Reminder

An equivalence relation on a set S is given by a subset $\mathscr{R} \subset S \times S$ with the following properties:

- Transitivity: $(x, x) \in \mathscr{R}$ for all $x \in S$.
- Symmetry: $(x, y) \in \mathscr{R} \Leftrightarrow (y, x) \in \mathscr{R}$.
- Transitivity: $(x, y) \in \mathscr{R}$ and $(y, z) \in \mathscr{R} \Rightarrow (x, z) \in \mathscr{R}$.

When $(x, y) \in \mathscr{R}$ we say that x and y are *equivalent* and write $x \sim y$.

The set $\mathscr{R}$ is called the *graph* of the equivalence relation.

Definition

Let $\sim$ be an equivalence relation on S.

- The *class* of $x \in S$, denoted $[x]$, is the subset of S consisting of all $y \in S$ that are equivalent to x.
- The set of equivalence classes is denoted $S/\sim$ and is called the *quotient* of S by $\sim$.
- The map $\pi : S \to S/\sim$, $x \to [x]$ is called the *natural projection map* (or *canonical projection*)

Remarks

1. The equivalence classes form of partition of S.
2. The canonical projection $\pi : S \to S/\sim$ is always onto.

The Quotient Topology

Fact

Suppose that S is a topological space. Let $\mathcal{T}$ be the collection of subsets $U \subset S/\!\sim$ such that $\pi^{-1}(U)$ is an open in S.

- $\mathcal{T}$ is closed under unions and finite intersections: if $U_\alpha \in \mathcal{T}$ and $V_i \in \mathcal{T}$, then

$$\pi^{-1}(\bigcup U_\alpha) = \bigcup \pi^{-1}(U_\alpha) \text{ and } \pi^{-1}(V_1 \cap V_2) = \pi^{-1}(V_1) \cap \pi^{-1}(V_2)$$

  are again contained in $\mathcal{T}$.
- Therefore $\mathcal{T}$ defines a topology on $S/\!\sim$.

Definition

- The topology $\mathcal{T}$ is called the *quotient topology*.
- Equipped with this topology $S/\!\sim$ is called the *quotient space* of S by $\sim$.

Remarks

1. A subset $U \subset S/\!\sim$ is open if and only if $\pi^{-1}(U)$ is an open in S.
2. This implies that the projection map $\pi : S \to S/\!\sim$ is automatically continuous.
3. The quotient topology is actually the strongest topology on $S/\!\sim$ for which the map $\pi : S \to S/\!\sim$ is continuous.

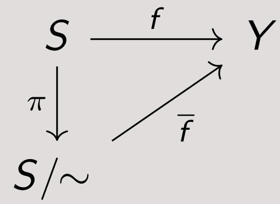
Continuity of a Map on a Quotient

Fact

Let $f : S \to Y$ be a map that is constant on each equivalence class, i.e.,
$$x \sim y \Rightarrow f(x) = f(y).$$
Then f descends to a map $\overline{f} : S/\sim \to Y$ such that
$$\overline{f}([x]) = f(x), \qquad x \in S.$$

Remarks

1. The definition of $\overline{f}$ means that if c is an equivalence class in $S/\sim$, then $\overline{f}(c) = f(x)$ for any $x \in c$.
2. The equality $\overline{f}([x]) = f(x)$ for all $x \in S$ means that $\overline{f} \circ \pi = f$. That is, we have a commutative diagram,



Continuity of a Map on a Quotient

Proposition (Proposition 7.1)

The induced map $\overline{f} : S/\sim \to Y$ is continuous if and only if the original map $f : S \to Y$ is continuous.

Corollary

A map $g : S/\sim \to Y$ is continuous if and only if the composition $g \circ \pi : S \to Y$ is continuous.

Indentification of a Subset to a Point

Fact

Let A be a subset of S. We can define an equivalence relation $\sim$ on S by declaring:

$$x \sim x \qquad \text{for all } x \in S,$$
$$x \sim y \qquad \text{for all } x, y \in A.$$

In other words, if we let $\Delta = \{(x,x); x \in S\}$ be the diagonal of $S \times S$, then the graph of the relation is just

$$\mathscr{R} = \Delta \cup (A \times A).$$

It can be checked this is an equivalence relation.

