

Mathematics

Robin Adams

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Chapter 1

Primitive Terms and Axioms

1.1 Primitive Terms

Let there be *sets*. We write $A : \text{Set}$ for: A is a set.

For any set A , let there be *elements* of A . We write $a : \text{El}(A)$ for: a is an element of A .

For any sets A and B , let there be *functions* from A to B . We write $f : A \rightarrow B$ iff f is a function from A to B .

For any function $f : A \rightarrow B$ and element $a : \text{El}(A)$, let there be an element $f(a) : \text{El}(B)$, the *value* of the function f at the *argument* a .

1.2 Axioms

Axiom Schema 1.1 (Choice). *Let $P[X, Y, x, y]$ be a formula where X and Y are set variables, $x : \text{El}(X)$ and $y : \text{El}(Y)$. Then the following is an axiom.*

Let A and B be sets. Assume that, for all $a : \text{El}(A)$, there exists $b : \text{El}(B)$ such that $P[A, B, a, b]$. Then there exists a function $f : A \rightarrow B$ such that $\forall a : \text{El}(A). P[A, B, a, f(a)]$.

Axiom 1.2 (Pairing). *For any sets A and B , there exists a set $A \times B$, the Cartesian product of A and B , and functions $\pi_1 : A \times B \rightarrow A$ and $\pi_2 : A \times B \rightarrow B$ such that, for all $a : \text{El}(A)$ and $b : \text{El}(B)$, there exists a unique $(a, b) : \text{El}(A \times B)$ such that $\pi_1(a, b) = a$ and $\pi_2(a, b) = b$.*

Definition 1.3 (Injective). A function $f : A \rightarrow B$ is *injective* or an *injection* iff, for all $x, y : \text{El}(A)$, if $f(x) = f(y)$ then $x = y$.

Axiom Schema 1.4 (Separation). *For every property $P[X, x]$ where X is a set variable and $x : \text{El}(X)$, the following is an axiom:*

For every set A , there exists a set $S = \{x : \text{El}(A) \mid P[A, x]\}$ and an injection $i : S \rightarrow A$ such that, for all $x : \text{El}(A)$, we have

$$(\exists y : S. i(y) = x) \Leftrightarrow P[A, x] .$$

Axiom 1.5 (Infinity). *There exists a set \mathbb{N} , an element $0 : \text{El}(\mathbb{N})$, and a function $s : \mathbb{N} \rightarrow \mathbb{N}$ such that:*

- $\forall n : \text{El}(\mathbb{N}). s(n) \neq 0$
- $\forall m, n : \text{El}(\mathbb{N}). s(m) = s(n) \Rightarrow m = n.$

1.3 Consequences of the Axioms

1.3.1 Definitions

Definition 1.6. Let $f, g : A \rightarrow B$. We say f and g are *equal*, $f = g$, iff $\forall x : \text{El}(A). f(x) = g(x)$.

Definition 1.7 (Surjective). A function $f : A \rightarrow B$ is *surjective* iff, for all $y : \text{El}(B)$, there exists $x : \text{El}(A)$ such that $f(x) = y$.

Definition 1.8 (Bijective). A function $f : A \rightarrow B$ is *bijective* or a *bijection* iff it is injective and surjective.

Sets A and B are *equinumerous*, $A \approx B$, iff there exists a bijection between them.

If we prove there exists a set X such that $P(X)$, and that any two sets that satisfy P are bijective, then we may introduce a constant C and define "Let C be the set such that $P(C)$ ".

1.3.2 The Empty Set

Theorem 1.9. *There exists a set which has no elements.*

PROOF:

$\langle 1 \rangle 1$. PICK a set A

PROOF: By the Axiom of Infinity, a set exists.

$\langle 1 \rangle 2$. LET: $S = \{x : \text{El}(A) \mid \perp\}$ with injection $i : S \rightarrow A$

PROOF: Axiom of Separation.

$\langle 1 \rangle 3$. S has no elements.

□

Theorem 1.10. *If E and E' have no elements then $E \approx E'$.*

PROOF:

$\langle 1 \rangle 1$. LET: E and E' have no elements.

$\langle 1 \rangle 2$. PICK a function $F : E \rightarrow E'$.

PROOF: Axiom of Choice since vacuously $\forall x : \text{El}(E). \exists y : \text{El}(E'). \top$.

⟨1⟩3. F is injective.

PROOF: Vacuously, for all $x, y : \text{El}(E)$, if $F(x) = F(y)$ then $x = y$.

⟨1⟩4. F is surjective.

PROOF: Vacuously, for all $y : \text{El}(E)$, there exists $x : \text{El}(E)$ such that $F(x) = y$.

□

Definition 1.11 (Empty Set). The *empty set* \emptyset is the set with no elements.

1.3.3 The Singleton

Theorem 1.12. *There exists a set that has exactly one element.*

PROOF:

⟨1⟩1. PICK a set A that has an element.

PROOF: By the Axiom of Infinity, there exists a set that has an element.

⟨1⟩2. PICK $a : \text{El}(A)$

⟨1⟩3. LET: $R : A \looparrowright A$ be the relation such that, for all $x, y : \text{El}(A)$, we have xRy if and only if $x = y = a$.

PROOF: By the Axiom of Comprehension.

⟨1⟩4. LET: $|R|$ be the tabulation of R with projections $p, q : |R| \rightarrow A$.

PROVE: $|R|$ has exactly one element.

PROOF: By the Axiom of Tabulations.

⟨1⟩5. LET: $r : \text{El}(|R|)$ be the element such that $p(r) = q(r) = a$

PROOF: Since aRa by ⟨1⟩3.

⟨1⟩6. LET: $s : \text{El}(|R|)$

PROVE: $s = r$

⟨1⟩7. $p(s)Rq(s)$

PROOF: By the Axiom of Tabulations.

