

Mathematics

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Part I

Set Theory

Chapter 1

Primitive Terms and Axioms

1.1 Primitive Terms

Let there be *sets*.

For any set A , let there be *elements* of A . We write $a \in A$ for: a is an element of A .

For any sets A and B , let there be a set B^A , whose elements are called *functions* from A to B . We write $f : A \rightarrow B$ for $f \in B^A$.

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

1.2 Injections, Surjections and Bijections

Definition 1.2.1 (Injective). We say a function $f : A \rightarrow B$ is *injective* or an *injection*, and write $f : A \rightarrowtail B$, iff, for all $x, y \in A$, if $f(x) = f(y)$ then $x = y$.

We say a set A is *dominated* by a set B , and write $A \leqslant B$, iff there exists an injection from A to B .

Definition 1.2.2 (Surjective). We say a function $f : A \rightarrow B$ is *surjective* or a *surjection*, and write $f : A \twoheadrightarrow B$, iff, for all $y \in B$, there exists $x \in A$ such that $f(x) = y$.

Definition 1.2.3 (Bijective). We say a function $f : A \rightarrow B$ is *bijective* or a *bijection*, and write $f : A \approx B$, iff it is injective and surjective.

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

We say the set A is *strictly* dominated by the set B , and write $A < B$, iff $A \leqslant B$ and $A \not\approx B$.

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 Axioms

Axiom Schema 1.3.1 (Choice). *Let $P[X, Y, x, y]$ be a formula where X and Y are set variables, $x \in X$ and $y \in Y$. Then the following is an axiom.*

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

Axiom 1.3.2 (Extensionality). *Let $f, g : A \rightarrow B$. If, for all $x \in A$, we have $f(x) = g(x)$, then $f = g$.*

Axiom 1.3.3 (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 $a \in A$ and $b \in B$, there exists a unique $(a, b) \in A \times B$ such that $\pi_1(a, b) = a$ and $\pi_2(a, b) = b$.*

Axiom Schema 1.3.4 (Separation). *For every property $P[X, x]$ where X is a set variable and $x \in X$, the following is an axiom:*

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

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

Axiom 1.3.5 (Infinity). *There exists a set \mathbb{N} , an element $0 \in \mathbb{N}$, and a function $s : \mathbb{N} \rightarrow \mathbb{N}$ such that:*

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

Axiom Schema 1.3.6 (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 exist sets B and Y and functions $p : B \rightarrow A$, and $m : B \times Y \Rightarrow \mathbb{N}$ such that:

- m is injective.
- $\forall b \in B. P[A, \{y \in Y : m(b, y) = 0\}, p(b)]$
- For all $a \in A$, if $\exists Y. P[A, Y, a]$, then there exists $b \in B$ such that $a = p(b)$.

Definition 1.3.7 (Composition). Let $f : A \rightarrow B$ and $g : B \rightarrow C$. The composite $g \circ f : A \rightarrow C$ is the function such that, for all $a \in A$, we have

$$(g \circ f)(a) = g(f(a)) .$$

Axiom 1.3.8 (Universe). *There exists a set E , a set U and a function $el : E \rightarrow U$ such that the following holds.*

Let us say that a set A is small iff there exists $u \in U$ such that $A \approx \{e \in E : el(e) = u\}$.

- \mathbb{N} is small.
- For any U -small sets A and B , the set B^A is small.
- For any U -small sets A and B , the set $A \times B$ is small.
- Let $f : A \rightarrow B$ be a function. If B is small and $\{a \in A : f(a) = b\}$ is small for all $b \in B$, then A is small.
- If $p : B \twoheadrightarrow A$ is a surjective function such that A is small, then there exists a U -small set C , a surjection $q : C \twoheadrightarrow A$, and a function $f : C \rightarrow B$ such that $q = p \circ f$.

Chapter 2

Sets and Functions

2.1 Composition

Proposition 2.1.1. *Given functions $f : A \rightarrow B$, $g : B \rightarrow C$ and $h : C \rightarrow D$, we have*

$$h \circ (g \circ f) = (h \circ g) \circ f .$$

PROOF:

$\langle 1 \rangle 1$. For all $x \in A$ we have $(h \circ (g \circ f))(x) = ((h \circ g) \circ f)(x)$.

$\langle 2 \rangle 1$. LET: $x \in A$

$\langle 2 \rangle 2$. $(h \circ (g \circ f))(x) = ((h \circ g) \circ f)(x)$

PROOF:

$$(h \circ (g \circ f))(x) = h((g \circ f)(x)) \quad (\text{Definition of composition})$$

$$= h(g(f(x))) \quad (\text{Definition of composition})$$

$$= (h \circ g)(f(x)) \quad (\text{Definition of composition})$$

$$= ((h \circ g) \circ f)(x) \quad (\text{Definition of composition})$$

$\langle 1 \rangle 2$. Q.E.D.

PROOF: By the Axiom of Extensionality.

□

2.2 Injections

Proposition 2.2.1. *The composite of injective functions is injective.*

PROOF:

$\langle 1 \rangle 1$. LET: A , B and C be sets.

$\langle 1 \rangle 2$. LET: $f : A \rightarrow B$

$\langle 1 \rangle 3$. LET: $g : B \rightarrow C$

$\langle 1 \rangle 4$. ASSUME: g is injective.

$\langle 1 \rangle 5$. ASSUME: f is injective.

$\langle 1 \rangle 6$. LET: $x, y \in A$

$\langle 1 \rangle 7$. ASSUME: $(g \circ f)(x) = (g \circ f)(y)$

PROVE: $x = y$

$\langle 1 \rangle 8$. $g(f(x)) = g(f(y))$

PROOF:

$$g(f(x)) = (g \circ f)(x) \quad (\text{definition of composition})$$

$$= (g \circ f)(y) \quad (\langle 1 \rangle 7)$$

$$= g(f(y)) \quad (\text{definition of composition})$$

$\langle 1 \rangle 9$. $f(x) = f(y)$

PROOF: $\langle 1 \rangle 4, \langle 1 \rangle 8$

$\langle 1 \rangle 10$. $x = y$

PROOF: $\langle 1 \rangle 5, \langle 1 \rangle 9$

□

Proposition 2.2.2. *For functions $f : A \rightarrow B$ and $g : B \rightarrow C$, if $g \circ f$ is injective then f is injective.*

PROOF:

$\langle 1 \rangle 1$. LET: A, B and C be sets.

$\langle 1 \rangle 2$. LET: $f : A \rightarrow B$

$\langle 1 \rangle 3$. LET: $g : B \rightarrow C$

$\langle 1 \rangle 4$. ASSUME: $g \circ f$ is injective.

$\langle 1 \rangle 5$. LET: $x, y \in A$

$\langle 1 \rangle 6$. ASSUME: $f(x) = f(y)$

$\langle 1 \rangle 7$. $(g \circ f)(x) = (g \circ f)(y)$

PROOF:

$$(g \circ f)(x) = g(f(x)) \quad (\text{definition of composition})$$

$$= g(f(y)) \quad (\langle 1 \rangle 6)$$

$$= (g \circ f)(y) \quad (\text{definition of composition})$$

$\langle 1 \rangle 8$. $x = y$

PROOF: $\langle 1 \rangle 4, \langle 1 \rangle 7$

□

Proposition 2.2.3. *Let $f : A \rightarrow B$ be injective. For every set X and functions $x, y : X \rightarrow A$, if $f \circ x = f \circ y$ then $x = y$.*

PROOF:

$\langle 1 \rangle 1$. ASSUME: f is injective.

$\langle 1 \rangle 2$. LET: X be a set.

$\langle 1 \rangle 3$. LET: $x, y : X \rightarrow A$

$\langle 1 \rangle 4$. ASSUME: $f \circ x = f \circ y$

$\langle 1 \rangle 5$. $\forall t \in X. x(t) = y(t)$

$\langle 2 \rangle 1$. LET: $t \in X$

$\langle 2 \rangle 2$. $f(x(t)) = f(y(t))$

PROOF:

$$\begin{aligned} f(x(t)) &= (f \circ x)(t) && \text{(definition of composition)} \\ &= (f \circ y)(t) && (\langle 1 \rangle 4) \\ &= f(y(t)) && \text{(definition of composition)} \end{aligned}$$

$\langle 2 \rangle 3$. $x(t) = y(t)$

PROOF: $\langle 1 \rangle 1$, $\langle 2 \rangle 2$

$\langle 1 \rangle 6$. $x = y$

PROOF: Axiom of Extensionality, $\langle 1 \rangle 5$

□

We will prove the converse as Proposition 2.8.4.

2.3 Surjections

Proposition 2.3.1. *The composite of surjective functions is surjective.*

PROOF:

$\langle 1 \rangle 1$. LET: A , B and C be sets.

$\langle 1 \rangle 2$. LET: $f : A \rightarrow B$ and $g : B \rightarrow C$

$\langle 1 \rangle 3$. ASSUME: g is surjective.

$\langle 1 \rangle 4$. ASSUME: f is surjective.

$\langle 1 \rangle 5$. LET: $c \in C$

$\langle 1 \rangle 6$. PICK $b \in B$ such that $g(b) = c$.

PROOF: $\langle 1 \rangle 3$

$\langle 1 \rangle 7$. PICK $a \in A$ such that $f(a) = b$.

PROOF: $\langle 1 \rangle 4$

$\langle 1 \rangle 8$. $(g \circ f)(a) = c$

PROOF:

$$\begin{aligned} (g \circ f)(a) &= g(f(a)) && \text{(definition of composition)} \\ &= g(b) && (\langle 1 \rangle 7) \\ &= c && (\langle 1 \rangle 6) \end{aligned}$$

□

Proposition 2.3.2. *Let $f : A \rightarrow B$ and $g : B \rightarrow C$. If $g \circ f$ is surjective then g is surjective.*

PROOF:

$\langle 1 \rangle 1$. LET: A , B and C be sets.

$\langle 1 \rangle 2$. LET: $f : A \rightarrow B$ and $g : B \rightarrow C$.

$\langle 1 \rangle 3$. ASSUME: $g \circ f$ is surjective.

$\langle 1 \rangle 4$. LET: $c \in C$

$\langle 1 \rangle 5$. PICK $a \in A$ such that $(g \circ f)(a) = c$

PROOF: $\langle 1 \rangle 3$

$\langle 1 \rangle 6$. $g(f(a)) = c$

PROOF: From $\langle 1 \rangle 5$ and the definition of composition.

$\langle 1 \rangle 7$. Q.E.D.

PROOF: There exists $b \in B$ such that $g(b) = c$, namely $b = f(a)$.
 \square

Proposition 2.3.3. *Let $f : A \rightarrow B$ be a surjection. For any set X and functions $x, y : B \rightarrow X$, if $x \circ f = y \circ f$ then $x = y$.*

PROOF:

- $\langle 1 \rangle 1$. LET: $b \in B$
- $\langle 1 \rangle 2$. PICK $a \in A$ such that $f(a) = b$
- $\langle 1 \rangle 3$. $x(f(a)) = y(f(a))$
- $\langle 1 \rangle 4$. $x(b) = y(b)$
- $\langle 1 \rangle 5$. Q.E.D.

PROOF: Axiom of Extensionality.
 \square

We will prove the converse as Proposition 2.9.2.

