

# Notes on Lee's Manifolds

D. Zack Garza

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## 1 Point Set Review

### 1.1 Quotients

**Definition 1.0.1** (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  $Y$ , i.e.  $A$  is a union of fibers  $p^{-1}(b)$ .

**Definition 1.0.2** (Quotient Map).

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

Note that  $\Rightarrow$  comes from the definition of continuity of  $p$ , but  $\Leftarrow$  is a stronger condition.

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

**Definition 1.0.3** (Universal Property of Quotients).

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

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

Fact: an injective quotient map is a homeomorphism.

Fact: a product of quotient maps need not be a quotient map.

## 1.2 Subspaces

**Definition 1.0.4** (The Subspace Topology).

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

**Proposition 1.1** (*Universal Property of Subspaces*).

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

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

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  $A$ .

## 1.3 Products

**Definition 1.1.1** (The Product Topology).

The coarsest topology such that every projection map  $p_\alpha : \prod_{\beta} X_\beta \rightarrow X_\alpha$  is continuous, i.e. for

every  $U_\alpha \subseteq X_\alpha$  open,  $p_\alpha^{-1}(U_\alpha) \in \prod_{\beta} X_\beta$  is open. For finite index sets, we can take the box topology: the collection of sets of the form  $\prod_{i=1}^N U_i$  with each  $U_i$  open in  $X_i$  forms a basis for the

product topology on  $\prod_{i=1}^N X_i$ .

Why these differ: in  $\mathbb{R}^\infty$ , the set  $S = \prod (-1, 1)$  is open in the box topology but not the product topology, since  $\{0\}^\infty$  is not contained in any basic open neighborhood contained in  $S$ .

Some properties of products:

- Projections  $\pi_i$  are continuous by definition.
- A basis for the product topology can be obtained by taking the product of bases.
- A map  $f : X \rightarrow \prod Y_i$  into a product is continuous iff each component function  $F_i := \pi_i \circ f : X \rightarrow Y_i$  is continuous.

- 
- I.e. if we have continuous maps  $f_i : X \rightarrow Y_i$  then the composite map  $F = [f_1, f_2, \dots]$  is continuous.
  - Separate continuity does not imply joint continuity: A map  $f : \prod X_i \rightarrow Y$  out of a product need not be continuous even if (defining  $\iota_j : X_j \hookrightarrow \prod X_i$ ) the map  $f \circ \iota_j : X_j \rightarrow Y$  is continuous for all arbitrary inclusions  $\iota_j$ .
  - Any map of the form  $f_{\mathbf{a}_j} : X_j \rightarrow \prod_{i=1}^n X_i$  where  $x \mapsto (a_1, \dots, a_{j-1}, x, a_{j+1}, \dots, a_n)$  is a topological embedding.
  - If  $X_i$  are Hausdorff/first/second-countable, then so is  $\prod_{i=1}^n X_i$ .

## 2 Chapter 1

Pages 1- 29.

### 2.1 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

$$\sigma : S^n \setminus N \rightarrow \mathbb{R}^n$$

$$[x^1, \dots, x^{n+1}] \mapsto \frac{1}{1 - x^{n+1}} [x^1, \dots, x^n]$$

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 2.2 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

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

## 2.2 Notes

**Definition 2.0.1** (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 in the last condition,  $\hat{U}$  can equivalently be required to be an open ball or  $\mathbb{R}^n$  itself.

**Theorem 2.1** (*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 2.1.1** (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  $\varphi(p) = 0 \in \bar{U}$ , 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 2.1** (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  $f$ .