⟨1⟩8. $p(s) = q(s) = a$

PROOF: By ⟨1⟩3.

⟨1⟩9. $p(s) = p(r)$ and $q(s) = q(r)$

PROOF: By ⟨1⟩5.

⟨1⟩10. $s = r$

PROOF: By the Axiom of Tabulations.

□

Theorem 1.13. *If A and B both have exactly one element then $A \approx B$.*

PROOF:

⟨1⟩1. LET: A and B both have exactly one element.

⟨1⟩2. LET: $F : A \looparrowright B$ be the relation such that, for all $x : \text{El}(A)$ and $y : \text{El}(B)$, we have xFy .

⟨1⟩3. F is a function.

PROOF: If xFy and xFy' then $y = y'$ because B has only one element.

⟨1⟩4. F is injective.

PROOF: If $F(x) = F(x')$ then $x = x'$ because A has only one element.

- $\langle 1 \rangle 5.$ F is surjective.
- $\langle 2 \rangle 1.$ LET: $y : \text{El}(B)$
- $\langle 2 \rangle 2.$ LET: x be the element of A .
- $\langle 2 \rangle 3.$ $F(x) = y$

□

Definition 1.14 (Singleton). Let 1 be the set that has exactly one element. Let $*$ be its element.

1.3.4 Subsets

Definition 1.15 (Subset). A *subset* of a set A is a relation $1 \rightarrowtail S$.

Given $S : 1 \rightarrowtail S$ and $a : \text{El}(A)$, we write $a \in S$ for $*Sa$.

Theorem Schema 1.16. For any property $P[X, x]$ where X is a set variable and $x : \text{El}(X)$, the following is a theorem:

For any set A , there exists a set B and injection $i : B \rightarrow A$ such that, for all $x : \text{El}(A)$, we have $P[A, x]$ if and only if there exists $b : \text{El}(B)$ such that $i(b) = x$.

PROOF:

- $\langle 1 \rangle 1.$ LET: $S : 1 \rightarrowtail A$ be the relation such that, for all $e : \text{El}(1)$ and $a : \text{El}(A)$, we have eSa if and only if $P[A, a]$.

PROOF: Axiom of Comprehension.

- $\langle 1 \rangle 2.$ LET: B be the tabulation of S with projections $p : B \rightarrow 1$ and $i : B \rightarrow A$.

PROOF: Axiom of Tabulations.

- $\langle 1 \rangle 3.$ i is injective.

- $\langle 2 \rangle 1.$ LET: $r, s : \text{El}(B)$

- $\langle 2 \rangle 2.$ ASSUME: $i(r) = i(s)$

- $\langle 2 \rangle 3.$ $p(r) = p(s)$

PROOF: Since 1 has only one element.

- $\langle 2 \rangle 4.$ $r = s$

PROOF: Axiom of Tabulations.

- $\langle 1 \rangle 4.$ For all $x : \text{El}(A)$, we have $P[A, x]$ if and only if there exists $b : \text{El}(B)$ such that $i(b) = x$.

- $\langle 2 \rangle 1.$ LET: $x : \text{El}(A)$

- $\langle 2 \rangle 2.$ If $P[A, x]$ then there exists $b : \text{El}(B)$ such that $i(b) = x$

- $\langle 3 \rangle 1.$ ASSUME: $P[A, x]$

- $\langle 3 \rangle 2.$ $*Sx$

PROOF: $\langle 1 \rangle 1$

- $\langle 3 \rangle 3.$ There exists $b : \text{El}(B)$ such that $p(b) = *$ and $i(b) = x$

PROOF: Axiom of Tabulations.

- $\langle 2 \rangle 3.$ For all $b : \text{El}(B)$ we have $P[A, i(b)]$

- $\langle 3 \rangle 1.$ LET: $b : \text{El}(B)$

- $\langle 3 \rangle 2.$ $p(b)Si(b)$

PROOF: Axiom of Tabulations.

- $\langle 3 \rangle 3.$ $P[A, i(b)]$

PROOF: $\langle 1 \rangle 1$

□

1.4 Composition

Definition 1.17 (Composite). Let $\phi : A \rightarrowtail B$ and $\psi : B \rightarrowtail C$. The *composite* $\psi \circ \phi : A \rightarrowtail C$ is the relation such that $a(\psi \circ \phi)c$ iff there exists b such that $a\phi b$ and $b\psi c$.

Definition 1.18 (Identity). For any set A , the *identity* function $\text{id}_A : A \rightarrow A$ is the function defined by $\text{id}_A(a) = a$.

Theorem 1.19. *Composition of relations is associative, and the identity function is an identity for composition. The composite of functions is a function. The composite of injective functions is injective. The composite of surjective functions is surjective. The composite of bijections is a bijection. A function $f : A \rightarrow B$ is a bijection iff there exists a function $f^{-1} : B \rightarrow A$ such that $f^{-1}f = \text{id}_A$ and $ff^{-1} = \text{id}_B$, in which case f^{-1} is unique.*

1.5 Axioms Part Two

Axiom 1.20 (Power Set). *For any set A , there exists a set $\mathcal{P}A$, the power set of A , and a relation $\in : A \rightarrowtail \mathcal{P}A$, called membership, such that, for any subset S of A , there exists a unique $\bar{S} \in \mathcal{P}A$ such that, for all $x \in A$, we have $x \in \bar{S}$ if and only if $x \in S$.*

We usually write just S for \bar{S} .

Axiom Schema 1.21 (Collection). *Let $P[X, Y, x]$ be a formula with set variables X and Y and an element variable $x \in X$. Then the following is an axiom.*

For any set A , there exists a set B , a function $p : B \rightarrow A$, a set Y and a relation $M : B \rightarrowtail Y$ such that:

- $\forall b \in B. P[A, \{y \in Y : bMy\}, p(b)]$
- *For all $a \in A$, if $\exists Y. P[A, Y, a]$, then there exists $b \in B$ such that $a = p(b)$.*

Definition 1.22 (Universe). Let $E : U \rightarrowtail X$ be a relation. Let us say that a set A is *small* iff there exists $u \in U$ such that $A \approx \{x \in X : uEx\}$.