Definition

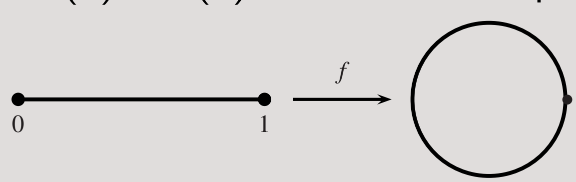
We say that the quotient space $S/\sim$ is obtained by *identifying A to a point*.

Identification of a Subset to a Point

Example

Let I be the unit interval $[0,1]$ and $I/\sim$ the quotient space by identifying $0, 1$ to a point, i.e., by identifying 0 and 1.

1. The equivalence classes consists of the singletons $\{t\}$, $t \in (0,1)$, and the pair $\{0,1\}$.
2. Let $\mathbb{S}^1 \subset \mathbb{C}$ be the unit circle, and define $f : I \to \mathbb{S}^1$ by $f(t) = e^{2i\pi t}$. As $f(0) = f(1)$ it induces a map $\overline{f} : I/\sim \to \mathbb{S}^1$.



3. The induced map $\overline{f} : I/\sim \to \mathbb{S}^1$ is continuous, since f is continuous.

Proposition (Proposition 7.3)

The induced map $\overline{f} : I/\sim \to \mathbb{S}^1$ is a homeomorphism.

A Necessary Condition for a Hausdorff Quotient

Facts

- If X is a Hausdorff topological space, then every singleton $\{x\}$, $x \in X$, is a closed set in X.
- If the quotient space $S/\sim$ is Hausdorff, then every singleton $\{[x]\}$, $x \in S$, is closed in $S/\sim$. This means that the preimage $\pi^{-1}(\{[x]\}) = [x]$ is closed in S.

Proposition (Proposition 7.4)

If the quotient space $S/\sim$ is Hausdorff, then all the equivalence classes $[x]$, $x \in S$, are closed sets in S.

Consequence

If there is an equivalence class that is not a closed set, then the quotient space $S/\sim$ is not Hausdorff.

A Necessary Condition for a Hausdorff Quotient

Example

Let $\sim$ be the equivalence relation on $\mathbb{R}$ obtained by identifying the open interval $(0, \infty)$ to a point. Then:

- The equivalence class $[1]$ is the whole interval $(0, \infty)$.
- As $(0, \infty)$ is a not a closed set in $\mathbb{R}$, the quotient space $\mathbb{R}/\sim$ is not Hausdorff.

Open Equivalence Relations

Reminder

A map $f : X \to Y$ is open when the image of any open set in X is an open set in Y.

Definition

We say that an equivalence relation $\sim$ on a topological space S is open when the projection $\pi : S \to S/\sim$ is an open map.

Remark

- If $A \subset S$, then $\pi(A)$ is open in $S/\sim$ if and only if $\pi^{-1}(\pi(U)) = \cup_{x\in A}[x]$ is an open set in S.
- Thus, the equivalence relation $\sim$ is open if and only if, for every open U in S, the set $\cup_{x\in U}[x]$ is open in S.

Open Equivalence Relations

Example

Let $\sim$ be the equivalence relation on $\mathbb{R}$ that identifies 1 and -1.

- We have $[x] = \{x\}$ for $x \neq \pm 1$ and $[-1] = [1] = \{\pm 1\}$.
- For the open interval $(-2, 0)$ we get

$$\bigcup_{x\in(-2,0)} [x] = \Big(\bigcup_{\substack{x\in(-2,0)\\ x\neq -1}} [x] \Big) \cup [-1] = (-2,0) \cup \{1\}.$$

- As $(-2, 0) \cup \{1\}$ is not an open set, the equivalence relation $\sim$ is not open.