2.4 Bijections

Proposition 2.4.1. *The composite of bijections is a bijection.*

PROOF:

- $\langle 1 \rangle 1$. LET: A, B and C be sets.
- $\langle 1 \rangle 2$. LET: $f : A \rightarrow B$ and $g : B \rightarrow C$
- $\langle 1 \rangle 3$. ASSUME: g is bijective.
- $\langle 1 \rangle 4$. ASSUME: f is bijective.
- $\langle 1 \rangle 5$. g is injective.
 PROOF: From $\langle 1 \rangle 3$.
- $\langle 1 \rangle 6$. g is surjective.
 PROOF: From $\langle 1 \rangle 3$.
- $\langle 1 \rangle 7$. f is injective.
 PROOF: From $\langle 1 \rangle 4$.
- $\langle 1 \rangle 8$. f is surjective.
 PROOF: From $\langle 1 \rangle 4$.
- $\langle 1 \rangle 9$. $g \circ f$ is injective.
 PROOF: Proposition 2.2.1, $\langle 1 \rangle 5$, $\langle 1 \rangle 7$.
- $\langle 1 \rangle 10$. $g \circ f$ is surjective.
 PROOF: Proposition 2.3.1, $\langle 1 \rangle 6$, $\langle 1 \rangle 8$.
- $\langle 1 \rangle 11$. $g \circ f$ is bijective.
 PROOF: $\langle 1 \rangle 9$, $\langle 1 \rangle 10$

\square

Proposition 2.4.2.

$$(A \times B)^C \approx A^C \times B^C$$

PROOF: The function that maps f to $(\pi_1 \circ f, \pi_2 \circ f)$ is a bijection. \square

Proposition 2.4.3.

$$A^{B \times C} \approx (A^B)^C$$

PROOF: The function Φ such that $\Phi(f)(c)(b) = f(b, c)$ is a bijection. \square

2.5 Domination

Definition 2.5.1 (Dominate). Let A and B be sets. We say that B *dominates* A , and write $A \leqslant B$, iff there exists an injective function $A \rightarrow B$.

Theorem 2.5.2 (Schroeder-Bernstein). *Let A and B be sets. If $A \leqslant B$ and $B \leqslant A$ then $A \approx B$.*

PROOF:

$\langle 1 \rangle 1$. LET: $f : A \rightarrow B$ and $g : B \rightarrow A$ be injections.

$\langle 1 \rangle 2$. Define the subsets A_n of A by

$$\begin{aligned} A_0 &:= A - g(B) \\ A_{n+1} &:= g(f(A_n)) \end{aligned}$$

$\langle 1 \rangle 3$. Define $h : A \rightarrow B$ by

$$h(x) = \begin{cases} f(x) & \text{if } \exists n. x \in A_n \\ g^{-1}(x) & \text{otherwise} \end{cases}$$

$\langle 1 \rangle 4$. h is injective.

$\langle 2 \rangle 1$. LET: $x, y \in A$

$\langle 2 \rangle 2$. ASSUME: $h(x) = h(y)$

$\langle 2 \rangle 3$. CASE: $x \in A_m$ and $y \in A_n$.

PROOF: Then $f(x) = f(y)$ so $x = y$ since f is injective.

$\langle 2 \rangle 4$. CASE: $x \in A_m$ and there is no y such that $y \in A_n$.

$\langle 3 \rangle 1$. $f(x) = g^{-1}(y)$

$\langle 3 \rangle 2$. $y = g(f(x))$

$\langle 3 \rangle 3$. $y \in A_{m+1}$

$\langle 3 \rangle 4$. Q.E.D.

PROOF: This is a contradiction.

$\langle 2 \rangle 5$. CASE: $y \in A_n$ and there is no m such that $x \in A_m$.

PROOF: Similar.

$\langle 2 \rangle 6$. CASE: There is no m such that $x \in A_m$ and there is no n such that $y \in A_n$.

PROOF: Then $g^{-1}(x) = g^{-1}(y)$ and so $x = y$.

$\langle 1 \rangle 5$. h is surjective.

$\langle 2 \rangle 1$. LET: $y \in B$

$\langle 2 \rangle 2$. CASE: $g(y) \in A_n$

$\langle 3 \rangle 1$. $n \neq 0$

$\langle 3 \rangle 2$. PICK $x \in A_{n-1}$ such that $g(y) = g(f(x))$

$\langle 3 \rangle 3$. $y = f(x)$

$\langle 3 \rangle 4$. $y = h(x)$

$\langle 2 \rangle 3$. CASE: There is no n such that $g(y) \in A_n$.

PROOF: Then $h(g(y)) = y$.

\square

2.6 Identity Function

Definition 2.6.1 (Identity). For any set A , the *identity* function $\text{id}_A : A \rightarrow A$ is the function defined by $\text{id}_A(a) = a$.

2.6.1 Injections, Surjections, Bijections

Proposition 2.6.2. For any set A , the identity function id_A is a bijection.

PROOF:

$\langle 1 \rangle 1$. LET: A be a set.

$\langle 1 \rangle 2$. id_A is injective.

PROOF: If $\text{id}_A(x) = \text{id}_A(y)$ then $x = y$.

$\langle 1 \rangle 3$. id_A is surjective.

PROOF: For any $y \in A$, there exists $x \in A$ such that $\text{id}_A(x) = y$, namely $x = y$.

□

2.6.2 Composition

Proposition 2.6.3. Let $f : A \rightarrow B$. Then $\text{id}_B \circ f = f = f \circ \text{id}_A$.

PROOF: Each is the function that maps a to $f(a)$. □

Proposition 2.6.4. Let $f : A \rightarrow B$.

1. If there exists $g : B \rightarrow A$ such that $g \circ f = \text{id}_A$ then f is injective.

2. If f is injective and A is nonempty, then there exists $g : B \rightarrow A$ such that $g \circ f = \text{id}_A$.

PROOF:

$\langle 1 \rangle 1$. If there exists $g : B \rightarrow A$ such that $g \circ f = \text{id}_A$ then f is injective.

PROOF: If $f(x) = f(y)$ then $x = g(f(x)) = g(f(y)) = y$.

$\langle 1 \rangle 2$. If f is injective and A is nonempty, then there exists $g : B \rightarrow A$ such that $g \circ f = \text{id}_A$.

$\langle 2 \rangle 1$. ASSUME: f is injective and A is nonempty.

$\langle 2 \rangle 2$. PICK $a \in A$

$\langle 2 \rangle 3$. Choose a function $g : B \rightarrow A$ such that $f(g(x)) = x$ if there exists $y \in A$ such that $f(y) = x$, otherwise $g(x) = a$.

$\langle 2 \rangle 4$. LET: $x \in A$

PROVE: $g(f(x)) = x$

$\langle 2 \rangle 5$. $f(g(f(x))) = f(x)$

$\langle 2 \rangle 6$. $g(f(x)) = x$

□

Proposition 2.6.5. Let $f : A \rightarrow B$. Then f is surjective if and only if there exists $g : B \rightarrow A$ such that $f \circ g = \text{id}_B$.

PROOF:

⟨1⟩1. If f is surjective then there exists $g : B \rightarrow A$ such that $f \circ g = \text{id}_B$.

⟨2⟩1. ASSUME: f is surjective.

⟨2⟩2. PICK $g : B \rightarrow A$ such that, for all $b \in B$, we have $f(g(b)) = b$.

PROOF: Axiom of Choice.

⟨2⟩3. $f \circ g = \text{id}_B$.

⟨1⟩2. If there exists $g : B \rightarrow A$ such that $f \circ g = \text{id}_B$ then f is surjective.

⟨2⟩1. LET: $g : B \rightarrow A$ such that $f \circ g = \text{id}_B$

⟨2⟩2. LET: X be a set.

⟨2⟩3. LET: $h, k : B \rightarrow X$

⟨2⟩4. ASSUME: $h \circ f = k \circ f$

⟨2⟩5. $h = k$

PROOF: $h = h \circ f \circ g = k \circ f \circ g = k$

□

Corollary 2.6.5.1. *Let A and B be sets.*

1. *If there exists a surjective function $A \rightarrow B$ then there exists an injective function $B \rightarrow A$.*
2. *If there exists an injective function $A \rightarrow B$ and A is nonempty then there exists a surjective function $B \rightarrow A$.*

Proposition 2.6.6. *Let $f : A \rightarrow B$. Then f is bijective if and only if there exists a function $f^{-1} : B \rightarrow A$, the inverse of f , such that $f \circ f^{-1} = \text{id}_B$ and $f^{-1} \circ f = \text{id}_A$, in which case the inverse is unique.*

PROOF:

⟨1⟩1. If f is bijective then there exists $f^{-1} : B \rightarrow A$ such that $f \circ f^{-1} = \text{id}_B$ and $f^{-1} \circ f = \text{id}_A$.

⟨2⟩1. ASSUME: f is bijective.

⟨2⟩2. PICK $g : B \rightarrow A$ such that $f \circ g = \text{id}_B$

PROOF: Proposition 2.9.2.

⟨2⟩3. $f \circ g \circ f = f$

⟨2⟩4. $g \circ f = \text{id}_A$

PROOF: Proposition 2.2.3.

⟨1⟩2. If there exists $f^{-1} : B \rightarrow A$ such that $f \circ f^{-1} = \text{id}_B$ and $f^{-1} \circ f = \text{id}_A$, then f is bijective.

⟨2⟩1. LET: $f^{-1} : B \rightarrow A$ satisfy $f \circ f^{-1} = \text{id}_B$ and $f^{-1} \circ f = \text{id}_A$

⟨2⟩2. f is injective.

PROOF: If $f(x) = f(y)$ then $x = f^{-1}(f(x)) = f^{-1}(f(y)) = y$.

⟨2⟩3. f is surjective.

PROOF: Proposition 2.9.2.

⟨1⟩3. If $g, h : B \rightarrow A$ satisfy $f \circ g = \text{id}_B$ and $g \circ f = \text{id}_A$ and $f \circ h = \text{id}_B$ and $h \circ f = \text{id}_A$ then $g = h$.

PROOF: We have $g = g \circ f \circ h = h$.

□

2.7 The Empty Set

Theorem 2.7.1. *There exists a set which has no elements.*

PROOF: Take $\{x \in \mathbb{N} : \perp\}$. \square

Theorem 2.7.2. *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 $\forall x \in E. \exists y \in E'. \top$.

$\langle 1 \rangle 3$. F is injective.

PROOF: Vacuously, for all $x, y \in E$, if $F(x) = F(y)$ then $x = y$.

$\langle 1 \rangle 4$. F is surjective.

PROOF: Vacuously, for all $y \in E'$, there exists $x \in E$ such that $F(x) = y$.

\square

Definition 2.7.3 (Empty Set). The *empty set* \emptyset is the set with no elements.

2.8 The Singleton

Theorem 2.8.1. *There exists a set that has exactly one element.*

PROOF: The set $\{x \in \mathbb{N} : x = 0\}$ has exactly one element. \square

Theorem 2.8.2. *If A and B both have exactly one element then $A \approx B$.*

PROOF:

$\langle 1 \rangle 1$. LET: A and B both have exactly one element a and b respectively.

$\langle 1 \rangle 2$. LET: $F : A \rightarrow B$ be the function such that, for all $x \in A$, we have
 $(x = a \wedge F(x) = b)$

$\langle 1 \rangle 3$. F is a bijection.

\square

Definition 2.8.3 (Singleton). Let 1 be the set that has exactly one element.
 Let $*$ be its element.

2.8.1 Injections

Proposition 2.8.4. *Let $f : A \rightarrow B$. Assume that, for every set X and functions $x, y : X \rightarrow A$, if $f \circ x = f \circ y$ then $x = y$. Then f is injective.*

PROOF: Take $X = 1$. \square

2.9 The Set Two

Definition 2.9.1 (The Set Two). Let $2 = \{x \in \mathbb{N} : x = 0 \vee x = 1\}$.

Proposition 2.9.2. *Let $f : A \rightarrow B$. Assume that, for any set X and functions $g, h : B \rightarrow X$, if $g \circ f = h \circ f$ then $g = h$. Then f is surjective.*

PROOF:

$\langle 1 \rangle 1$. ASSUME: For any set X and functions $g, h : B \rightarrow X$, if $g \circ f = h \circ f$ then $g = h$.