Then (U, X, E) form a *universe* if and only if:

- \mathbb{N} is U -small.
- For any U -small sets A and B and relation $R : A \rightarrowtail B$, the tabulation of R is U -small.
- If A is U -small then so is $\mathcal{P}A$
- Let $f : A \rightarrow B$ be a function. If B is U -small and $f^{-1}(b)$ is U -small for all $b \in B$, then A is U -small.

- If $p : B \twoheadrightarrow A$ is a surjective function such that A is U -small, then there exists a U -small set C , a surjection $q : C \twoheadrightarrow A$, and a function $f : C \rightarrow B$ such that $q = pf$.

Axiom 1.23 (Universe). *There exists a universe.*

Let $E : U \twoheadrightarrow X$ be a universe. We shall say a set is *small* iff it is U -small, and *large* otherwise.

1.6 Cartesian Product

Definition 1.24 (Cartesian Product). Let A and B be sets. The *Cartesian product* of A and B , $A \times B$, is the tabulation of the relation $A \twoheadrightarrow B$ that holds for all $a \in A$ and $b \in B$. The associated functions $\pi_1 : A \times B \rightarrow A$ and $\pi_2 : A \times B \rightarrow B$ are called the *projections*.

Given $a \in A$ and $b \in B$, we write (a, b) for the unique element of $A \times B$ such that $\pi_1(a, b) = a$ and $\pi_2(a, b) = b$.

1.7 Quotient Sets

Proposition 1.25. *Let \sim be an equivalence relation on X . Then there exists a set X/\sim , the quotient set of X with respect to \sim , and a surjective function $\pi : X \twoheadrightarrow X/\sim$, the canonical projection, such that, for all $x, y : \text{El}(X)$, we have $x \sim y$ if and only if $\pi(x) = \pi(y)$.*

Further, if $p : X \twoheadrightarrow Q$ is another quotient with respect to \sim , then there exists a unique bijection $\phi : X/\sim \approx Q$ such that $\phi \circ \pi = p$.

Chapter 2

Topology

2.1 Topological Spaces

Definition 2.1 (Topological Space). Let X be a set and $\mathcal{O} \subseteq \mathcal{P}X$. Then we say (X, \mathcal{O}) is a *topological space* iff:

- For any $\mathcal{U} \subseteq \mathcal{O}$ we have $\bigcup \mathcal{U} \in \mathcal{O}$.
- For any $U, V \in \mathcal{O}$ we have $U \cap V \in \mathcal{O}$.
- $X \in \mathcal{O}$

We call \mathcal{O} the *topology* of the topological space, and call its elements *open* sets. We shall often write X for the topological space (X, \mathcal{O}) .

Definition 2.2 (Closed Set). Let X be a topological space and $A \subseteq X$. Then A is *closed* iff $X - A$ is open.

Proposition 2.3. *A set B is open if and only if $X - B$ is closed.*

Proposition 2.4. *Let X be a set and $\mathcal{C} \subseteq \mathcal{P}X$. Then there exists a topology \mathcal{O} on X such that \mathcal{C} is the set of closed sets if and only if:*

- For any $\mathcal{D} \subseteq \mathcal{C}$ we have $\bigcap \mathcal{D} \in \mathcal{C}$
- For any $C, D \in \mathcal{C}$ we have $C \cup D \in \mathcal{C}$.
- $\emptyset \in \mathcal{C}$

In this case, \mathcal{O} is unique and is given by $\mathcal{O} = \{X - C : C \in \mathcal{C}\}$.

Definition 2.5 (Neighbourhood). Let X be a topological space, $x \in X$ and $U \subseteq X$. Then U is a *neighbourhood* of x , and x is an *interior* point of U , iff there exists an open set V such that $x \in V \subseteq U$.

Proposition 2.6. *A set B is open if and only if it is a neighbourhood of each of its points.*

Proposition 2.7. *Let X be a set and $\mathcal{N} : X \rightarrow \mathcal{P}X$. Then there exists a topology \mathcal{O} on X such that, for all $x \in X$, we have \mathcal{N}_x is the set of neighbourhoods of x , if and only if:*

- *For all $x \in X$ and $N \in \mathcal{N}_x$ we have $x \in N$*
- *For all $x \in X$ we have $X \in \mathcal{N}_x$*
- *For all $x \in X$, $N \in \mathcal{N}_x$ and $V \subseteq \mathcal{P}X$, if $N \subseteq V$ then $V \in \mathcal{N}_x$*
- *For all $x \in X$ and $M, N \in \mathcal{N}_x$ we have $M \cap N \in \mathcal{N}_x$*
- *For all $x \in X$ and $N \in \mathcal{N}_x$, there exists $M \in \mathcal{N}_x$ such that $M \subseteq N$ and $\forall y \in M. M \in \mathcal{N}_y$.*

In this case, \mathcal{O} is unique and is given by $\mathcal{O} = \{U : \forall x \in U. U \in \mathcal{N}_x\}$.

Definition 2.8 (Exterior Point). Let X be a topological space, $x \in X$ and $B \subseteq X$. Then x is an *exterior point* of B iff $B - X$ is a neighbourhood of x .

Definition 2.9 (Boundary Point). Let X be a topological space, $x \in X$ and $B \subseteq X$. Then x is a *boundary point* of B iff it is neither an interior point nor an exterior point of B .

Definition 2.10 (Interior). Let X be a topological space and $B \subseteq X$. The *interior* of B , B° , is the set of all interior points of B .