Open Equivalence Relations

Reminder

If $\sim$ is an equivalence relation, then its graph is

$$\mathscr{R} = \{(x, y) \in S \times S;\ x \sim y\} \subset S \times S.$$

Theorem (Theorem 7.7)

Suppose that $\sim$ is an open equivalence relation on a topological space S. Then the quotient space $S/\sim$ is Hausdorff if and only if the graph $\mathscr{R}$ of $\sim$ is closed in $S \times S$.

Open Equivalence Relations

Example

Let $\sim$ be the trivial equivalence relation $x \sim y \Leftrightarrow x = y$. Then:

- $[x] = \{x\}$ for all $x \in S$.
- The graph of $\sim$ is just the diagonal,

$$\Delta = \{(x, x);\ x \in S\} \subset S \times S.$$

- If S is a topological space, then the projection map $\pi : S \to S/\sim$ is a homeomorphism.

Corollary (Corollary 7.8)

A topological space S is Hausdorff if and only if the diagonal Δ is closed in $S \times S$.

Open Equivalence Relations

Proposition (Proposition 7.9)

Suppose that $\sim$ *is an open equivalence relation on* S. *If* $\{U_\alpha\}$ *is a basis for the topology of* S, *then* $\{\pi(U_\alpha)\}$ *is a basis for the quotient topology on* $S/\sim$.

Corollary (Corollary 7.10)

If $\sim$ *is an open equivalence relation on* S, *and* S *is second countable, then the quotient space* $S/\sim$ *is second countable.*

Real Projective Space

Remarks

1. Intuitively speaking the real projective space $\mathbb{R}P^n$ is the set of lines in $\mathbb{R}^{n+1}$ through the origin.
2. Two non-zero vectors $x, y \in \mathbb{R}^{n+1} \setminus 0$ are the same line through the origin if and only if there is $t \neq 0$ such that $y = tx$.

Fact

1. We define an equivalence relation $\sim$ on $\mathbb{R}^{n+1} \setminus 0$ by

$$x \sim y \iff y = tx \text{ for some } t \neq 0.$$

2. The conjugacy classes consist precisely of the lines through the origin (with the origin deleted).

Real Projective Space

Definition

The *real projective space* $\mathbb{R}P^n$ is the quotient space $(\mathbb{R}^{n+1} \setminus 0)/\sim$.

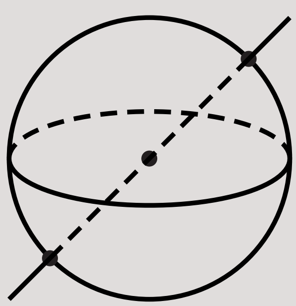
Remarks

1. We denote by $[a^0, \dots, a^n]$ the class of $(a^0, \dots, a^n) \in \mathbb{R}^{n+1}/\sim$.
2. We call $[a^0, \dots, a^n]$ *homogeneous coordinates* on $\mathbb{R}P^n$.
3. We also let $\pi : \mathbb{R}^{n+1} \setminus 0 \to \mathbb{R}P^n$ be the canonical projection.

Real Projective Space

Remark

1. Every line in $\mathbb{R}^{n+1}$ through the origin meets the unit sphere $\mathbb{S}^{n+1}$ at a pair of antipodal points.
2. Conversely, there is a unique line through the origin and two antipodal points of $\mathbb{S}^{n+1}$



Real Projective Space

Facts

- On $\mathbb{S}^{n+1}$ we define an equivalence relation by

$$x \sim y \Longleftrightarrow x = \pm y.$$

- The restriction of the canonical projection $\pi_{|\mathbb{S}^n} : \mathbb{S}^n \rightarrow \mathbb{R}P^n$ induces a continuous map $\overline{\pi} : \mathbb{S}^n/\!\sim \rightarrow \mathbb{R}P^n$.
- The continuous map $f : \mathbb{R}^{n+1} \setminus 0 \rightarrow \mathbb{S}^{n+1}$, $x \rightarrow \frac{x}{\|x\|}$ induces a continuous map $\overline{f} : \mathbb{R}P^n \rightarrow \mathbb{S}^n/\!\sim$.
- The maps $\overline{\pi} : \mathbb{S}^n/\!\sim \rightarrow \mathbb{R}P^n$ and $\overline{f} : \mathbb{R}P^n \rightarrow \mathbb{S}^n/\!\sim$ are inverses of each other.

