widehat{x^i}, \dots, x^{n+1}] \end{aligned}$$

yield  $2(n+1)$  charts that are graph coordinates for  $S^n$ .

### Definition 1.1.2 (Quotient Map).

A continuous surjective map  $p : X \twoheadrightarrow Y$  is a *quotient map* if  $U \subseteq Y$  is open iff  $p^{-1}(U) \subset X$  is open.

Equivalently,  $p$  is continuous and maps saturated subsets of  $X$  to open subsets of  $Y$ .

Note that this is stronger than continuity

**Definition 1.1.3** (Saturated).

A subset  $A \subseteq X$  is *saturated* with respect to  $p : X \rightarrow Y$  if whenever  $p^{-1}(\{y\}) \cap A \neq \emptyset$ , then  $p^{-1}(\{y\}) \subseteq A$ .

Equivalently,  $A = p^{-1}(B)$  for some  $B \subseteq Y$ , i.e. it is a complete inverse image of some subset of  $Y$ .

**Definition 1.1.4** (Universal Property of Quotient Maps).

For  $\pi : X \rightarrow Y$  a quotient map, if  $g : X \rightarrow Z$  is a map that is constant on each  $p^{-1}(\{y\})$ , then there is a unique map  $f$  making the following diagram commute:

$$\begin{array}{ccc} X & & \\ \downarrow \pi & \searrow g & \\ Y & \xrightarrow{f} & Z \end{array}$$

**Example 1.3** (Projective Space).

Define  $\mathbb{RP}^n$  as the space of 1-dimensional subspaces of  $\mathbb{R}^{n+1}$  with the quotient topology determined by the map

$$\begin{aligned} \pi : \mathbb{R}^{n+1} \setminus \{0\} &\longrightarrow \mathbb{RP}^n \\ \mathbf{x} &\mapsto \text{span}_{\mathbb{R}} \{\mathbf{x}\}. \end{aligned}$$

How is this map a quotient map?

Notation: for  $\mathbf{x} \in \mathbb{R}^{n+1} \setminus \{0\}$  write  $[\mathbf{x}] := \pi(\mathbf{x})$ , the line spanned by  $\mathbf{x}$ .

Define charts:

$$\tilde{U}_i := \left\{ \mathbf{x} \in \mathbb{R}^{n+1} \setminus \{0\} \mid x^i \neq 0 \right\}, \quad U_i = \pi(\tilde{U}_i) \subseteq \mathbb{RP}^n$$

and chart maps

$$\begin{aligned} \tilde{\varphi}_i : \tilde{U}_i &\longrightarrow \mathbb{R}^n \\ \left[ x^1, \dots, x^{n+1} \right] &\mapsto \left[ \frac{x^1}{x^i}, \dots, \frac{x^{n+1}}{x^i} \right]. \end{aligned}$$

Then (claim) this descends to a continuous map  $\varphi_i : U_i \rightarrow \mathbb{R}^n$  by the universal property of the quotient:

$$\begin{array}{ccc} \tilde{U}_i & & \\ \downarrow \pi_U & \searrow \tilde{\varphi}_i & \\ U_i & \xrightarrow{\varphi_i} & \mathbb{R}^n \end{array}$$

- The restriction  $\pi_U : \tilde{U}_i \rightarrow U_i$  of  $\pi$  is still a quotient map because  $\tilde{U}_i = \pi_U^{-1}(U_i)$  where  $U_i \subseteq \mathbb{RP}^n$  is open in the quotient topology and thus  $\tilde{U}_i$  is saturated.

Thus  $\pi_U$  sends saturated sets to open sets and is thus a quotient map.

- $\tilde{\varphi}_i$  is constant on preimages under  $\pi_U$ : fix  $y \in U_i$ , then  $\pi_U^{-1}(\{y\}) = \{\lambda \mathbf{y} \mid \lambda \in \mathbb{R} \setminus \{0\}\}$ , i.e. the point  $y \in \mathbb{RP}^n$  pulls back to every nonzero point on the line spanned by  $\mathbf{y} \in \mathbb{R}^n$ .

But

$$\begin{aligned}\tilde{\varphi}_i(\lambda \mathbf{y}) &= \varphi_i\left(\left[\lambda y^1, \dots, \lambda y^i, \dots, \lambda y^n\right]\right) \\ &= \left[\frac{\lambda y^1}{\lambda y^i}, \dots, \widehat{\lambda y^i}, \dots, \frac{\lambda y^{n+1}}{\lambda y^i}\right] \\ &= \left[\frac{y^1}{y^i}, \dots, \widehat{y^i}, \dots, \frac{y^{n+1}}{y^i}\right] \\ &= \tilde{\varphi}_i(\mathbf{y}).\end{aligned}$$

So this yields a continuous map

$$\varphi_i : U_i \longrightarrow \mathbb{R}^n.$$

We can now verify that  $\varphi$  is a homeomorphism since it has a continuous inverse given by

$$\begin{aligned}\varphi_i^{-1} : \mathbb{R}^n &\longrightarrow U_i \subseteq \mathbb{RP}^n \\ \mathbf{u} := [u^1, \dots, u^n] &\mapsto [u^1, \dots, u^{i-1}, \mathbf{1}, u^{i+1}, \dots, u^n].\end{aligned}$$

It remains to check:

Exercise

1. The  $n+1$  sets  $U_1, \dots, U_{n+1}$  cover  $\mathbb{RP}^n$ .
2.  $\mathbb{RP}^n$  is Hausdorff
3.  $\mathbb{RP}^n$  is second-countable.

**Exercise (1.6)** Show that  $\mathbb{RP}^n$  is Hausdorff and second countable.

**Exercise (1.7)** Show that  $\mathbb{RP}^n$  is compact. (Hint: show that  $\pi$  restricted to  $S^n$  is surjective.)

**Definition 1.1.5** (Topological Embedding).

A continuous map  $f : X \longrightarrow Y$  is a *topological embedding* iff it is injective and  $\tilde{f} : X \longrightarrow f(X)$  is a homeomorphism.

Some facts from the appendix:

Subspaces  $A \subseteq X$ :

**Definition 1.1.6** (The Subspace Topology).

$U \subset A$  is open iff  $U = V \cap A$  for some open  $V \subseteq X$ .

**Proposition 1.2** (*Universal Property of Subspaces*).

If  $X$  and  $\iota_S : S \hookrightarrow Y$  is a subspace, then every continuous map  $f : X \longrightarrow S$  lifts to a continuous map  $\tilde{f} : X \longrightarrow Y$  where  $\tilde{f} := \iota_S \circ f$ :



$$\begin{array}{ccc}
 & Y & \\
 \exists! \tilde{f} \nearrow & \uparrow \iota_S & \\
 X & \xrightarrow{f} & S
 \end{array}$$

Note that we can view  $\iota_S := \text{id}_Y|_S$ . The subspace topology is the unique topology for which this property holds.

Some properties of subspace:

- The inclusion  $\iota_S$  is a topological embedding.
- Restricting a continuous map to a subspace is still continuous.
- A basis for the subspace topology for  $A \subset X$  can be obtained by intersecting basis elements of  $X$  with  $A$ .
- If  $X$  is Hausdorff/first/second-countable, then so is  $A$ .

**Example 1.4** (Product Manifolds).

Let  $M := M_1 \times \cdots \times M_k$  be a product of manifolds of dimensions  $n_1, \dots, n_k$  respectively.

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