Proposition 2.11. *The interior of B is the union of all the open sets included in B .*

Definition 2.12 (Closure). Let X be a topological space and $B \subseteq X$. The *closure* of B , \overline{B} , is the set of all points that are not exterior points of B .

Proposition 2.13. *The closure of B is the intersection of all the closed sets that include B .*

Proposition 2.14. *A set B is open iff $X - B = \overline{X - B}$.*

Proposition 2.15 (Kuratowski Closure Axioms). *Let X be a set and $- : \mathcal{P}X \rightarrow \mathcal{P}X$. Then there exists a topology \mathcal{O} such that, for all $B \subseteq X$, \overline{B} is the closure of B , if and only if:*

- $\overline{\emptyset} = \emptyset$
- *For all $A \subseteq X$ we have $A \subseteq \overline{A}$*
- *For all $A \subseteq X$ we have $\overline{\overline{A}} = \overline{A}$*
- *For all $A, B \subseteq X$ we have $\overline{A \cup B} = \overline{A} \cup \overline{B}$*

In this case, \mathcal{O} is unique and is defined by $\mathcal{O} = \{U : X - U = \overline{X - U}\}$.

2.1.1 Subspaces

Definition 2.16 (Subspace). Let X be a topological space and $X_0 \subseteq X$. The *subspace topology* on X_0 is $\{U \cap X_0 : U \text{ is open in } X\}$.

Example 2.17. The *unit sphere* S^2 is $\{x \in \mathbb{R}^3 : \|x\| = 1\}$ as a subspace of \mathbb{R}^3 .

2.1.2 Topological Disjoint Union

Definition 2.18. Let X and Y be topological spaces. The *disjoint union* is $X + Y$ where $U \subseteq X + Y$ is open if and only if $\kappa_1^{-1}(U)$ is open in X and $\kappa_2^{-1}(U)$ is open in Y .

2.1.3 Product Topology

Definition 2.19. Let X and Y be topological spaces. The *product topology* on $X \times Y$ is the set of all subsets $W \subseteq X \times Y$ such that, for all $(x, y) \in W$, there exist neighbourhoods U of x in X and V of y in Y such that $U \times V \subseteq W$.

2.1.4 Bases

Definition 2.20 (Basis). Let X be a topological space. A *basis* for the topology on X is a set of open sets \mathcal{B} such that every open set is the union of a subset of \mathcal{B} .

2.1.5 Subbases

Definition 2.21 (Subbasis). Let X be a topological space. A *subbasis* for the topology on X is a subset $\mathcal{S} \subseteq \mathcal{P}X$ such that every open set is a union of finite intersections of \mathcal{S} .

2.2 Continuous Functions

Definition 2.22 (Continuous). Let X and Y be topological spaces. A function $f : X \rightarrow Y$ is *continuous* iff, for every open set V in Y , the inverse image $f^{-1}(V)$ is open in X .

Proposition 2.23. 1. id_X is continuous

2. The composite of two continuous functions is continuous.

3. If $f : X \rightarrow Y$ is continuous and $X_0 \subseteq X$ then $f|_{X_0} : X_0 \rightarrow Y$ is continuous.

4. If $f : X + Y \rightarrow Z$, then f is continuous iff $f \circ \kappa_1 : X \rightarrow Z$ and $f \circ \kappa_2 : Y \rightarrow Z$ are continuous.

5. If $f : Z \rightarrow X \times Y$, then f is continuous iff $\pi_1 \circ f$ and $\pi_2 \circ f$ are continuous.

Definition 2.24 (Homeomorphism). Let X and Y be topological spaces. A *homeomorphism* between X and Y is a bijection $f : X \approx Y$ such that f and f^{-1} are continuous.

Definition 2.25 (Retraction). Let X be a topological space and A a subspace of X . A continuous function $\rho : X \rightarrow A$ is a *retraction* iff $\rho|_A = \text{id}_A$. We say A is a *retract* of X iff there exists a retraction.

2.3 Convergence

Definition 2.26 (Convergence). Let X be a topological space. Let (x_n) be a sequence in X . A point $a \in \text{El}(X)$ is a *limit* of the sequence iff, for every neighbourhood U of a , there exists n_0 such that $\forall n \geq n_0, x_n \in U$.

2.4 Connected Spaces

Definition 2.27 (Connected). A topological space is *connected* iff it is not the union of two nonempty open disjoint subsets.

Proposition 2.28. *The continuous image of a connected space is connected.*

Proposition 2.29. *Let X be a topological space and $A, B \subseteq X$. If $X = A \cup B$, $A \cap B \neq \emptyset$, and A and B are connected, then X is connected.*

Proposition 2.30. *If X and Y are nonempty topological spaces, then $X \times Y$ is connected if and only if X and Y are connected.*

Definition 2.31 (Path-connected). A topological space X is *path-connected* iff, for any points $a, b \in X$, there exists a continuous function $\alpha : [0, 1] \rightarrow X$, called a *path*, such that $\alpha(0) = a$ and $\alpha(1) = b$.

Proposition 2.32. *The continuous image of a path connected space is path connected.*

Proposition 2.33. *Let X be a topological space and $A, B \subseteq X$. If $X = A \cup B$, $A \cap B \neq \emptyset$, and A and B are path connected, then X is path connected.*

Proposition 2.34. *If X and Y are nonempty topological spaces, then $X \times Y$ is path connected if and only if X and Y are path connected.*

2.5 Hausdorff Spaces

Definition 2.35 (Hausdorff). A topological space is a *Hausdorff* space or a T_2 space iff any two distinct points have disjoint neighbourhoods.