Proposition (Exercise 7.11)

The real projective space $\mathbb{R}P^n$ is homeomorphic to the quotient space $\mathbb{S}^n/\!\sim$.

Real Projective Space

Example (Real projective line $\mathbb{R}P^1$; see also Example 7.12)

- If we regard as the unit circle $\mathbb{S}^1$ as a subset of $\mathbb{C}$, then the map $\mathbb{S}^1 \rightarrow \mathbb{S}^1$, $z \rightarrow z^2$ induces a continuous map $\mathbb{S}^1/\!\sim \rightarrow \mathbb{S}^1$.
- This is a continuous bijection between compact spaces, and hence this is a homeomorphism (by Corollary A.36).
- Here $\mathbb{S}^1/\!\sim$ is compact, since this is the image of $\mathbb{S}^1$ by the canonical projection map $\mathbb{S}^1 \rightarrow \mathbb{S}^1/\!\sim$, which is continuous.
- We thus have a sequence of homeomorphisms,

$$\mathbb{R}P^1 \simeq \mathbb{S}^1/\!\sim \simeq \mathbb{S}^1.$$

Real Projective Space

Proposition (Proposition 7.14)

The equivalence relation $\sim$ on $\mathbb{R}^{n+1} \setminus 0$ is an open equivalence relation.

Corollary (Corollary 7.15)

The real projective space $\mathbb{R}P^n$ is second countable.

Corollary (Corollary 7.16)

The real projective space $\mathbb{R}P^n$ is Hausdorff.

The Standard Differentiable Structure of $\mathbb{R}P^n$

Facts

- For $i = 0, \ldots, n$, define
$$U_i = \left\{[a^0, \ldots, a^n] \in \mathbb{R}P^n;\ a^i \neq 0\right\}.$$
- As the property $a^i \neq 0$ remains unchanged when we replace $(a^0, \ldots, a^n)$ by $(ta^0, \ldots, ta^n)$ with $t \neq 0$, we see that U_i is well defined.
- We have $\pi^{-1}(U_i) = \pi^{-1}(\tilde{U}_i)$, where
$$\tilde{U}_i = \left\{(a^0, \ldots, a^n) \in \mathbb{R}^{n+1} \setminus 0;\ a^i \neq 0\right\}.$$
- As $\tilde{U}_i$ is an open set in $\mathbb{R}^{n+1} \setminus 0$, this shows that U_i is an open set in $\mathbb{R}P^n$.

The Standard Differentiable Structure of $\mathbb{R}P^n$

Facts

- Define $\tilde{\phi}_i : \tilde{U}_i \to \mathbb{R}^n$ by
$$\tilde{\phi}_i(a^0, \ldots, a^n) = \left(\frac{a^0}{a^i}, \ldots, \frac{a^{i-1}}{a^i}, \frac{a^{i+1}}{a^i}, \ldots, \frac{a^n}{a^i}\right).$$
- As $\tilde{\phi}_i(ta^0, \ldots, ta^n) = \tilde{\phi}_i(a^0, \ldots, a^n)$ for all $t \neq 0$, the map $\tilde{\phi}_i$ induces a map $\phi_i : U_i \to \mathbb{R}^n$ such that
$$\begin{aligned}\phi\left([a^0, \ldots, a^n]\right) &= \tilde{\phi}_i(a^0, \ldots, a^n), \\ &= \left(\frac{a^0}{a^i}, \ldots, \frac{a^{i-1}}{a^i}, \frac{a^{i+1}}{a^i}, \ldots, \frac{a^n}{a^i}\right).\end{aligned}$$
- As $\tilde{\phi}_i : \tilde{U}_i \to \mathbb{R}^n$ is a continuous map, the induced map $\phi_i : U_i \to \mathbb{R}^n$ is continuous as well.