$\langle 1 \rangle 2$. LET: $b \in B$

$\langle 1 \rangle 3$. LET: $h : B \rightarrow 2$ be the function that maps everything to 1.

$\langle 1 \rangle 4$. LET: $k : B \rightarrow 2$ be the function that maps b to 0 and everything else to 1.

$\langle 1 \rangle 5$. $h \neq k$

$\langle 1 \rangle 6$. $h \circ f \neq k \circ f$

$\langle 1 \rangle 7$. PICK $a \in A$ such that $h(f(a)) \neq k(f(a))$

$\langle 1 \rangle 8$. $f(a) = b$

□

2.10 Subsets

Definition 2.10.1 (Subset). A *subset* of a set A consists of a set S and an injection $i : S \rightarrow A$. We write $(S, i) \subseteq A$.

We say two subsets (S, i) and (T, j) are *equal*, $(S, i) = (T, j)$, iff there exists a bijection $\phi : S \approx T$ such that $j \circ \phi = i$.

Proposition 2.10.2. *For any subset (S, i) of A we have $(S, i) = (S, i)$.*

PROOF: We have $\text{id}_S : S \approx S$ and $i \circ \text{id}_S = i$.

Proposition 2.10.3. *If $(S, i) = (T, j)$ then $(T, j) = (S, i)$.*

PROOF: If $\phi : S \approx T$ and $j \circ \phi = i$ then $\phi^{-1} : T \approx S$ and $i \circ \phi^{-1} = j$. □

Proposition 2.10.4. *If $(R, i) = (S, j)$ and $(S, j) = (T, k)$ then $(R, i) = (T, k)$.*

PROOF: If $\phi : R \approx S$ and $j \circ \phi = i$, and $\psi : S \approx T$ and $k \circ \psi = j$, then $\psi \circ \phi : R \approx T$ and $k \circ \psi \circ \phi = i$. □

Definition 2.10.5 (Membership). Given $(S, i) \subseteq A$ and $a \in A$, we write $a \in (S, i)$ for $\exists s \in S. i(s) = a$.

Proposition 2.10.6. *If $a \in (S, i)$ and $(S, i) = (T, j)$ then $a \in (T, j)$.*

PROOF: If $i(s) = a$ then $j(\phi(s)) = a$. □

Definition 2.10.7 (Union). Given subsets S and T of A , the *union* is the subset $\{x \in A : x \in S \vee x \in T\}$.

Definition 2.10.8 (Intersection). Given subsets S and T of A , the *intersection* is the subset $\{x \in A : x \in S \wedge x \in T\}$.

Proposition 2.10.9 (Distributive Law).

$$R \cap (S \cup T) = (R \cap S) \cup (R \cap T)$$

Proposition 2.10.10 (Distributive Law).

$$R \cup (S \cap T) = (R \cup S) \cap (R \cup T)$$

Definition 2.10.11. Given a set A , we write \emptyset for the subset $(\emptyset, !)$ where $!$ is the unique function $\emptyset \rightarrow A$.

Proposition 2.10.12.

$$S \cup \emptyset = S$$

Proposition 2.10.13.

$$S \cap \emptyset = \emptyset$$

Definition 2.10.14 (Inclusion). Given subsets (S, i) and (T, j) of a set A , we write $(S, i) \subseteq (T, j)$ iff there exists $f : S \rightarrow T$ such that $j \circ f = i$.

Proposition 2.10.15.

$$\emptyset \subseteq S$$

Definition 2.10.16 (Disjoint). Subsets S and T of A are *disjoint* iff $S \cap T = \emptyset$.

Definition 2.10.17 (Difference). Given subsets S and T of A , the *difference* of S and T is $S - T = \{x \in A : x \in S \wedge x \notin T\}$.

Proposition 2.10.18 (De Morgan's Law).

$$R - (S \cup T) = (R - S) \cap (R - T)$$

Proposition 2.10.19 (De Morgan's Law).

$$R - (S \cap T) = (R - S) \cup (R - T)$$

2.11 Power Set

Definition 2.11.1 (Power Set). The *power set* of a set A is

$$\mathcal{P}A := 2^A$$

Definition 2.11.2 (Cover). Let X be a set and $\mathcal{A} \subseteq \mathcal{P}X$. Then \mathcal{A} is a *cover* of X , or *covers* X , iff $\bigcup \mathcal{A} = X$.

Given a subset Y of X and $\mathcal{A} \subseteq \mathcal{P}X$, we say \mathcal{A} *covers* Y iff $Y \subseteq \bigcup \mathcal{A}$.

2.12 Saturated Set

Definition 2.12.1 (Saturated). Let A and B be sets. Let $f : A \rightarrow B$ be surjective. Let $C \subseteq A$. Then C is *saturated* with respect to f iff, for all $x \in C$ and $y \in A$, if $f(x) = f(y)$ then $y \in C$.

2.13 Union

Definition 2.13.1 (Union). Given $\mathcal{A} \in \mathcal{PPX}$, its *union* is

$$\bigcup \mathcal{A} := \{x \in X : \exists S \in \mathcal{A}. x \in S\} \in \mathcal{PX} .$$

2.13.1 Intersection

Definition 2.13.2 (Intersection). Given $\mathcal{A} \in \mathcal{PPX}$, its *intersection* is

$$\bigcap \mathcal{A} := \{x \in X : \forall S \in \mathcal{A}. x \in S\} \in \mathcal{PX} .$$

2.13.2 Direct Image

Definition 2.13.3 (Direct Image). Let $f : A \rightarrow B$. Let S be a subset of A . The *(direct) image* of S under f is the subset of B given by

$$f(S) := \{f(a) : a \in S\} .$$

Proposition 2.13.4.

1. If $S \subseteq T$ then $f(S) \subseteq f(T)$
2. $f(\bigcup \mathcal{S}) = \bigcup_{S \in \mathcal{S}} f(S)$

Example 2.13.5. It is not true in general that $f(\bigcap \mathcal{S}) = \bigcap_{S \in \mathcal{S}} f(S)$. Take f to be the only function $\{0, 1\} \rightarrow \{0\}$, and $\mathcal{S} = \{\{0\}, \{1\}\}$. Then $f(\bigcap \mathcal{S}) = \emptyset$ but $\bigcap_{S \in \mathcal{S}} f(S) = \{0\}$.

Example 2.13.6. It is not true in general that $f(S - T) = f(S) - f(T)$. Take f to be the only function $\{0, 1\} \rightarrow \{0\}$, $S = \{0\}$ and $T = \{1\}$. Then $f(S - T) = \{0\}$ but $f(S) - f(T) = \emptyset$.

2.14 Inverse Image

Definition 2.14.1 (Inverse Image). Let $f : A \rightarrow B$. Let S be a subset of B . The *inverse image* or *preimage* of S under f is the subset of A given by

$$f^{-1}(S) := \{x \in A : f(x) \in S\} .$$

Proposition 2.14.2. 1. If $S \subseteq T$ then $f^{-1}(S) \subseteq f^{-1}(T)$

2. $f^{-1}(\bigcup \mathcal{S}) = \bigcup_{S \in \mathcal{S}} f^{-1}(S)$
3. $f^{-1}(\bigcap \mathcal{S}) = \bigcap_{S \in \mathcal{S}} f^{-1}(S)$
4. $f^{-1}(S - T) = f^{-1}(S) - f^{-1}(T)$
5. $S \subseteq f^{-1}(f(S))$. Equality holds if f is injective.
6. $f(f^{-1}(T)) \subseteq T$. Equality holds if f is surjective.
7. $(g \circ f)^{-1}(S) = f^{-1}(g^{-1}(S))$

2.14.1 Saturated Sets

Proposition 2.14.3. *Let A and B be sets. Let $f : A \rightarrow B$ be surjective. Let $C \subseteq A$. Then C is saturated if and only if there exists $D \subseteq B$ such that $C = f^{-1}(D)$.*

PROOF:

$\langle 1 \rangle 1$. If C is saturated then there exists $D \subseteq B$ such that $C = f^{-1}(D)$.

$\langle 2 \rangle 1$. ASSUME: C is saturated.

$\langle 2 \rangle 2$. LET: $D = f(C)$

$\langle 2 \rangle 3$. $C \subseteq f^{-1}(D)$

$\langle 3 \rangle 1$. LET: $x \in C$

$\langle 3 \rangle 2$. $f(x) \in D$

PROOF: $\langle 2 \rangle 2$

$\langle 3 \rangle 3$. $x \in f^{-1}(D)$

$\langle 2 \rangle 4$. $f^{-1}(D) \subseteq C$

$\langle 3 \rangle 1$. LET: $x \in f^{-1}(D)$

$\langle 3 \rangle 2$. $f(x) \in D$

$\langle 3 \rangle 3$. PICK $y \in C$ such that $f(x) = f(y)$

PROOF: $\langle 2 \rangle 2$

$\langle 3 \rangle 4$. $x \in C$

PROOF: $\langle 2 \rangle 1$

$\langle 1 \rangle 2$. If there exists $D \subseteq B$ such that $C = f^{-1}(D)$ then C is saturated.

$\langle 2 \rangle 1$. LET: $D \subseteq B$ be such that $C = f^{-1}(D)$.

$\langle 2 \rangle 2$. LET: $x \in C$ and $y \in A$

$\langle 2 \rangle 3$. ASSUME: $f(x) = f(y)$

$\langle 2 \rangle 4$. $f(x) \in D$

$\langle 2 \rangle 5$. $f(y) \in D$

$\langle 2 \rangle 6$. $y \in C$

□

2.15 Relations

Definition 2.15.1 (Relation). Let A and B be sets. A *relation* R between A and B , $R : A \rightarrow B$, is a subset of $A \times B$.

Given $a \in A$ and $b \in B$, we write aRb for $(a, b) \in R$.

A relation *on* a set A is a relation between A and A .

Definition 2.15.2 (Reflexive). A relation R on a set A is *reflexive* iff $\forall a \in A. aRa$.

Definition 2.15.3 (Symmetric). A relation R on a set A is *symmetric* iff, whenever xRy , then yRx .

Definition 2.15.4 (Transitive). A relation R on a set A is *transitive* iff, whenever xRy and yRz , then xRz .

2.15.1 Equivalence Relations

Definition 2.15.5 (Equivalence Relation). A relation R on a set A is an *equivalence relation* iff it is reflexive, symmetric and transitive.

Definition 2.15.6 (Equivalence Class). Let R be an equivalence relation on a set A and $a \in A$. The *equivalence class* of a with respect to R is

$$\{x \in A : xRa\} .$$

Proposition 2.15.7. *Two equivalence classes are either disjoint or equal.*

2.16 Power Set

Definition 2.16.1 (Power Set). The *power set* of a set A is $\mathcal{P}A := 2^A$.

Given $S \in \mathcal{P}A$ and $a \in A$, we write $a \in S$ for $S(a) = 1$.

Definition 2.16.2 (Pairwise Disjoint). Let $P \subseteq \mathcal{P}A$. We say the members of P are *pairwise disjoint* iff, for all $S, T \in P$, if $S \neq T$ then $S \cap T = \emptyset$.

2.16.1 Partitions

Definition 2.16.3 (Partition). Let A be a set. A *partition* of A is a set $P \in \mathcal{P}\mathcal{P}A$ such that:

- $\bigcup P = A$
- Every member of P is nonempty.
- The members of P are pairwise disjoint.

2.17 Cartesian Product

Definition 2.17.1 (Cartesian Product). Let A and B be sets. The *Cartesian product* of A and B , $A \times B$, is the tabulation of the relation $A \looparrowright B$ 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 $\pi_2(a, b) = b$.