Proposition 2.36. *In a Hausdorff space, a sequence has at most one limit.*

Proposition 2.37. *1. Every subspace of a Hausdorff space is Hausdorff.*

2. The disjoint union of two Hausdorff spaces is Hausdorff.

3. The product of two Hausdorff spaces is Hausdorff.

Proposition 2.38. *Let A be a topological space and B a Hausdorff space. Let $f, g : A \rightarrow B$ be continuous. Let $X \subseteq A$ be dense. If f and g agree on X , then $f = g$.*

PROOF:

$\langle 1 \rangle 1$. ASSUME: for a contradiction $a \in A$ and $f(a) \neq g(a)$.

$\langle 1 \rangle 2$. PICK disjoint neighbourhoods U and V of $f(a)$ and $g(a)$ respectively.

$\langle 1 \rangle 3$. PICK $x \in f^{-1}(U) \cap g^{-1}(V)$

$\langle 1 \rangle 4$. $f(x) = g(x) \in U \cap V$

$\langle 1 \rangle 5$. Q.E.D.

PROOF: This is a contradiction.

□

Proposition 2.39. *Let X and Y be metric spaces. Let $f : X \rightarrow Y$ be uniformly continuous. Let \hat{X} and \hat{Y} be the completions of X and Y . Then f extends uniquely to a continuous map $\hat{X} \rightarrow \hat{Y}$.*

PROOF: The extension maps $\lim_{n \rightarrow \infty} x_n$ to $\lim_{n \rightarrow \infty} f(x_n)$. □

2.6 Compactness

Definition 2.40 (Compact). A topological space is *compact* iff every open cover has a finite subcover.

Proposition 2.41. *Let X be a compact topological space. Let P be a set of open sets such that, for all $U, V \in P$, we have $U \cup V \in P$. Assume that every point has an open neighbourhood in P . Then $X \in P$.*

PROOF:

$\langle 1 \rangle 1$. P is an open cover of X

$\langle 1 \rangle 2$. PICK a finite subcover $U_1, \dots, U_n \in P$

$\langle 1 \rangle 3$. $X = U_1 \cup \dots \cup U_n \in P$

□

Corollary 2.41.1. *Let f be a compact space and $f : X \rightarrow \mathbb{R}$ be locally bounded. Then f is bounded.*

PROOF: Take $P = \{U \text{ open in } X : f \text{ is bounded on } U\}$. □

Proposition 2.42. *The continuous image of a compact space is compact.*

Proposition 2.43. *A closed subspace of a compact space is compact.*

Proposition 2.44. *Let X and Y be nonempty spaces. Then the following are equivalent.*

1. X and Y are compact.
2. $X + Y$ is compact.
3. $X \times Y$ is compact.

Proposition 2.45. *A compact subspace of a Hausdorff space is closed.*

Proposition 2.46. *A continuous bijection from a compact space to a Hausdorff space is a homeomorphism.*

2.7 Quotient Spaces

Definition 2.47 (Quotient Space). Let X be a topological space and \sim an equivalence relation on X . The *quotient topology* on X/\sim is defined by: $U : \text{El}(\mathcal{P}X)$ is open in X/\sim if and only if $\pi^{-1}(U)$ is open in X .

Proposition 2.48. *Let X and Y be topological spaces. Let \sim be an equivalence relation on X . Let $f : X/\sim \rightarrow Y$. Then f is continuous if and only if $f \circ \pi$ is continuous.*

Proposition 2.49. *Let X and Y be topological spaces. Let \sim be an equivalence relation on X . Let $\phi : Y \rightarrow X/\sim$.*

Assume that, for all $y \in Y$, there exists a neighbourhood U of y and a continuous function $\Phi : U \rightarrow X$ such that $\pi \circ \Phi = \phi|_U$. Then ϕ is continuous.

Proposition 2.50. *A quotient of a connected space is connected.*

Proposition 2.51. *A quotient of a path connected space is path connected.*

Proposition 2.52. *Let X be a topological space and \sim an equivalence relation on X . If X/\sim is Hausdorff then every equivalence class of \sim is closed in X .*

Definition 2.53. Let X be a topological space and $A_1, \dots, A_r \subseteq X$. Then $X/A_1, \dots, A_r$ is the quotient space of X with respect to \sim where $x \sim y$ iff $x = y$ or $\exists i(x \in A_i \wedge y \in A_i)$.

Definition 2.54 (Cone). Let X be a topological space. The *cone over X* is the space $(X \times [0, 1])/(X \times \{1\})$.

Definition 2.55 (Suspension). Let X be a topological space. The *suspension* of X is the space

$$\Sigma X := (X \times [-1, 1])/(X \times \{-1\}), (X \times \{1\})$$

Definition 2.56 (Wedge Product). Let $x_0 \in X$ and $y_0 \in Y$. The *wedge product* $X \vee Y$ is $(X \times \{y_0\}) \cup (\{x_0\} \times Y)$ as a subspace of $X \times Y$.

Definition 2.57 (Smash Product). Let $x_0 \in X$ and $y_0 \in Y$. The *smash product* $X \wedge Y$ is $(X \times Y)/(X \vee Y)$.

Example 2.58. $D^n/S^{n-1} \cong S^n$

PROOF:

$\langle 1 \rangle 1$. LET: $\phi : D^n/S^{n-1} \rightarrow S^n$ be the function induced by the map $D^n \rightarrow S^n$ that maps the radii of D^n onto the meridians of S^n from the north to the south pole.

$\langle 1 \rangle 2$. ϕ is a bijection.

$\langle 1 \rangle 3$. ϕ is a homeomorphism.

PROOF: Since D^n/S^{n-1} is compact and S^n is Hausdorff.

□

2.8 Gluing

Definition 2.59 (Gluing). Let X and Y be topological spaces, $X_0 \subseteq X$ and $\phi : X_0 \rightarrow Y$ a continuous map. Then $Y \cup_\phi X$ is the quotient space $(X + Y)/\sim$, where \sim is the equivalence relation generated by $x \sim \phi(x)$ for all $x : \text{El}(X)$.