The Standard Differentiable Structure of $\mathbb{R}P^n$

Facts

- The map $\phi_i : U_i \to \mathbb{R}^n$ is a bijection with inverse $\psi_i : \mathbb{R}^n \to U_j$, where
$$\psi_i(x^1, \ldots, x^n) = [x^1, \ldots, x^i, 1, x^{i+1}, \ldots, x^n].$$
- The inverse map $\psi_i = \phi_i^{-1}$ is continuous, since $\psi_i = \pi \circ \tilde{\psi}_i$, where $\tilde{\psi}_i : \mathbb{R}^n \to \tilde{U}_i$ is the continuous map given by
$$\tilde{\psi}_i(x^1, \ldots, x^n) = (x^0, \ldots, x^i, 1, x^{i+1}, \ldots, x^n).$$
- Thus, the map $\phi_i : U_i \to \mathbb{R}^n$ is a homeomorphism.

The Standard Differentiable Structure of $\mathbb{R}P^n$

Facts

- We have

$$\phi_0(U_0 \cap U_1) = \left\{ \left(\frac{a^1}{a^0}, \ldots, \frac{a^n}{a^0} \right); a^j \in \mathbb{R},\ a^0 \neq 0,\ a^1 \neq 0 \right\}$$
$$= \left\{ (x^1, \ldots, x^n) \in \mathbb{R}^n;\ x^1 \neq 0 \right\}.$$

- The transition map $\phi_1 \circ \phi_0^{-1} : \phi_0(U_0 \cap U_1) \to \mathbb{R}^n$ is given by

$$\phi_0 \circ \phi_1^{-1}(x^1, \ldots, x^n) = \phi_0\left([1, x^1, \ldots, x^n]\right),$$
$$= \left(\frac{1}{x^1}, \frac{x^2}{x^1}, \ldots, \frac{x^n}{x^1} \right).$$

  In particular, this is a C^∞ map.

- It can be similarly shown that all the other transition maps $\phi_i \circ \phi_j^{-1} : \phi_j(U_i \cap U_j) \to \mathbb{R}^n$ are C^∞ maps.

The Standard Differentiable Structure of $\mathbb{R}P^n$

Conclusion

The collection $\{(U_i, \phi_i)\}_{i=0}^n$ is a C^∞ atlas for $\mathbb{R}P^n$, and so $\mathbb{R}P^n$ is a smooth manifold.

Definition

The differentiable structure defined by the atlas $\{(U_i, \phi_i)\}_{i=0}^n$ is called the *standard differentiable structure* of $\mathbb{R}P^n$.

Complex Projective Space

Facts

We also define complex projective spaces.

- On $\mathbb{C}^{n+1}$ consider the equivalence relation
$$x \sim y \iff \exists \lambda \in \mathbb{C} \setminus 0 \text{ such that } x = \lambda y.$$
In other words $x \sim y$ if and only if x and y lie on the same complex line through the origin.
- The equivalence classes are the complex lines through the origin (minus the origin).
- The *complex projective space* $\mathbb{C}P^n$ is the quotient space $(\mathbb{C}^{n+1} \setminus 0)/\!\sim$.
- The class of $a = (a^0, \ldots, a^n)$ is denoted $[a^0, \ldots, a^n]$. We call $[a^0, \ldots, a^n]$ *homogeneous coordinates*.
- The space $\mathbb{C}P^n$ is Hausdorff and 2nd countable.