2.18 Quotient Sets

Proposition 2.18.1. *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 $x, y \in X$, 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 $\phi \circ \pi = p$.

2.19 Partitions

Definition 2.19.1 (Partition). A *partition* of a set X is a set of pairwise disjoint subsets of X whose union is X .

2.20 Disjoint Union

Theorem 2.20.1. For any sets A and B , there exists a set $A + B$, the disjoint union of A and B , and functions $\kappa_1 : A \rightarrow A + B$ and $\kappa_2 : B \rightarrow A + B$, the injections, such that, for every set X and functions $f : A \rightarrow X$ and $g : B \rightarrow X$, there exists a unique function $[f, g] : A + B \rightarrow X$ such that $[f, g] \circ \kappa_1 = f$ and $[f, g] \circ \kappa_2 = g$.

PROOF:

$\langle 1 \rangle 1$. LET: $A + B := \{p \in \mathcal{P}A \times \mathcal{P}B : \exists a \in A. p = (\{a\}, \emptyset) \vee \exists b \in B. p = (\emptyset, \{b\})\}$

Definition 2.20.2 (Restriction). Let $f : A \rightarrow B$ and let (S, i) be a subset of A . The *restriction* of f to S is the function $f \upharpoonright S : S \rightarrow B$ defined by $f \upharpoonright S = f \circ i$.

2.21 Natural Numbers

Theorem 2.21.1 (Principle of Recursive Definition). Let A be a set. Let F be the set of all functions $\{m \in \mathbb{N} : m < n\} \rightarrow A$ for some n . Let $\rho : F \rightarrow A$. Then there exists a unique $g : \mathbb{N} \rightarrow A$ such that, for all $n \in \mathbb{N}$, we have

$$g(n) = \rho(g \upharpoonright \{m \in \mathbb{N} : m < n\}) .$$

PROOF:

$\langle 1 \rangle 1$. Given a subset $B \subseteq \mathbb{N}$, let us say that a function $g : B \rightarrow A$ is *acceptable* iff, for all $n \in B$, we have

$$\forall m < n. m \in B$$

and

$$g(n) = \rho(g \upharpoonright \{m \in \mathbb{N} : m < n\}) .$$

$\langle 1 \rangle 2$. For all $n \in \mathbb{N}$, there exists an acceptable function $\{m \in \mathbb{N} : m < n\} \rightarrow A$.

$\langle 2 \rangle 1$. LET: $P[n]$ be the property: There exists an acceptable function $\{m \in \mathbb{N} : m < n\} \rightarrow A$.

$\langle 2 \rangle 2$. $P[0]$

PROOF: The unique function $\emptyset \rightarrow A$ is acceptable.

$\langle 2 \rangle 3$. For any natural number n , if $P[n]$ then $P[n + 1]$.

$\langle 3 \rangle 1$. ASSUME: $P[n]$

$\langle 3 \rangle 2$. PICK an acceptable $f : \{m \in \mathbb{N} : m < n\} \rightarrow A$.

$\langle 3 \rangle 3$. LET: $g : \{m \in \mathbb{N} : m < n + 1\} \rightarrow A$ be the function

$$g(m) = \begin{cases} f(m) & \text{if } m < n \\ \rho(f) & \text{if } m = n \end{cases}$$

$\langle 3 \rangle 4$. g is acceptable.

- ⟨1⟩3. If $g : B \rightarrow A$ and $h : C \rightarrow A$ are acceptable, then g and h agree on $B \cap C$.
 ⟨1⟩4. Define $g : \mathbb{N} \rightarrow A$ by: $g(n) = a$ iff there exists an acceptable $h : \{m \in \mathbb{N} : m < n + 1\}$ such that $h(n) = a$.
 ⟨1⟩5. g is acceptable.
 ⟨1⟩6. If $g' : \mathbb{N} \rightarrow A$ is acceptable then $g' = g$.
 □

2.22 Finite and Infinite Sets

Definition 2.22.1 (Finite). A set A is *finite* iff there exists $n \in \mathbb{N}$ such that $A \approx \{m \in \mathbb{N} : m < n\}$. In this case, we say A has *cardinality* n .

Proposition 2.22.2. Let $n \in \mathbb{N}$. Let A be a set. Let $a_0 \in A$. Then $A \approx \{m \in \mathbb{N} : m < n + 1\}$ if and only if $A - \{a_0\} \approx \{m \in \mathbb{N} : m < n\}$.

Theorem 2.22.3. Let A be a set. Suppose that $A \approx \{m \in \mathbb{N} : m < n\}$. Let B be a proper subset of A . Then $B \not\approx \{m \in \mathbb{N} : m < n\}$ but there exists $m < n$ such that $B \approx \{k \in \mathbb{N} : k < m\}$.

PROOF:

- ⟨1⟩1. LET: $P[n]$ be the property: for every set A , if $A \approx \{m \in \mathbb{N} : m < n\}$, then for every proper subset B of A , we have $B \not\approx \{m \in \mathbb{N} : m < n\}$ but there exists $m < n$ such that $B \approx \{k \in \mathbb{N} : k < m\}$.
 ⟨1⟩2. $P[0]$
 PROOF: If $A \approx \{m \in \mathbb{N} : m < 0\}$ then A is empty and so has no proper subset.
 ⟨1⟩3. For every natural number n , if $P[n]$ then $P[n + 1]$.
 ⟨2⟩1. LET: n be a natural number.
 ⟨2⟩2. ASSUME: $P[n]$
 ⟨2⟩3. LET: A be a set.
 ⟨2⟩4. ASSUME: $A \approx \{m \in \mathbb{N} : m < n + 1\}$
 ⟨2⟩5. LET: B be a proper subset of A .
 ⟨2⟩6. CASE: $B = \emptyset$
 PROOF: Then $B \not\approx \{m \in \mathbb{N} : m < n + 1\}$ but $B \approx \{k \in \mathbb{N} : k < 0\}$.
 ⟨2⟩7. CASE: $B \neq \emptyset$
 ⟨3⟩1. PICK $b_0 \in B$
 ⟨3⟩2. $A - \{b_0\} \approx \{m \in \mathbb{N} : m < n\}$
 ⟨3⟩3. $B - \{b_0\}$ is a proper subset of $A - \{b_0\}$
 ⟨3⟩4. $B - \{b_0\} \not\approx \{m \in \mathbb{N} : m < n\}$
 ⟨3⟩5. $B \approx \{m \in \mathbb{N} : m < n + 1\}$
 ⟨3⟩6. PICK $m < n$ such that $B - \{b_0\} \approx \{k \in \mathbb{N} : k < m\}$
 ⟨3⟩7. $m + 1 < n + 1$
 ⟨3⟩8. $B \approx \{k \in \mathbb{N} : k < m + 1\}$
 □

Corollary 2.22.3.1. If A is finite then there is no bijection between A and a proper subset of A .

Corollary 2.22.3.2. \mathbb{N} is infinite.

Corollary 2.22.3.3. The cardinality of a finite set is unique.

Corollary 2.22.3.4. A subset of a finite set is finite.

Corollary 2.22.3.5. If A is finite and B is a proper subset of A then $|B| < |A|$.

Corollary 2.22.3.6. Let A be a set. Then the following are equivalent:

1. A is finite.
2. There exists a surjection from an initial segment of \mathbb{N} onto A .
3. There exists an injection from A to an initial segment of \mathbb{N} .

Corollary 2.22.3.7. A finite union of finite sets is finite.

Corollary 2.22.3.8. A finite Cartesian product of finite sets is finite.

Theorem 2.22.4. Let A be a set. The following are equivalent:

1. There exists an injective function $\mathbb{N} \rightarrow A$.
2. There exists a bijection between A and a proper subset of A .
3. A is infinite.

PROOF:

$\langle 1 \rangle 1. 1 \Rightarrow 2$

$\langle 2 \rangle 1.$ LET: $f : \mathbb{N} \rightarrow A$ be injective.

$\langle 2 \rangle 2.$ LET: $s : \mathbb{N} \approx \mathbb{N} - \{0\}$ be the function $s(n) = n + 1$.

$\langle 2 \rangle 3.$ $f \circ s \circ f^{-1} : A \approx A - \{f(0)\}$

$\langle 1 \rangle 2. 2 \Rightarrow 3$

PROOF: Corollary 2.22.3.1.

$\langle 1 \rangle 3. 3 \Rightarrow 1$

PROOF: Choose a function $f : \mathbb{N} \rightarrow A$ such that $f(n) \in A - \{f(m) : m < n\}$ for all n .

□

2.23 Countable Sets

Definition 2.23.1 (Countable). A set A is *countably infinite* iff $A \approx \mathbb{N}$.

Proposition 2.23.2. $\mathbb{N} \times \mathbb{N}$ is countably infinite.

PROOF: Define $f : \mathbb{N} \times \mathbb{N} \approx \{(x, y) \in \mathbb{N} \times \mathbb{N} : y \leq x\}$ by

$$f(x, y) = (x + y, y)$$

Define $g : \{(x, y) \in \mathbb{N} \times \mathbb{N} : y \leq x\} \approx \mathbb{N}$ by

$$g(x, y) = x(x - 1)/2 + y. \quad \square$$

Proposition 2.23.3. *Every infinite subset of \mathbb{N} is countably infinite.*

PROOF:

$\langle 1 \rangle 1$. LET: C be an infinite subset of \mathbb{N}

$\langle 1 \rangle 2$. Define $h : \mathbb{Z} \rightarrow C$ by recursion thus: $h(n)$ is the smallest element of $C - \{h(m) : m < n\}$.

$\langle 1 \rangle 3$. h is injective.

PROOF: If $m < n$ then $h(m) \neq h(n)$ because $h(n) \in C - \{h(m) : m < n\}$.

$\langle 1 \rangle 4$. h is surjective.

$\langle 2 \rangle 1$. For all $n \in \mathbb{N}$ we have $n \leq h(n)$.

$\langle 2 \rangle 2$. LET: $c \in C$

$\langle 2 \rangle 3$. $c \leq h(c)$

$\langle 2 \rangle 4$. LET: n be least such that $c \leq h(n)$

$\langle 2 \rangle 5$. $c \in C - \{h(m) : m < n\}$

$\langle 2 \rangle 6$. $h(n) \leq c$

$\langle 2 \rangle 7$. $h(n) = c$

□

Definition 2.23.4 (Countable). A set is *countable* iff it is either finite or countably infinite; otherwise it is *uncountable*.

Proposition 2.23.5. *Let B be a nonempty set. Then the following are equivalent.*

1. B is countable.
2. There exists a surjection $\mathbb{N} \twoheadrightarrow B$.
3. There exists an injection $B \hookrightarrow \mathbb{N}$.

PROOF:

$\langle 1 \rangle 1$. $1 \Rightarrow 2$

$\langle 2 \rangle 1$. ASSUME: B is countable.

$\langle 2 \rangle 2$. CASE: B is finite.

$\langle 3 \rangle 1$. PICK a natural number n and bijection $f : \{m \in \mathbb{N} : m < n\} \approx B$

$\langle 3 \rangle 2$. PICK $b \in B$

$\langle 3 \rangle 3$. Extend f to a surjection $g : \mathbb{N} \twoheadrightarrow B$ by setting $g(m) = b$ for $m \geq n$.

$\langle 2 \rangle 3$. CASE: B is countably infinite.

PROOF: Then there exists a bijection $\mathbb{N} \approx B$.

$\langle 1 \rangle 2$. $2 \Rightarrow 3$

PROOF: Given a surjection $f : \mathbb{N} \twoheadrightarrow B$, define $g : B \hookrightarrow \mathbb{N}$ by $g(b)$ is the smallest number such that $f(g(b)) = b$.