Proposition 2.60. Y is a subspace of $Y \cup_\phi X$.

Definition 2.61. Let X be a topological space and $\alpha : X \cong X$ a homeomorphism. Then $(X \times [0, 1])/\alpha$ is the quotient space of $X \times [0, 1]$ by the equivalence relation generated by $(x, 0) \sim (\alpha(x), 1)$ for all $x : \text{El}(X)$.

Definition 2.62 (Möbius Strip). The *Möbius strip* is $([-1, 1] \times [0, 1])/\alpha$ where $\alpha(x) = -x$.

Definition 2.63 (Klein Bottle). The *Klein bottle* is $(S^1 \times [0, 1])/\alpha$ where $\alpha(z) = \bar{z}$.

Proposition 2.64. Let M be the Möbius strip and K the Klein bottle. Then $M \cup_{\text{id}_M} M \cong K$.

PROOF:

$\langle 1 \rangle 1$. LET: $f : ([-1, 1] \times [0, 1]) + ([-1, 1] \times [0, 1]) \rightarrow S^1 \times [0, 1]$ be the function that maps $\kappa_1(\theta, t)$ to $(e^{\pi i \theta/2}, t)$ and $\kappa_2(\theta, t)$ to $(-e^{-\pi i \theta/2}, t)$.

$\langle 1 \rangle 2$. f induces a bijection $M \cup_{\text{id}_M} M \approx K$

$\langle 1 \rangle 3$. f is a homeomorphism.

□

2.9 Metric Spaces

Definition 2.65 (Metric Space). Let X be a set and $d : X^2 \rightarrow \mathbb{R}$. We say (X, d) is a *metric space* iff:

- For all $x, y \in X$ we have $d(x, y) \geq 0$
- For all $x, y \in X$ we have $d(x, y) = 0$ iff $x = y$
- For all $x, y \in X$ we have $d(x, y) = d(y, x)$

- (*Triangle Inequality*) For all $x, y, z \in X$ we have $d(x, z) \leq d(x, y) + d(y, z)$

We call d the *metric* of the metric space (X, d) . We often write X for the metric space (X, d) .

Definition 2.66 (Topology of a Metric Space). Let (X, d) be a metric space. The topology *induced* by the metric d is defined by: for $V \subseteq X$, we have V is open if and only if, for all $x \in V$, there exists $\epsilon > 0$ such that $\{y \in X : d(x, y) < \epsilon\} \subseteq V$.

Definition 2.67 (Metriizable). A topological space is *metrizable* iff there exists a metric that induces its topology.

Proposition 2.68. *Every metrizable space is Hausdorff.*

2.10 Complete Metric Spaces

Definition 2.69 (Complete). A metric space is *complete* iff every Cauchy sequence converges.

Example 2.70. \mathbb{R} is complete.

Proposition 2.71. *The product of two complete metric spaces is complete.*

Proposition 2.72. *Every compact metric space is complete.*

Proposition 2.73. *Let X be a complete metric space and $A \subseteq X$. Then A is complete if and only if A is closed.*

Definition 2.74 (Completion). Let X be a metric space. A *completion* of X is a complete metric space \hat{X} and injection $i : X \rightarrow \hat{X}$ such that:

- The metric on X is the restriction of the metric on \hat{X}
- X is dense in \hat{X} .

Proposition 2.75. *Let $i_1 : X \rightarrow Y_1$ and $i_2 : X \rightarrow Y_2$ be completions of X . Then there exists a unique isometry $\phi : Y_1 \cong Y_2$ such that $\phi \circ i_1 = i_2$.*

PROOF: Define $\phi(\lim_{n \rightarrow \infty} i_1(x_n)) = \lim_{n \rightarrow \infty} i_2(x_n)$. \square

Theorem 2.76. *Every metric space has a completion.*

PROOF: Let \hat{X} be the set of Cauchy sequences in X quotiented by \sim where $(x_n) \sim (y_n)$ if and only if $d(x_n, y_n) \rightarrow 0$. \square

Chapter 3

Homotopy Theory

3.1 Homotopies

Definition 3.1 (Homotopy). Let X and Y be topological spaces. Let $f, g : X \rightarrow Y$ be continuous. A *homotopy* between f and g is a continuous function $h : X \times [0, 1] \rightarrow Y$ such that

- $\forall x : \text{El}(X) . h(x, 0) = f(x)$
- $\forall x : \text{El}(X) . h(x, 1) = g(x)$

We say f and g are *homotopic*, $f \simeq g$, iff there exists a homotopy between them.

Let $[X, Y]$ be the set of all homotopy classes of functions $X \rightarrow Y$.

Proposition 3.2. Let $f, f' : X \rightarrow Y$ and $g, g' : Y \rightarrow Z$ be continuous. If $f \simeq f'$ and $g \simeq g'$ then $g \circ f \simeq g' \circ f'$.

3.2 Homotopy Equivalence

Definition 3.3 (Homotopy Equivalence). Let X and Y be topological spaces. A *homotopy equivalence* between X and Y , $f : X \simeq Y$, is a continuous function $f : X \rightarrow Y$ such that there exists a continuous function $g : Y \rightarrow X$, the *homotopy inverse* to f , such that $g \circ f \simeq \text{id}_X$ and $f \circ g \simeq \text{id}_Y$.

Definition 3.4 (Contractible). A topological space X is *contractible* iff $X \simeq 1$.

Example 3.5. \mathbb{R}^n is contractible.

Example 3.6. D^n is contractible.

Definition 3.7 (Deformation Retract). Let X be a topological space and A a subspace of X . A retraction $\rho : X \rightarrow A$ is a *deformation retraction* iff $i \circ \rho \simeq \text{id}_X$, where i is the inclusion $A \hookrightarrow X$. We say A is a *deformation retract* of X iff there exists a deformation retraction.