Differentiable Structure on $\mathbb{C}P^n$

Facts

- For $i = 1, \ldots, n$, define
$$U_i = \left\{[a^0, \ldots, a^n];\ (a^0, \ldots, a^n) \in \mathbb{C}^{n+1} \setminus 0,\ a^i \neq 0\right\}.$$
This is an open set in $\mathbb{C}P^n$.
- Define $\phi_i : U_i \rightarrow \mathbb{C}^n$ by
$$\phi_i\left([a^0, \ldots, a^n]\right) = \left(\frac{a^0}{a^i}, \ldots, \frac{a^{i-1}}{a^i}, \frac{a^{i+1}}{a^i}, \ldots, \frac{a^n}{a^i}\right).$$
This is a homeomorphism from U_i on $\mathbb{C}^n$. It has inverse
$$\psi_i(z^1, \ldots, z^n) = \left(z^1, \ldots, z^i, 1, z^{i+1}, \ldots, z^n\right).$$
- The transition maps $\phi_i \circ \phi_j^{-1}$ are C^∞ maps (they even are holomorphic maps).
- Thus, $\{(U_i, \phi_i)\}_{i=1}^n$ is a C^∞ atlas for $\mathbb{C}P^n$, and so the complex projective space $\mathbb{C}P^n$ is a manifold.

Submanifolds

Definition (Regular Submanifold)

Given a manifold N of dimension, a subset $S \subset N$ is called a *regular submanifold* of dimension k if, for every $p \in S$, there is a chart $(U, x^1, \ldots, x^n)$ about p in N such that

$$U \cap S = \left\{ q \in U; x^{k+1}(q) = \cdots = x^n(q) = 0 \right\}.$$

Remarks

1. A chart $(U, x^1, \ldots, x^n)$ as above is called an *adapted chart* relative to S.
2. We call $n - k$ the *codimension* of S.
3. We always assume that S is equipped with the induced topology.
4. There are other types of submanifold. By a submanifold we shall always mean a regular submanifold.

Submanifolds

Remark

Let $S \subset N$ be a regular submanifold of dimension k, and $(U, \phi) = (U, x^1, \ldots, x^n)$ be an adapted chart relative to S.

- We have $\phi = (x^1, \ldots, x^k, 0, \ldots, 0)$ on $U \cap S$.
- Define $\phi_S : U \cap S \to \mathbb{R}^k$ by

$$\phi(q) = \left(x^1(q), \ldots, x^k(q)\right), \qquad q \in U \cap S.$$

  Then ϕ_S is a homeomorphism from $U \cap S$ onto its image
- Let $(r^1, \ldots, r^n)$ be the coordinates in $\mathbb{R}^n$. We have

$$\phi_S(U \cap S) \times \{0\}^{n-k} = \phi(U \cap S) = \phi(U) \cap \{r^{k+1} = \cdots = r^n = 0\}.$$

  Thus, $\phi_S(U \cap S) \times \{0\}^{n-k}$ is open in $\mathbb{R}^k) \times \{0\}^{n-k}$, and hence $\phi_S(U \cap S)$ is an open in $\mathbb{R}^k$.
- It then follows that (U, ϕ_S) is a (topological) chart for S.

Submanifolds

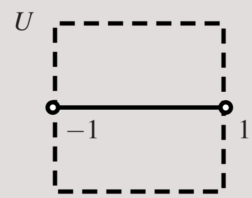
Example

Any open set $U \subset N$ is a regular submanifold of codimension 0.

Example

- The open interval $S = (-1, 1)$ on the x-axis is a regular submanifold of dimension 1 of the xy-plane.
- An adapted chart is (U, x, y), with $U = (-1, 1) \times (-1, 1)$, since

$$U \cap \{y = 0\} = (-1, 1) \times \{0\} = S.$$



Submanifolds

Facts

Let $(U, \phi) = (U, x^1, \dots, x^n)$ and $(V, \psi) = (V, y^1, \dots, y^n)$ be adapted charts relative to S about a point $p \in S$. Denote by $(r^1, \dots, r^n)$ the coordinates in $\mathbb{R}^n = \mathbb{R}^k \times \mathbb{R}^{n-k}$.