$\langle 1 \rangle 3$. $3 \Rightarrow 1$

$\langle 2 \rangle 1$. LET: $f : B \hookrightarrow \mathbb{N}$ be injective.

$\langle 2 \rangle 2$. $f(B)$ is countable.

$\langle 2 \rangle 3$. $B \approx f(B)$

$\langle 2 \rangle 4$. B is countable.

□

Corollary 2.23.5.1. *A subset of a countable set is countable.*

Corollary 2.23.5.2. $\mathbb{N} \times \mathbb{N}$ *is countably infinite.*

PROOF: The function that maps (m, n) to $2^m 3^n$ is injective. \square

Corollary 2.23.5.3. *The Cartesian product of two countable sets is countable.*

Theorem 2.23.6. *A countable union of countable sets is countable.*

PROOF:

$\langle 1 \rangle 1$. LET: A be a set.

$\langle 1 \rangle 2$. LET: $\mathcal{B} \subseteq \mathcal{P}A$ be a countable set of countable sets such that $\bigcup \mathcal{B} = A$

$\langle 1 \rangle 3$. PICK a surjection $B : \mathbb{N} \rightarrow \mathcal{B}$

$\langle 1 \rangle 4$. ASSUME: w.l.o.g. each $B(n)$ is nonempty.

$\langle 1 \rangle 5$. For $n \in \mathbb{N}$, PICK a surjective function $g_n : \mathbb{N} \rightarrow B(n)$

$\langle 1 \rangle 6$. LET: $h : \mathbb{N} \times \mathbb{N} \rightarrow A$ be the function $h(m, n) = g_m(n)$

$\langle 1 \rangle 7$. h is surjective.

\square

Theorem 2.23.7. $2^{\mathbb{N}}$ *is uncountable.*

PROOF:

$\langle 1 \rangle 1$. LET: $f : \mathbb{N} \rightarrow 2^{\mathbb{N}}$

PROVE: f is not surjective.

$\langle 1 \rangle 2$. Define $g : \mathbb{N} \rightarrow 2$ by $g(n) = 1 - f(n)(n)$.

$\langle 1 \rangle 3$. For all $n \in \mathbb{N}$ we have $g(n) \neq f(n)(n)$.

$\langle 1 \rangle 4$. For all $n \in \mathbb{N}$ we have $g \neq f(n)$.

\square

Theorem 2.23.8. *For any set A , there is no surjective function $A \rightarrow \mathcal{P}A$.*

PROOF:

$\langle 1 \rangle 1$. LET: $f : A \rightarrow \mathcal{P}A$

$\langle 1 \rangle 2$. LET: $S = \{x \in A : x \notin f(x)\}$

$\langle 1 \rangle 3$. For all $a \in A$ we have $S \neq f(a)$

PROOF: We have $a \in S$ if and only if $a \notin f(a)$.

\square

Corollary 2.23.8.1. *For any set A , there is no injective function $\mathcal{P}A \rightarrow A$.*

2.24 Fixed Points

Definition 2.24.1 (Fixed Point). Let A be a set and $f : A \rightarrow A$. A *fixed point* of f is an element $a \in A$ such that $f(a) = a$.

2.25 Finite Intersection Property

Definition 2.25.1 (Finite Intersection Property). Let X be a set. Let $\mathcal{C} \subseteq \mathcal{P}X$. Then \mathcal{C} has the *finite intersection property* iff every finite nonempty subset of \mathcal{C} has nonempty intersection.

Chapter 3

Relations

Definition 3.0.1 (Reflexive). A relation $R \subseteq A \times A$ is *reflexive* iff, for all $a \in A$, we have $(a, a) \in R$.

Definition 3.0.2 (Antisymmetric). A relation $R \subseteq A \times A$ is *antisymmetric* iff, for all $a, b \in A$, if $(a, b) \in R$ and $(b, a) \in R$ then $a = b$.

Definition 3.0.3 (Transitive). A relation $R \subseteq A \times A$ is *transitive* iff, for all $a, b, c \in A$, if $(a, b) \in R$ and $(b, c) \in R$ then $(a, c) \in R$.

Definition 3.0.4 (Partial Order). A *partial order* on a set A is a relation on A that is reflexive, antisymmetric and transitive.

We say (A, \leq) is a *partially ordered set* or *poset* iff \leq is a partial order on A .

Definition 3.0.5 (Greatest). Let A be a poset and $a \in A$. Then a is the *greatest* element iff $\forall x \in A. x \leq a$.

Definition 3.0.6 (Least). Let A be a poset and $a \in A$. Then a is the *least* element iff $\forall x \in A. a \leq x$.

Definition 3.0.7 (Upper Bound). Let A be a poset, $S \subseteq A$, and $u \in A$. Then u is an *upper bound* for S iff $\forall x \in S. x \leq u$. We say S is *bounded above* iff it has an upper bound.

Definition 3.0.8 (Lower Bound). Let A be a poset, $S \subseteq A$, and $l \in A$. Then l is a *lower bound* for S iff $\forall x \in S. l \leq x$. We say S is *bounded below* iff it has a lower bound.

Definition 3.0.9 (Supremum). Let A be a poset, $S \subseteq A$ and $s \in A$. Then s is the *supremum* or *least upper bound* for S iff s is the least element in the sub-poset of upper bounds for A .

Definition 3.0.10 (Infimum). Let A be a poset, $S \subseteq A$ and $i \in A$. Then i is the *infimum* or *greatest lower bound* for S iff i is the greatest element in the sub-poset of lower bounds for A .

Definition 3.0.11 (Least Upper Bound Property). A poset A has the *least upper bound property* iff every nonempty subset of A that is bounded above has a least upper bound.

Proposition 3.0.12. *Let A be a poset. Then A has the least upper bound property if and only if every nonempty subset of A that is bounded below has a greatest lower bound.*

PROOF:

$\langle 1 \rangle 1$. If A has the least upper bound property then every subset of A that is bounded below has a greatest lower bound.

$\langle 2 \rangle 1$. ASSUME: A has the least upper bound property.

$\langle 2 \rangle 2$. LET: $S \subseteq A$ be nonempty and bounded below.

$\langle 2 \rangle 3$. LET: L be the set of lower bounds of S .

$\langle 2 \rangle 4$. L is nonempty.

PROOF: Because S is bounded below.

$\langle 2 \rangle 5$. L is bounded above.

PROOF: Pick an element $s \in S$. Then s is an upper bound for L .

$\langle 2 \rangle 6$. LET: s be the supremum of L .

$\langle 2 \rangle 7$. s is the greatest lower bound of S .

$\langle 3 \rangle 1$. s is a lower bound of S .

$\langle 4 \rangle 1$. LET: $x \in S$

$\langle 4 \rangle 2$. x is an upper bound for L .

$\langle 4 \rangle 3$. $s \leq x$

$\langle 3 \rangle 2$. For any lower bound l of S we have $l \leq s$.

PROOF: Immediate from $\langle 2 \rangle 6$.

$\langle 1 \rangle 2$. If every subset of A that is bounded below has a greatest lower bound, then A has the least upper bound property.

PROOF: Dual.

□

Chapter 4

Order Theory

4.1 Strict Partial Orders

Definition 4.1.1 (Strict Partial Order). A *strict partial order* on a set A is a relation on A that is irreflexive and transitive.

Proposition 4.1.2. 1. If \leq is a partial order on A then $<$ is a strict partial order on A , where $x < y$ iff $x \leq y \wedge x \neq y$.

2. If $<$ is a strict partial order on A then \leq is a partial order on A , where $x \leq y$ iff $x < y \vee x = y$.

3. These two relations are inverses of one another.

4.1.1 Linear Orders

Definition 4.1.3 (Linear Order). A *linear order* on a set A is a partial order \leq on A such that, for all $x, y \in A$, we have $x \leq y$ or $y \leq x$.

A *linearly ordered set* is a pair (X, \leq) such that X is a set and \leq is a linear order on X .

Definition 4.1.4 (Open Interval). Let X be a linearly ordered set and $a, b \in X$. The *open interval* (a, b) is the set

$$\{x \in X : a < x < b\} .$$

Definition 4.1.5 (Immediate Predecessor, Immediate Successor). Let X be a linearly ordered set and $a, b \in X$. Then b is the (*immediate*) *successor* of a , and a is the (*immediate*) *predecessor* of b , iff $a < b$ and there is no x such that $a < x < b$.

Definition 4.1.6 (Dictionary Order). Let A and B be linearly ordered sets. The *dictionary order* on $A \times B$ is the order defined by

$$(a, b) < (a', b') \Leftrightarrow a < a' \vee (a = a' \wedge b < b') .$$

Theorem 4.1.7 (Maximum Principle). *Every poset has a maximal linearly ordered subset.*

PROOF:

⟨1⟩1. LET: (A, \leq) be a poset.

⟨1⟩2. PICK a well ordering \preceq of A .

PROOF: Well Ordering Theorem.

⟨1⟩3. LET: $h : A \rightarrow 2$ be the function defined by \preceq -recursion thus:

$$h(a) = \begin{cases} 1 & \text{if } a \text{ is } \leq\text{-comparable with every } b < a \text{ such that } h(b) = 1 \\ 0 & \text{otherwise} \end{cases}$$

⟨1⟩4. LET: $B = \{x \in A : h(x) = 1\}$

PROVE: B is a maximal subset linearly ordered by \leq .

⟨1⟩5. B is linearly ordered by \leq .

⟨2⟩1. LET: $x, y \in B$

⟨2⟩2. ASSUME: w.l.o.g. $x \preceq y$

⟨2⟩3. y is \leq -comparable with x

⟨1⟩6. For any subset $C \subseteq A$ linearly ordered by \leq , if $B \subseteq C$ then $B = C$.

⟨2⟩1. LET: $x \in C$

⟨2⟩2. x is comparable with every $y \preceq x$ such that $h(y) = 1$

⟨2⟩3. $x \in B$

□

Theorem 4.1.8 (Zorn's Lemma). *Let A be a poset. If every linearly ordered subset of A is bounded above, then A has a maximal element.*

PROOF:

⟨1⟩1. PICK a maximal linearly ordered subset B of A .

PROOF: Maximal Principle

⟨1⟩2. PICK an upper bound c for B .

PROVE: c is maximal.

⟨1⟩3. LET: $x \in A$

⟨1⟩4. ASSUME: $c \leq x$

PROVE: $x = c$

⟨1⟩5. x is an upper bound for B .

⟨1⟩6. $x \in B$

PROOF: By the maximality of B , since $B \cup \{x\}$ is linearly ordered.

⟨1⟩7. $x \leq c$

PROOF: ⟨1⟩2

⟨1⟩8. $x = c$

□

Corollary 4.1.8.1 (Kuratowski's Lemma). *Let $\mathcal{A} \subseteq \mathcal{P}X$. Suppose that, for every subset $\mathcal{B} \subseteq \mathcal{A}$ that is linearly ordered by inclusion, we have $\bigcup \mathcal{B} \in \mathcal{A}$. Then \mathcal{A} has a maximal element.*

Definition 4.1.9 (Closed Interval). Let X be a linearly ordered set. Let $a, b \in X$ with $a < b$. The *closed interval* $[a, b]$ is

$$[a, b] := \{x \in X : a \leq x \leq b\} .$$

Definition 4.1.10 (Half-Open Interval). Let X be a linearly ordered set. Let $a, b \in X$ with $a < b$. The *half-open intervals* $(a, b]$ and $[a, b)$ are defined by

$$\begin{aligned}(a, b] &:= \{x \in X : a < x \leq b\} \\ [a, b) &:= \{x \in X : a \leq x < b\}\end{aligned}$$

Definition 4.1.11 (Open Ray). Let X be a linearly ordered set and $a \in X$. The *open rays* $(a, +\infty)$ and $(-\infty, a)$ are defined by:

$$\begin{aligned}(a, +\infty) &:= \{x \in X : a < x\} \\ (-\infty, a) &:= \{x \in X : x < a\}\end{aligned}$$

Definition 4.1.12 (Closed Ray). Let X be a linearly ordered set and $a \in X$. The *closed rays* $[a, +\infty)$ and $(-\infty, a]$ are defined by:

$$\begin{aligned}[a, +\infty) &:= \{x \in X : a \leq x\} \\ (-\infty, a] &:= \{x \in X : x \leq a\}\end{aligned}$$

Definition 4.1.13 (Convex). Let X be a linearly ordered set and $Y \subseteq X$. Then Y is *convex* iff, for all $a, b \in Y$ and $c \in X$, if $a < c < b$ then $c \in Y$.