Definition 3.8 (Strong Deformation Retract). Let X be a topological space and A a subspace of X . A *strong deformation retraction* $\rho : X \rightarrow A$ is a continuous function such that there exists a homotopy $h : X \times [0, 1] \rightarrow X$ between $i \circ \rho$ and id_X such that, for all $a : \text{El}(X)$ and $t : \text{El}([0, 1])$, we have $h(a, t) = a$.

We say A is a *strong deformation retract* of X iff a strong deformation retraction exists.

Example 3.9. $\{0\}$ is a strong deformation retract of \mathbb{R}^n and of D^n .

Example 3.10. S^1 is a strong deformation retract of the torus $S^1 \times D^2$.

Example 3.11. S^{n-1} is a strong deformation retract of $D^n - \{0\}$.

Example 3.12. For any topological space X , the singleton consisting of the vertex is a strong deformation retract of the cone over X .

Chapter 4

Topological Groups

Definition 4.1 (Topological Group). A *topological group* is a group G with a topology such that the function $G^2 \rightarrow G$ that maps (x, y) to xy^{-1} is continuous.

Example 4.2. $GL(n, \mathbb{R})$ and $GL(n, \mathbb{C})$ are topological groups.

Proposition 4.3. Any subgroup of a topological group is a topological group under the subspace topology.

Definition 4.4 (Homogeneous Space). A *homogeneous space* is a topological space of the form G/H , where G is a topological group and H is a normal subgroup of G , under the quotient topology.

Proposition 4.5. Let G be a topological group and H a normal subgroup of G . Then G/H is Hausdorff if and only if H is closed.

PROOF: See Bourbaki, N., General Topology. III.12 \square

4.1 Continuous Actions

Definition 4.6 (Continuous Action). Let G be a topological group and X a topological space. A *continuous action* of G on X is a continuous function $\cdot : G \times X \rightarrow X$ such that:

- $\forall x : \text{El}(X) . ex = x$
- $\forall g, h : \text{El}(G) . \forall x : \text{El}(X) . g(hx) = (gh)x$

A G -space consists of a topological space X and a continuous action of G on X .

Definition 4.7 (Orbit). Let X be a G -space and $x \in X$. The *orbit* of x is $\{gx : g \in G\}$.

The *orbit space* X/G is the set of all orbits under the quotient topology.

Proposition 4.8. *Define an action of $SO(2)$ on S^2 by $g(x_1, x_2, x_3) = (g(x_1, x_2), x_3)$. Then $S^2/SO(2) \cong [-1, 1]$.*

PROOF:

$\langle 1 \rangle 1$. LET: $f_3 : S^2/SO(2) \rightarrow [-1, 1]$ be the function induced by $\pi_3 : S^2 \rightarrow [-1, 1]$

$\langle 1 \rangle 2$. f_3 is bijective.

$\langle 1 \rangle 3$. $S^2/SO(2)$ is compact.

PROOF: It is the continuous image of S^2 which is compact.

$\langle 1 \rangle 4$. $[-1, 1]$ is Hausdorff.

$\langle 1 \rangle 5$. f_3 is a homeomorphism.

□

Definition 4.9 (Stabilizer). Let X be a G -space and $x \in X$. The *stabilizer* of x is $G_x := \{g \in G \mid gx = x\}$.

Proposition 4.10. *The function that maps gG_x to gx is a continuous bijection from G/G_x to Gx .*

PROOF:

$\langle 1 \rangle 1$. If $gG_x = hG_x$ then $gx = hx$.

$\langle 2 \rangle 1$. ASSUME: $gG_x = hG_x$

$\langle 2 \rangle 2$. $g^{-1}h \in G_x$

$\langle 2 \rangle 3$. $g^{-1}hx = x$

$\langle 2 \rangle 4$. $gx = hx$

$\langle 1 \rangle 2$. If $gx = hx$ then $gG_x = hG_x$.

PROOF: Similar.

$\langle 1 \rangle 3$. The function is continuous.

PROOF: Proposition 2.48.

□

Chapter 5

Topological Vector Spaces

Definition 5.1 (Topological Vector Space). Let K be either \mathbb{R} or \mathbb{C} . A *topological vector space* over K consists of a vector space E over K and a topology on E such that:

- Subtraction is a continuous function $E^2 \rightarrow E$
- Multiplication is a continuous function $K \times E \rightarrow E$

Proposition 5.2. *Every topological vector space is a topological group under addition.*

PROOF: Immediate from the definition. \square

Theorem 5.3. *The usual topology on a finite dimensional vector space over K is the only one that makes it into a Hausdorff topological vector space.*

PROOF: See Bourbaki. Elements de Mathematique, Livre V: Espaces Vectoriels Topologiques, Th. 2, p. 18 \square

Proposition 5.4. *Let E be a topological vector space and E_0 a subspace of E . Then $\overline{E_0}$ is a subspace of E .*

Definition 5.5. Let E be a topological vector space. The topological space associated with E is $E/\overline{\{0\}}$.

5.1 Cauchy Sequences

Definition 5.6 (Cauchy Sequence). Let E be a topological vector space. A sequence (x_n) in E is a *Cauchy sequence* iff, for every neighbourhood U of 0, there exists n_0 such that $\forall m, n \geq n_0, x_n - x_m \in U$.

Definition 5.7 (Complete Topological Vector Space). A topological vector space is *complete* iff every Cauchy sequence converges.

5.2 Seminorms

Definition 5.8 (Seminorm). Let E be a vector space over K . A *seminorm* on E is a function $\| \cdot \| : E \rightarrow \mathbb{R}$ such that:

1. $\forall x : \text{El}(E) . \|x\| \geq 0$
2. $\forall \alpha : \text{El}(K) . \forall x : \text{El}(E) . \|\alpha x\| = |\alpha| \|x\|$
3. *Triangle Inequality* $\forall x, y : \text{El}(E) . \|x + y\| \leq \|x\| + \|y\|$

Example 5.9. The function that maps (x_1, \dots, x_n) to $|x_i|$ is a seminorm on \mathbb{R}^n .