- On $U \cap V \cap S$ we have

$$\phi = (x^1, \dots, x^k, 0, \dots, 0) = (\phi_S, 0, \dots, 0),$$
$$\psi = (y^1, \dots, y^k, 0, \dots, 0) = (\psi_S, 0, \dots, 0).$$

- Thus, on $\phi(U \cap V \cap S) = \phi_S(U \cap V \cap S) \times \{0\}^{n-k}$ we have

$$\psi \circ \phi^{-1}(r^1, \dots, r^k, 0, \dots, 0) = (\psi_S \circ \phi_S^{-1}(r^1, \dots, r^k), 0, \dots, 0).$$

- As $\psi \circ \phi^{-1} = (y^1 \circ \phi^{-1}, \dots, y^n \circ \phi^{-1})$, we get

$$\psi_S \circ \phi_S^{-1} = (z^1, \dots, z^k), \quad \text{where } z^i = y^i \circ \phi^{-1}(r^1, \dots, r^k, 0, \dots, 0).$$

In particular, the transition map $\psi_S \circ \phi_S^{-1}$ is smooth.

Submanifolds

Proposition (Proposition 9.4)

Let S be a regular submanifold of dimension k in a manifold N of dimension n. Let $\{(U, \phi)\}$ be a collection of adapted charts relative to S that covers S. Then:

1. *The collection $\{(U \cap S, \phi_S)\}$ is a C^∞ atlas for S.*
2. *S is a manifold of dimension k.*

Remark

It can be shown that the differentiable structure on S defined above is unique, i.e., it does not depend on the choice of the collection $\{(U, \phi)\}$.

Level Sets of a Function

Definition

- Given $F : N \to M$ and $c \in M$, the preimage $F^{-1}(c)$ is called a *level set* of level c.
- When $N = \mathbb{R}^n$ we call $F^{-1}(0)$ the *zero set* of F and denote it by $Z(F)$.

Reminder

If $F : N \to M$ is a smooth map, then we say that c is a regular value when, either $c \notin F(M)$, or for every point $p \in F^{-1}(c)$ the differential $F_{*,p} : T_pM \to T_cN$ is onto.

Definition

Let $F : N \to M$ be a smooth map, and let $c \in M$.

- If c is a regular value, then $F^{-1}(c)$ is called a *regular level set*.
- If $N = \mathbb{R}^n$ and 0 is a regular value, then we say that $Z(F)$ is a *regular zero set*.

Remark

Let $f : N \to \mathbb{R}$ be a smooth function.

- If $p \in N$, then $f_{*,p} : T_p M \to T_{f(p)} R \simeq \mathbb{R}$ is onto if and only if it is non-zero.
- If $c \in f(M)$, then $f^{-1}(c)$ is a regular level set if and only if $f_{*,p} \neq 0$ for all $p \in f^{-1}(c)$.

Example (Example 9.6; the 2-sphere in $\mathbb{R}^3$)

- The unit sphere $\mathbb{S}^2 \subset \mathbb{R}^3$ is the zero set of the function,

$$f(x, y, z) = x^2 + y^2 + z^2 - 1.$$

- For every $p = (x, y, z) \in \mathbb{S}^2$ we have

$$\left(\frac{\partial f}{\partial x}(p), \frac{\partial f}{\partial y}(p), \frac{\partial f}{\partial z}(p)\right) = (2x, 2y, 2z) \neq 0.$$

  Therefore, $\mathbb{S}^2$ is a regular zero set.

Level Sets of a Function

Example (The 2-sphere in $\mathbb{R}^3$; continued)

- Suppose that $p = (x(p), y(p), z(p))$ is such that $x_0 \neq 0$. It can be checked that the map $F = (f, y, z)$ has a non-zero Jacobian determinant at p.
- By Corollary 6.27 (consequence of the inverse function theorem) there is an open U about p such that $(U, F_{|U}) = (U, f_{|U}, y_{|U}, z_{|U})$ is a chart about p in $\mathbb{R}^3$.
- Set $u^1 = y_{|U}$, $u^2 = z_{|U}$, and $u^3 = f_{|U}$. Then (U, u^1, u^2, u^3) is a chart about p in $\mathbb{R}^3$, and we have

$$\{u^3 = 0\} = \{f_{|U} = 0\} = U \cap \{f = 0\} = U \cap \mathbb{S}^2.$$

  Thus, (U, u^1, u^2, u^3) is an adapted chart relative to $\mathbb{S}^2$.
- Similarly, if $y(p) \neq 0$ or $z(p) \neq 0$, then there is an adapted chart about p.
- Thus, $\mathbb{S}^2 \subset \mathbb{R}^3$ is a regular submanifold of codimension 1.