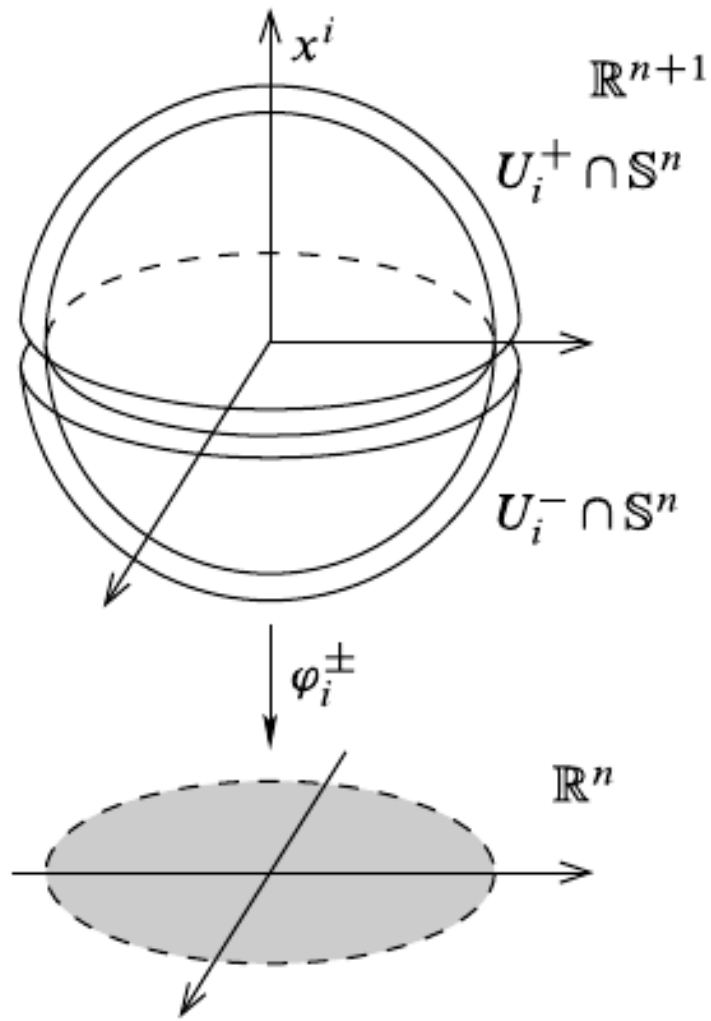
Thus graphs of continuous functions  $f : \mathbb{R}^n \rightarrow \mathbb{R}^k$  are locally Euclidean?

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 2.2** (Spheres).

$S^n$  is a subspace of  $\mathbb{R}^{n+1}$  and is thus Hausdorff and second-countable by exercise 2.2.



**Fig. 1.3** Charts for  $\mathbb{S}^n$

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)

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

This is because

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

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

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

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

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

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

### Example 2.3 (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

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

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

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

- The restriction  $\pi_U : \tilde{U}_i \longrightarrow U_i$  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  $\pi_U^{-1}(\{y\}) = \left\{ \lambda \mathbf{y} \mid \lambda \in \mathbb{R} \setminus \{0\} \right\}$ , 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 2.1.2** (Topological Embedding).

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

**Example 2.4** (Product Manifolds).

Let  $M := M_1 \times \dots \times M_k$  be a product of manifolds of dimensions  $n_1, \dots, n_k$  respectively. A product of Hausdorff/second-countable spaces is still Hausdorff/second-countable, so just need to check that it's locally Euclidean.

- Let  $\mathbf{p} \in \prod_{i=1}^N M_i$ , so  $p_i \in M_i$
- Choose a chart  $(U_i, \varphi_i)$  with  $p_i \in U_i$  and assemble a product map:

$$\Phi := \prod \varphi_i : \prod U_i \rightarrow \prod \mathbb{R}^{n_i} \cong \mathbb{R}^{\sum n_i} := \mathbb{R}^N.$$

- Claim:  $\Phi$  is a homeomorphism onto its image in  $\mathbb{R}^N$ .
  - Each  $\varphi_i$  is a homeomorphism onto  $\varphi_i(U_i)$  (by the definition of a chart on  $M_i$ )
  - It suffices to show that  $\Phi^{-1}$  exists and is continuous, where

$$\Phi^{-1}(V) := \left( \prod \varphi_i \right)^{-1}(\prod V_i).$$

- $\Phi$  is a product of continuous functions and thus continuous.
- $\Phi^{-1} := \left( \prod \varphi_i \right)^{-1} = \prod \varphi_i^{-1}$ , which are all assumed continuous since  $\varphi_i$  were homeomorphisms.

**Example 2.5** (Torii).

$T^n := \prod_{i=1}^n S^1$  is a topological  $n$ -manifold.

**Proposition 2.2.**

Every topological manifold has a countable basis of precompact coordinate balls.

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