Definition 5.10. Let E be a vector space over K . Let Λ be a set of seminorms on E . The topology *generated* by Λ is the topology generated by the subbasis consisting of all sets of the form $B_\epsilon^\lambda(x) = \{y \in E : \lambda(y - x) < \epsilon\}$ for $\epsilon > 0$, $\lambda \in \Lambda$ and $x : \text{El}(E)$.

Proposition 5.11. E is a topological vector space under this topology. It is Hausdorff iff, for all $x : \text{El}(E)$, if $\forall \lambda \in \Lambda . \lambda(x) = 0$ then $x = 0$.

5.3 Fréchet Spaces

Definition 5.12 (Pre-Fréchet Space). A *pre-Fréchet space* is a Hausdorff topological vector space whose topology is generated by a countable set of seminorms.

Proposition 5.13. Let E be a pre-Fréchet space whose topology is generated by the family of seminorms $\{\| \cdot \|_n : n \in \mathbb{Z}^+\}$. Then

$$d(x, y) = \sum_{n=1}^{\infty} \frac{1}{2^n} \frac{\|x - y\|_n}{1 + \|x - y\|_n}$$

is a metric that induces the same topology. The two definitions of Cauchy sequence agree.

Definition 5.14 (Fréchet Space). A *Fréchet space* is a complete pre-Fréchet space.

5.4 Normed Spaces

Definition 5.15 (Normed Space). Let E be a vector space over K . A *norm* on E is a function $\| \cdot \| : E \rightarrow \mathbb{R}$ is a seminorm such that, $\forall x \in E . \|x\| = 0 \Leftrightarrow x = 0$.

A *normed space* consists of a vector space with a norm.

Proposition 5.16. If E is a normed space then $d(x, y) = \|x - y\|$ is a metric on E that makes E into a topological vector space. The two definitions of Cauchy sequence agree on E .

Proposition 5.17. *Let $\| \cdot \|$ be a seminorm on the vector space E . Then $\| \cdot \|$ defines a norm on $E/\{0\}$.*

Proposition 5.18. *Let E and F be normed spaces. Any continuous linear map $E \rightarrow F$ is uniformly continuous.*

Definition 5.19. For $p \geq 1$, let $\mathcal{L}^p(\mathbb{R}^n)$ be the vector space of all Lebesgue-measurable functions $f : \mathbb{R}^n \rightarrow \mathbb{R}$ such that $|f|^p$ is Lebesgue-integrable. Then

$$\|f\|_p := \sqrt[p]{\int_{\mathbb{R}^n} |f(x)|^p dx}$$

defines a seminorm on $\mathcal{L}^p(\mathbb{R}^n)$. Let

$$L^p(\mathbb{R}^n) := \mathcal{L}^p(\mathbb{R}^n)/\{0\} .$$

5.5 Inner Product Spaces

Proposition 5.20. *If E is an inner product space then $\|x\| = \sqrt{\langle x, x \rangle}$ is a norm on E .*

5.6 Banach Spaces

Definition 5.21 (Banach Space). A *Banach space* is a complete normed space.

Example 5.22. For any topological space X , the set $C(X)$ of bounded continuous functions $X \rightarrow \mathbb{R}$ is a Banach space under $\|f\| = \sup_{x \in X} |f(x)|$.

Proposition 5.23. *The completion of a normed space is a Banach space.*

Proposition 5.24. *Let E and F be normed spaces. Let $f : E \rightarrow F$ be a continuous linear map. Then the extension to the completions $\hat{E} \rightarrow \hat{F}$ is linear.*

Proposition 5.25. $L^p(\mathbb{R}^n)$ is a Banach space.

5.7 Hilbert Spaces

Definition 5.26 (Hilbert Space). A *Hilbert space* is a complete inner product space.

Example 5.27. The set of *square-integrable functions* is the set of Lebesgue integrable functions $[-\pi, \pi] \rightarrow \mathbb{R}$ quotiented by: $f \sim g$ iff $\{x \in [-\pi, \pi] : f(x) \neq g(x)\}$ has measure 0. This is a Hilbert space under

$$\langle f, g \rangle = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x)g(x)dx .$$

Proposition 5.28. *The completion of an inner product space is a Hilbert space.*

5.8 Locally Convex Spaces

Definition 5.29 (Locally Convex Space). A topological vector space is *locally convex* iff every neighbourhood of 0 includes a convex neighbourhood of 0.

Proposition 5.30. *A topological vector space is locally convex if and only if its topology is generated by a set of seminorms.*

PROOF: See Köthe, G. Topological Vector Spaces 1. Section 18. \square

Proposition 5.31. *A locally convex topological vector space is a pre-Fréchet space if and only if it is metrizable.*

PROOF: See Köthe, G. Topological Vector Spaces 1. Section 18. \square

Example 5.32. Let E be an infinite dimensional Hilbert space. Let E' be the same vector space under the *weak topology*, the coarsest topology such that every continuous linear map $E \rightarrow \mathbb{R}$ is continuous as a map $E' \rightarrow \mathbb{R}$. Then E is locally convex Hausdorff but not metrizable.

Proof: See Dieudonne, J. A., Treatise on Analysis, Vol. II, New York and London: Academic Press, 1970, p. 76.

Definition 5.33 (Thom Space). Let E be a vector bundle with a Riemannian metric, $DE = \{x : \text{El}(E) \mid \|x\| \leq 1\}$ its disc bundle and $SE := \{v : \text{El}(E) \mid \|v\| = 1\}$ its sphere bundle. The *Thom space* of E is the quotient space DE/SE .