Level Sets of a Function

More generally, we have the following result:

Theorem (Theorem 9.8)

Let $g : N \to \mathbb{R}$ be a smooth function. Any non-empty regular level set $g^{-1}(c)$ is a regular submanifold of codimension 1.

Remark

A codimension 1 submanifold is called a *hypersurface*.

Example (Example 9.11)

Let S be the solution set of $x^3 + y^3 + z^3 = 1$ in $\mathbb{R}^3$.

- S is the zero set of $f(x, y, z) = x^3 + y^3 + z^3 - 1$.
- If $p = (x, y, z) \in S$, then

$$\left(\frac{\partial f}{\partial x}(p), \frac{\partial f}{\partial y}(p), \frac{\partial f}{\partial z}(p)\right) = (3x^2, 3y^2, 3z^2) \neq 0.$$

  Thus, every $p \in S$ is a regular point.
- Therefore, S is a regular zero set, and hence is a regular hypersurface.

Example (Example 9.13; Special Linear Group)

- Let $\mathbb{R}^{n\times n}$ be the vector space of $n \times n$ matrices with real entries. The general linear group is

$$\mathrm{GL}(n, \mathbb{R}) = \left\{A \in \mathbb{R}^{n\times n};\ \det A \neq 0\right\}.$$

  This an open set in $\mathbb{R}^{n\times n}$, and hence is a manifold of dimension n^2.
- The *special linear group* is

$$\mathrm{SL}(n, \mathbb{R}) = \{A \in \mathrm{GL}(n, \mathbb{R});\ \det A = 1\}.$$

  This is the level set $f^{-1}(1)$ of the function $f(A) = \det A$.

Level Sets of a Function

Example (Special Linear Group, continued)

- If $A = [a_{ij}] \in \mathrm{GL}(n, \mathbb{R})$ and $m_{ij} = \det S_{ij}$ is the (i, j)-minor, then
$$\frac{\partial f}{a_{ij}} = (-1)^{i+j} m_{ij}.$$
- If $A \in \mathrm{GL}(n, \mathbb{R})$, then at least one minor is non-zero, and so A is a regular point of f.
- In particular, every $A \in \mathrm{SL}(n, \mathbb{R})$ is a regular point.
- Therefore, $\mathrm{SL}(n, \mathbb{R})$ is a regular level set, and hence is a regular hypersurface in $\mathrm{GL}(n, \mathbb{R})$.

The Regular Level Set Theorem

Even more generally we have:

Theorem (Regular Level Set Theorem; Theorem 9.9)

Let $F : N \to M$ be a C^∞ map. Any non-empty regular level set $F^{-1}(c)$ is a regular submanifold of codimension equal to $\dim M$.

The Regular Level Set Theorem

Example (Example 9.12)

Let S be the solution set in $\mathbb{R}^3$ of the polynomial equations,

$$x^3 + y^3 + z^3 = 1, \quad x + y + z = 0.$$

- By definition S is the level set $F^{-1}(1,0)$, where $F : \mathbb{R}^3 \to \mathbb{R}^2$ is the smooth function given by
$$F(x,y,z) = \left(x^3 + y^3 + z^3, x + y + z\right).$$
- The Jacobian matrix of F is
$$J(F) = \begin{bmatrix} 3x^2 & 3y^2 & 3z^2 \\ 1 & 1 & 1 \end{bmatrix}.$$
It has rank 2 unless $x^2 = y^2 = z^2$, i.e., $x = \pm y = \pm z$.
- For such a point $F(x,y,z) = \lambda(x^3, x) \neq (1,0)$, so all the points of S are regular points.
- Thus, S is a regular level set of F, and hence is a regular submanifold of codimension 2.