4.1.2 Sets of Finite Type

Definition 4.1.14 (Finite Type). Let X be a set. Let $\mathcal{A} \subseteq \mathcal{P}X$. Then \mathcal{A} is of *finite type* if and only if, for any $B \subseteq X$, we have $B \in \mathcal{A}$ if and only if every finite subset of B is in \mathcal{A} .

Proposition 4.1.15 (Tukey's Lemma). *Let X be a set. Let $\mathcal{A} \subseteq \mathcal{P}X$. If \mathcal{A} is of finite type, then \mathcal{A} has a maximal element.*

PROOF:

$\langle 1 \rangle 1$. For every subset $\mathcal{B} \subseteq \mathcal{A}$ that is linearly ordered by inclusion, we have $\bigcup \mathcal{B} \in \mathcal{A}$.

$\langle 2 \rangle 1$. LET: $\mathcal{B} \subseteq \mathcal{A}$

$\langle 2 \rangle 2$. ASSUME: \mathcal{B} is linearly ordered by inclusion.

$\langle 2 \rangle 3$. Every finite subset of $\bigcup \mathcal{B}$ is in \mathcal{A}

$\langle 2 \rangle 4$. $\bigcup \mathcal{B} \in \mathcal{A}$

$\langle 1 \rangle 2$. Q.E.D.

PROOF: Kuratowski's Lemma.

□

4.2 Linear Continua

Definition 4.2.1 (Linear Continuum). A *linear continuum* is a linearly ordered set with more than one element that is dense and has the least upper bound property.

Proposition 4.2.2. *Every convex subset of a linear continuum with more than one element is a linear continuum.*

PROOF: Easy. \square

Corollary 4.2.2.1. *Every interval and ray in a linear continuum is a linear continuum.*

4.3 Well Orders

Definition 4.3.1 (Well Ordered Set). A *well ordered set* is a linearly ordered set such that every nonempty subset has a least element.

Proposition 4.3.2. *Any subset of a well ordered set is well ordered.*

Proposition 4.3.3. *The product of two well ordered sets is well ordered under the dictionary order.*

Theorem 4.3.4 (Well Ordering Theorem). *Every set has a well ordering.*

PROOF:

$\langle 1 \rangle 1$. LET: X be a set.

$\langle 1 \rangle 2$. PICK a choice function $c : \mathcal{P}X - \{\emptyset\} \rightarrow X$

$\langle 1 \rangle 3$. Define a *tower* to be a pair $(T, <)$ where $T \subseteq X$, $<$ is a well ordering of T , and

$$\forall x \in T. x = c(X - \{y \in T : y < x\}) .$$

$\langle 1 \rangle 4$. Given two towers, either they are equal or one is a section of the other.

$\langle 2 \rangle 1$. LET: $(T_1, <_1)$ and $(T_2, <_2)$ be towers.

$\langle 2 \rangle 2$. ASSUME: w.l.o.g. there exists a strictly monotone function $h : T_1 \rightarrow T_2$

$\langle 2 \rangle 3$. $h(T_1)$ is either T_2 or a section of T_2

PROOF: Proposition 4.3.11.

$\langle 2 \rangle 4$. $\forall x \in T_1. h(x) = x$

$\langle 3 \rangle 1$. LET: $x \in T_1$

$\langle 3 \rangle 2$. ASSUME: as transfinite induction hypothesis $\forall y < x. h(y) = y$

$\langle 3 \rangle 3$. $h(x)$ is the least element of $T_2 - \{h(y) \in T_1 : y < x\}$

$\langle 3 \rangle 4$. $h(x)$ is the least element of $T_2 - \{y \in T_1 : y < x\}$

PROOF: $\langle 3 \rangle 2$

$\langle 3 \rangle 5$. $h(x) = x$

PROOF:

$$h(x) = c(X - \{y \in T_2 : y < h(x)\}) \quad (\langle 1 \rangle 3)$$

$$= c(X - \{y \in T_2 : y < x\}) \quad (\langle 3 \rangle 4)$$

$$= c(X - \{y \in T_1 : y < x\}) \quad (\langle 3 \rangle 2)$$

$$= x \quad (\langle 1 \rangle 3)$$

$\langle 1 \rangle 5$. If $(T, <)$ is a tower and $T \neq X$, then there exists a tower of which $(T, <)$ is a section.

PROOF: Let $T_1 = T \cup \{c(T)\}$ and $<_1$ be the extension of $<$ such that $x < c(T)$ for all $x \in T$.

- $\langle 1 \rangle 6$. LET: $\mathbf{T} = \bigcup \{T : \exists R. (T, R) \text{ is a tower}\}$ and $\mathbf{R} = \bigcup \{R : \exists T. (T, R) \text{ is a tower}\}$
 $\langle 1 \rangle 7$. (\mathbf{T}, \mathbf{R}) is a tower.
 $\langle 2 \rangle 1$. \mathbf{R} is irreflexive.
 PROOF: Since for every tower $(T, <)$ we have $<$ is irreflexive.
 $\langle 2 \rangle 2$. \mathbf{R} is transitive.
 $\langle 3 \rangle 1$. ASSUME: $x\mathbf{R}y$ and $y\mathbf{R}z$
 $\langle 3 \rangle 2$. PICK towers $(T_1, <_1)$ and $(T_2, <_2)$ such that $x <_1 y$ and $y <_2 z$
 $\langle 3 \rangle 3$. ASSUME: w.l.o.g. $(T_1, <_1)$ is either $(T_2, <_2)$ or a section of $(T_2, <_2)$
 $\langle 3 \rangle 4$. $x <_2 y <_2 z$
 $\langle 3 \rangle 5$. $x <_2 z$
 $\langle 3 \rangle 6$. $x\mathbf{R}z$
 $\langle 2 \rangle 3$. For all $x, y \in \mathbf{T}$, either $x\mathbf{R}y$ or $x = y$ or $y\mathbf{R}x$
 PROOF: There exists a tower that has both x and y .
 $\langle 2 \rangle 4$. Every nonempty subset of \mathbf{T} has an \mathbf{R} -least element.
 $\langle 3 \rangle 1$. LET: $A \subseteq \mathbf{T}$ be nonempty.
 $\langle 3 \rangle 2$. PICK $a \in A$
 $\langle 3 \rangle 3$. PICK a tower $(T, <)$ such that $a \in T$.
 $\langle 3 \rangle 4$. LET: b be the $<$ -least element of $A \cap T$
 PROVE: b is \mathbf{R} -least in A .
 $\langle 3 \rangle 5$. LET: $x \in A$
 $\langle 3 \rangle 6$. Etc.
 $\langle 2 \rangle 5$. $\forall x \in \mathbf{T}. x = c(X - \{y \in \mathbf{T} : y\mathbf{R}x\})$
 $\langle 1 \rangle 8$. $\mathbf{T} = X$
 $\langle 1 \rangle 9$. \mathbf{R} is a well ordering of X .
 \square

Proposition 4.3.5. *There exists a well-ordered set with a largest element Ω such that $(-\infty, \Omega)$ is uncountable but, for all $\alpha < \Omega$, we have $(-\infty, \alpha)$ is countable.*

PROOF:

- $\langle 1 \rangle 1$. PICK an uncountable well ordered set B .
 $\langle 1 \rangle 2$. LET: $C = 2 \times B$ under the dictionary order.
 $\langle 1 \rangle 3$. LET: Ω be the least element of C such that $(-\infty, \Omega)$ is uncountable.
 $\langle 1 \rangle 4$. LET: $A = (-\infty, \Omega]$
 $\langle 1 \rangle 5$. A is a well ordered set with largest element Ω such that $(-\infty, \Omega)$ is uncountable but, for all $\alpha < \Omega$, we have $(-\infty, \alpha)$ is countable.
 \square

Proposition 4.3.6. *Every well ordered set has the least upper bound property.*

PROOF: For any subset that is bounded above, the set of upper bounds is nonempty, hence has a least element. \square

Proposition 4.3.7. *In a well ordered set, every element that is not greatest has a successor.*

PROOF: If a is not greatest, then $\{x : x > a\}$ is nonempty, hence has a least element. \square

Theorem 4.3.8 (Transfinite Induction). *Let J be a well ordered set. Let $S \subseteq J$. Assume that, for every $\alpha \in J$, if $\forall x < \alpha. x \in S$ then $\alpha \in S$. Then $S = J$.*

PROOF: Otherwise $J - S$ would be a nonempty subset of J with no least element. \square

Proposition 4.3.9. *Let I be a well ordered set. Let $\{A_i\}_{i \in I}$ be a family of well ordered sets. Define $<$ on $\coprod_{i \in I} A_i$ by: $\kappa_i(a) < \kappa_j(b)$ iff either $i < j$, or $i = j$ and $a < b$ in A_i . Then $<$ well orders $\coprod_{i \in I} A_i$.*

PROOF: Easy. \square

Theorem 4.3.10 (Principle of Transfinite Recursion). *Let J be a well ordered set. Let C be a set. Let \mathcal{F} be the set of all functions from a section of J into C . Let $\rho : \mathcal{F} \rightarrow C$. Then there exists a unique function $h : J \rightarrow C$ such that, for all $\alpha \in J$, we have*

$$h(\alpha) = \rho(h \upharpoonright (-\infty, \alpha)) .$$

PROOF:

$\langle 1 \rangle 1$. For a function h mapping either a section of J or all of J into C , let us say h is *acceptable* iff, for all $x \in \text{dom } h$, we have $(-\infty, x) \subseteq \text{dom } h$ and $h(x) = \rho(h \upharpoonright (-\infty, x))$.

$\langle 1 \rangle 2$. If h and k are acceptable functions then $h(x) = k(x)$ for all x in both domains.

$\langle 2 \rangle 1$. LET: $x \in J$

$\langle 2 \rangle 2$. ASSUME: as transfinite induction hypothesis that, for all $y < x$ and any acceptable functions h and k with $y \in \text{dom } h \cap \text{dom } k$, we have $h(y) = k(y)$

$\langle 2 \rangle 3$. LET: h and k be acceptable functions with $x \in \text{dom } h \cap \text{dom } k$

$\langle 2 \rangle 4$. $h \upharpoonright (-\infty, x) = k \upharpoonright (-\infty, x)$

PROOF: By $\langle 2 \rangle 2$.

$\langle 2 \rangle 5$. $h(x) = k(x)$

PROOF: By $\langle 2 \rangle 3$, each is the least element of the set in $\langle 2 \rangle 4$.

$\langle 1 \rangle 3$. For $\alpha \in J$, if there exists an acceptable function $(-\infty, \alpha) \rightarrow C$, then there exists an acceptable function $(-\infty, \alpha] \rightarrow C$.

$\langle 2 \rangle 1$. LET: $\alpha \in J$

$\langle 2 \rangle 2$. LET: $f : (-\infty, \alpha) \rightarrow C$ be acceptable.

$\langle 2 \rangle 3$. LET: $g : (-\infty, \alpha] \rightarrow C$ be the function given by

$$g(x) = \begin{cases} f(x) & \text{if } x < \alpha \\ \rho(f) & \text{if } x = \alpha \end{cases}$$

$\langle 2 \rangle 4$. g is acceptable.

$\langle 1 \rangle 4$. Let $K \subseteq J$. Assume that, for all $\alpha \in K$, there exists an acceptable function $(-\infty, \alpha) \rightarrow C$. Then there exists an acceptable function $\bigcup_{\alpha \in K} (-\infty, \alpha) \rightarrow C$.

$\langle 2 \rangle 1$. Define $f : \bigcup_{\alpha \in K} (-\infty, \alpha) \rightarrow C$ by: $f(x) = y$ iff there exists $\alpha \in K$ and $g : (-\infty, \alpha) \rightarrow C$ acceptable such that $g(x) = y$.

$\langle 1 \rangle 5$. For every $\beta \in J$, there exists an acceptable function $(-\infty, \beta) \rightarrow C$

- ⟨2⟩1. LET: $\beta \in J$
- ⟨2⟩2. ASSUME: as transfinite induction hypothesis that, for all $\alpha < \beta$, there exists an acceptable function $(-\infty, \alpha) \rightarrow C$
- ⟨2⟩3. CASE: β has a predecessor
 - ⟨3⟩1. LET: α be the predecessor of β .
 - ⟨3⟩2. There exists an acceptable function $(-\infty, \alpha) \rightarrow C$.
 - ⟨3⟩3. There exists an acceptable function $(-\infty, \beta) \rightarrow C$.
 - PROOF: By ⟨1⟩3 since $(-\infty, \beta) = (-\infty, \alpha]$.
- ⟨2⟩4. CASE: β has no predecessor.
 - PROOF: The result follows by ⟨1⟩4 since $(-\infty, \beta) = \bigcup_{\alpha < \beta} (-\infty, \alpha)$.
- ⟨1⟩6. There exists an acceptable function $J \rightarrow C$.
 - ⟨2⟩1. CASE: J has a greatest element.
 - ⟨3⟩1. LET: g be greatest.
 - ⟨3⟩2. There exists an acceptable function $(-\infty, g) \rightarrow C$.
 - PROOF: ⟨1⟩5
 - ⟨3⟩3. There exists an acceptable function $J \rightarrow C$.
 - PROOF: By ⟨1⟩3 since $J = (-\infty, g]$.
 - ⟨2⟩2. CASE: J has no greatest element.
 - PROOF: By ⟨1⟩4 since $J = \bigcup_{\alpha \in J} (-\infty, \alpha)$.

□

Corollary 4.3.10.1 (Cardinal Comparability). *Let A and B be sets. Then either $A \leq B$ or $B \leq A$.*

PROOF: Choose well orderings of A and B . Then either there exists a surjection $A \twoheadrightarrow B$, or there exists an injective function $h : A \rightarrow B$ defined by transfinite recursion by $h(x)$ is the least element of $B - h((-\infty, x))$. □

Proposition 4.3.11. *Let J and E be well ordered sets. Let $h : J \rightarrow E$. Then the following are equivalent.*

1. h is strictly monotone and $h(J)$ is either E or a section of E .
2. For all $\alpha \in J$, we have $h(\alpha)$ is the least element of $E - h((-\infty, \alpha))$.

PROOF:

- ⟨1⟩1. $1 \Rightarrow 2$
 - ⟨2⟩1. ASSUME: 1
 - ⟨2⟩2. $h(J)$ is closed downwards.
 - ⟨2⟩3. LET: $\alpha \in J$
 - ⟨2⟩4. $h(\alpha) \in E - h((-\infty, \alpha))$
 - PROOF: If $\beta < \alpha$ then $h(\beta) < h(\alpha)$.
 - ⟨2⟩5. For all $y \in E - h((-\infty, \alpha))$ we have $h(\alpha) \leq y$
 - ⟨3⟩1. ASSUME: for a contradiction $y < h(\alpha)$
 - ⟨3⟩2. $y \in h(J)$
 - ⟨3⟩3. PICK $\beta \in J$ such that $h(\beta) = y$
 - ⟨3⟩4. $h(\beta) < h(\alpha)$
 - ⟨3⟩5. $\beta < \alpha$

⟨3⟩6. Q.E.D.

PROOF: This contradicts the fact that $y \notin h((-\infty, \alpha))$.

⟨1⟩2. $2 \Rightarrow 1$

⟨2⟩1. ASSUME: 2

⟨2⟩2. h is strictly monotone.

⟨3⟩1. LET: $\alpha, \beta \in J$ with $\alpha < \beta$

⟨3⟩2. $h(\alpha) \neq h(\beta)$

PROOF: Because $h(\beta) \in E - h((-\infty, \beta))$.

⟨3⟩3. $h(\alpha) \leq h(\beta)$

PROOF: Because $h(\alpha)$ is least in $E - h((-\infty, \alpha))$.

⟨3⟩4. $h(\alpha) < h(\beta)$

⟨2⟩3. $h(J)$ is either E or a section of E .

⟨3⟩1. ASSUME: $h(J) \neq E$

⟨3⟩2. LET: e be least in $E - h(J)$

PROVE: $h(J) = (-\infty, e)$

⟨3⟩3. $h(J) \subseteq (-\infty, e)$

⟨4⟩1. LET: $\alpha \in J$

⟨4⟩2. $h(\alpha) \neq e$

PROOF: $e \notin h(J)$

⟨4⟩3. $h(\alpha) \leq e$

PROOF: Since $h(\alpha)$ is least in $E - h((-\infty, \alpha))$.

⟨4⟩4. $h(\alpha) < e$

⟨3⟩4. $(-\infty, e) \subseteq h(J)$

PROOF: If $e' < e$ then $e' \in h(J)$ by leastness of e .

□

Part II

Category Theory

Chapter 5

Category Theory

5.1 Categories

Definition 5.1.1. A *category* \mathcal{C} consists of:

- a set $\text{Ob}(\mathcal{C})$ of *objects*. We write $A \in \mathcal{C}$ for $A \in \text{Ob}(\mathcal{C})$.
- for any objects X and Y , a set $\mathcal{C}[X, Y]$ of *morphisms* from X to Y . We write $f : X \rightarrow Y$ for $f \in \mathcal{C}[X, Y]$.
- for any objects X, Y and Z , a function $\circ : \mathcal{C}[Y, Z] \times \mathcal{C}[X, Y] \rightarrow \mathcal{C}[X, Z]$, called *composition*.

such that:

- Given $f : X \rightarrow Y, g : Y \rightarrow Z$ and $h : Z \rightarrow W$, we have $h \circ (g \circ f) = (h \circ g) \circ f$
- For any object X , there exists a morphism $\text{id}_X : X \rightarrow X$, the *identity morphism* on X , such that:
 - for any object Y and morphism $f : Y \rightarrow X$ we have $\text{id}_X \circ f = f$
 - for any object Y and morphism $f : X \rightarrow Y$ we have $f \circ \text{id}_X = f$

We write the composite of morphism f_1, \dots, f_n as $f_n \circ \dots \circ f_1$. This is unambiguous thanks to Associativity.

Definition 5.1.2. Let **Set** be the category of small sets and functions.

Definition 5.1.3. Let **LPos** be the category of linearly ordered sets and monotone functions.

Proposition 5.1.4. Any finite linearly ordered set is isomorphic to $\{m \in \mathbb{N} : m < n\}$ for some n .

PROOF:

⟨1⟩1. Every finite nonempty linearly ordered set has a greatest element.

- $\langle 2 \rangle 1$. LET: $P[n]$ be the property: for any linearly ordered set A , if there exists a bijection $A \approx \{m \in \mathbb{N} : m < n\}$ and A is nonempty then A has a greatest element.
- $\langle 2 \rangle 2$. $P[0]$
 PROOF: Vacuous.
- $\langle 2 \rangle 3$. $\forall n \in \mathbb{N}. P[n] \Rightarrow P[n+1]$
- $\langle 3 \rangle 1$. LET: $n \in \mathbb{N}$
- $\langle 3 \rangle 2$. ASSUME: $P[n]$
- $\langle 3 \rangle 3$. LET: A be a nonempty linearly ordered set.
- $\langle 3 \rangle 4$. LET: $f : A \approx \{m \in \mathbb{N} : m < n+1\}$
- $\langle 3 \rangle 5$. LET: $a = f^{-1}(n)$
- $\langle 3 \rangle 6$. $f \upharpoonright (A - \{a\}) : A - \{a\} \approx \{m \in \mathbb{N} : m < n\}$
- $\langle 3 \rangle 7$. ASSUME: w.l.o.g. a is not greatest in A .
- $\langle 3 \rangle 8$. LET: b be greatest in $A - \{a\}$
 PROOF: $\langle 3 \rangle 2$
- $\langle 3 \rangle 9$. b is greatest in A .
- $\langle 1 \rangle 2$. LET: $P[n]$ be the property: for any linearly ordered set A , if there exists a bijection $A \approx \{m \in \mathbb{N} : m < n\}$ then there exists an isomorphism in **LPos** $A \cong \{m \in \mathbb{N} : m < n\}$.
- $\langle 1 \rangle 3$. $P[0]$
 PROOF: If there exists a bijection $A \approx \emptyset$ then A is empty and so the unique function $A \rightarrow \emptyset$ is an order isomorphism.
- $\langle 1 \rangle 4$. For every natural number n , if $P[n]$ then $P[n+1]$.
- $\langle 2 \rangle 1$. LET: n be a natural number.
- $\langle 2 \rangle 2$. ASSUME: $P[n]$
- $\langle 2 \rangle 3$. LET: A be a linearly ordered set.
- $\langle 2 \rangle 4$. ASSUME: A has $n+1$ elements.
- $\langle 2 \rangle 5$. LET: a be the greatest element in A .
- $\langle 2 \rangle 6$. LET: $f : A - \{a\} \cong \{m \in \mathbb{N} : m < n\}$ be an order isomorphism.
 PROOF: $\langle 2 \rangle 2$
- $\langle 2 \rangle 7$. Define $g : A \rightarrow \{m \in \mathbb{N} : m < n+1\}$ by

$$g(x) = \begin{cases} f(x) & \text{if } x \neq a \\ n & \text{if } x = a \end{cases}$$
- $\langle 2 \rangle 8$. g is an order isomorphism.
- $\langle 1 \rangle 5$. $\forall n \in \mathbb{N}. P[n]$
 \square

Corollary 5.1.4.1. *Any finite linearly ordered set is well ordered.*

Proposition 5.1.5. *Let J and E be well ordered sets. Suppose there is a strictly monotone map $J \rightarrow E$. Then J is isomorphic either to E or a section of E .*

PROOF:

- $\langle 1 \rangle 1$. LET: $k : J \rightarrow E$ be strictly monotone.
- $\langle 1 \rangle 2$. ASSUME: w.l.o.g. E is nonempty.
- $\langle 1 \rangle 3$. PICK $e_0 \in E$

⟨1⟩4. LET: $h : J \rightarrow E$ be the function defined by transfinite recursion thus:

$$h(\alpha) = \begin{cases} \text{the least element in } E - h((-\infty, \alpha)) & \text{if } h((-\infty, \alpha)) \neq E \\ e_0 & \text{if } h((-\infty, \alpha)) = E \end{cases}$$

⟨1⟩5. $\forall \alpha \in J, h(\alpha) \leq k(\alpha)$

⟨2⟩1. LET: $\alpha \in J$

⟨2⟩2. ASSUME: as transfinite induction hypothesis $\forall \beta < \alpha, h(\beta) \leq k(\beta)$.

⟨2⟩3. $\forall \beta < \alpha, h(\beta) < k(\alpha)$

⟨2⟩4. $h((-\infty, \alpha)) \neq E$

⟨2⟩5. $h(\alpha)$ is the least element in $E - h((-\infty, \alpha))$.

⟨2⟩6. $k(\alpha) \in E - h((-\infty, \alpha))$

⟨2⟩7. $h(\alpha) \leq k(\alpha)$

⟨1⟩6. $\forall \alpha \in J, h((-\infty, \alpha)) \neq E$

PROOF: For $\beta < \alpha$ we have $h(\beta) \leq k(\beta) < k(\alpha)$ so $k(\alpha) \notin h((-\infty, \alpha))$.

⟨1⟩7. For all $\alpha \in J$, we have $h(\alpha)$ is the least element of $E - h((-\infty, \alpha))$.

⟨1⟩8. h is strictly monotone and $h(J)$ is either E or a section of E .

PROOF: Proposition 4.3.11.

□

Proposition 5.1.6. *If A and B are well ordered sets, then exactly one of the following conditions hold: $A \cong B$, or A is isomorphic to a section of B , or B is isomorphic to a section of A .*

PROOF:

⟨1⟩1. At least one of the conditions holds.

⟨2⟩1. B is isomorphic to either $A + B$ or a section of $A + B$.

⟨2⟩2. CASE: $B \cong A + B$

⟨3⟩1. LET: ϕ be the isomorphism $B \cong A + B$

⟨3⟩2. LET: b_0 be the least element in B .

⟨3⟩3. A is isomorphic to the section $(-\infty, \phi^{-1}(\kappa_2(b_0)))$ of B .

⟨2⟩3. CASE: $a \in A$ and $B \cong (-\infty, \kappa_1(a))$

PROOF: Then B is isomorphic to the section $(-\infty, a)$ of A .

⟨2⟩4. CASE: $b \in B$ and $\phi : B \cong (-\infty, \kappa_2(b))$

⟨3⟩1. CASE: b is least in B .

PROOF: Then $A \cong B$.

⟨3⟩2. CASE: b is not least in B .

⟨4⟩1. LET: b_0 be least in B .

⟨4⟩2. A is isomorphic to the section $(-\infty, \phi^{-1}(\kappa_2(b_0)))$ of B .

⟨1⟩2. At most one of the conditions holds.

PROOF: Since a well ordered set cannot be isomorphic to a section of itself.

□

Theorem 5.1.7. *There exists a well ordered set, unique up to order isomorphism, that is uncountable but such that every section is countable.*

PROOF:

⟨1⟩1. There exists a well ordered set that is uncountable but such that every section is countable.

- $\langle 2 \rangle 1$. PICK a well ordered set A with an element $\Omega \in A$ such that $(-\infty, \Omega)$ is uncountable but $\forall \alpha < \Omega. (-\infty, \alpha)$ is countable.
 $\langle 2 \rangle 2$. LET: $(-\infty, \Omega)$ is uncountable but every section is countable.
 $\langle 1 \rangle 2$. If A and B are uncountable well ordered sets such that every section is countable, then $A \cong B$.

PROOF: Since it cannot be that one of A and B is isomorphic to a section of the other.

□

Definition 5.1.8 (Minimal Uncountable Well Ordered Set). The *minimal uncountable well ordered set* Ω is the well ordered set that is uncountable but such that every section is countable.

We write $\bar{\Omega}$ for the well ordered set $\Omega \cup \{\Omega\}$ where Ω is greatest.

Proposition 5.1.9. *Every countable subset of Ω is bounded above.*

PROOF:

- $\langle 1 \rangle 1$. LET: A be a countable subset of Ω .
 $\langle 1 \rangle 2$. For all $a \in A$ we have $(-\infty, a)$ is countable.
 $\langle 1 \rangle 3$. $\bigcup_{a \in A} (-\infty, a)$ is countable.
 $\langle 1 \rangle 4$. $\bigcup_{a \in A} (-\infty, a) \neq \Omega$
 $\langle 1 \rangle 5$. PICK $x \in \Omega - \bigcup_{a \in A} (-\infty, a)$
 $\langle 1 \rangle 6$. x is an upper bound for A .

□

Proposition 5.1.10. *Ω has no greatest element.*

PROOF: For any $\alpha \in \Omega$ we have $(-\infty, \alpha]$ is countable and hence not the whole of Ω . □

Proposition 5.1.11. *There are uncountably many elements of Ω that have no predecessor.*

PROOF:

- $\langle 1 \rangle 1$. LET: A be the set of all elements of Ω that have no predecessor.
 $\langle 1 \rangle 2$. LET: $f : A \times \mathbb{N} \rightarrow \Omega$ be the function that maps (a, n) to the n th successor of a .
 $\langle 1 \rangle 3$. f is surjective.
 $\langle 2 \rangle 1$. ASSUME: for a contradiction $x \in \Omega$ and there is no element $a \in A$ and $n \in \mathbb{N}$ such that x is the n th successor of a .
 $\langle 2 \rangle 2$. LET: x_n be the n th predecessor of x for $n \in \mathbb{N}$.
 $\langle 2 \rangle 3$. $\{x_n : n \in \mathbb{N}\}$ is a nonempty subset of Ω with no least element.
 $\langle 1 \rangle 4$. $A \times \mathbb{N}$ is uncountable.
 $\langle 1 \rangle 5$. A is uncountable.

□

Definition 5.1.12. We identify a poset (A, \leq) with the category with:

- set of objects A

- for $a, b \in A$, the set of homomorphisms is $\{x \in 1 : a \leq b\}$

Proposition 5.1.13. *A category is a poset iff, for any two objects, there exists at most one morphism between them.*

Proposition 5.1.14. *The identity morphism on an object is unique.*

PROOF:

$\langle 1 \rangle 1$. LET: \mathcal{C} be a category.

$\langle 1 \rangle 2$. LET: $A \in \mathcal{C}$

$\langle 1 \rangle 3$. LET: $i, j : A \rightarrow A$ be identity morphisms on A .

$\langle 1 \rangle 4$. $i = j$

PROOF:

$$\begin{aligned} i &= i \circ j & (j \text{ is an identity on } A) \\ &= j & (i \text{ is an identity on } A) \end{aligned}$$

□

Proposition 5.1.15. *Let A be a linearly ordered set. Then A is well ordered if and only if it does not contain a subset of order type \mathbb{N}^{op} .*

PROOF:

$\langle 1 \rangle 1$. If A is well ordered then it does not contain a subset of order type \mathbb{N}^{op} .

PROOF: A subset of order type \mathbb{N}^{op} would be a subset with no least element.

$\langle 1 \rangle 2$. If A is not well ordered then it contains a subset of order type \mathbb{N}^{op} .

$\langle 2 \rangle 1$. ASSUME: A is not well ordered.

$\langle 2 \rangle 2$. PICK a nonempty subset S with no least element.

$\langle 2 \rangle 3$. PICK $a_0 \in S$

$\langle 2 \rangle 4$. Extend to a sequence (a_n) in S such that $a_{n+1} < a_n$ for all n .

$\langle 2 \rangle 5$. $\{a_n : n \in \mathbb{N}\}$ has order type \mathbb{N}^{op} .

□

Corollary 5.1.15.1. *Let A be a linearly ordered set. If every countable subset of A is well ordered, then A is well ordered.*

Definition 5.1.16. Given $f : A \rightarrow B$ and an object C , define the function $f^* : \mathcal{C}[B, C] \rightarrow \mathcal{C}[A, C]$ by $f^*(g) = g \circ f$.

Definition 5.1.17. Given $f : A \rightarrow B$ and an object C , define the function $f_* : \mathcal{C}[C, A] \rightarrow \mathcal{C}[C, B]$ by $f_*(g) = f \circ g$.

5.1.1 Monomorphisms

Definition 5.1.18 (Monomorphism). Let $f : A \rightarrow B$. Then f is *monic* or a *monomorphism*, $f : A \rightarrowtail B$, iff, for any object X and functions $x, y : X \rightarrow A$, if $f \circ x = f \circ y$ then $x = y$.

5.1.2 Epimorphisms

Definition 5.1.19 (Epimorphism). Let $f : A \rightarrow B$. Then f is *epic* or an *epimorphism*, $f : A \twoheadrightarrow B$, iff, for any object X and functions $x, y : B \rightarrow X$, if $x \circ f = y \circ f$ then $x = y$.

5.1.3 Sections and Retractions

Definition 5.1.20 (Section, Retraction). Let $r : A \rightarrow B$ and $s : B \rightarrow A$. Then r is a *retraction* of s , and s is a *section* of r , iff $rs = \text{id}_B$.

Proposition 5.1.21. Let $f : A \rightarrow B$ and $r, s : B \rightarrow A$. If r is a retraction of f and s is a section of f then $r = s$.

PROOF:

$$\begin{aligned}
 r &= r \text{id}_B && \text{(Unit Law)} \\
 &= rfs && (s \text{ is a section of } f) \\
 &= \text{id}_A s && (r \text{ is a retraction of } f) \\
 &= s && \text{(Unit Law)} \square
 \end{aligned}$$

Proposition 5.1.22. Every section is monic.

PROOF:

$\langle 1 \rangle 1$. LET: $s : B \rightarrow A$ be a section of $r : A \rightarrow B$.

$\langle 1 \rangle 2$. LET: X be an object and $x, y : X \rightarrow B$

$\langle 1 \rangle 3$. ASSUME: $s \circ x = s \circ y$

$\langle 1 \rangle 4$. $x = y$

PROOF: $x = r \circ s \circ x = r \circ s \circ y = y$.

\square

Proposition 5.1.23. Every retraction is epic.

PROOF: Dual. \square

5.1.4 Isomorphisms

Definition 5.1.24 (Isomorphism). A morphism $f : A \rightarrow B$ is an *isomorphism*, $f : A \cong B$, iff there exists a morphism $f^{-1} : B \rightarrow A$ that is both a retraction and section of f .

Objects A and B are *isomorphic*, $A \cong B$, iff there exists an isomorphism between them.

Proposition 5.1.25. The inverse of an isomorphism is unique.

PROOF: From Proposition 5.1.21. \square

Proposition 5.1.26. If $f : A \cong B$ then $f^{-1} : B \cong A$ and $(f^{-1})^{-1} = f$.

PROOF: Since $ff^{-1} = \text{id}_B$ and $f^{-1}f = \text{id}_A$. \square

Isomorphism.

Define the opposite category.

Slice categories

Definition 5.1.27. Let \mathcal{C} be a category and $B \in \mathcal{C}$. The category \mathcal{C}_B^B of objects *over and under* B is the category with:

- objects all triples (X, u, p) such that $u : B \rightarrow X$ and $p : X \rightarrow B$
- morphisms $f : (X, u, p) \rightarrow (Y, u', p')$ all morphisms $f : X \rightarrow Y$ such that $fu = u'$ and $p'f = p$.

Proposition 5.1.28.

$$\mathcal{C}_B^B \cong (\mathcal{C}/B) \backslash \text{id}_B \cong (\mathcal{C} \backslash B) / \text{id}_B$$

$(B, \text{id}_B, \text{id}_B)$ is the zero object in \mathcal{C}_B^B .

5.1.5 Initial Objects

Definition 5.1.29 (Initial Object). An object I is *initial* iff, for any object X , there exists exactly one morphism $I \rightarrow X$.

Proposition 5.1.30. *The empty set is initial in Set.*

PROOF: For any set A , the nowhere-defined function is the unique function $\emptyset \rightarrow A$. \square

Proposition 5.1.31. *If I and I' are initial objects, then there exists a unique isomorphism $I \cong I'$.*

PROOF:

$\langle 1 \rangle 1$. LET: $i : I \rightarrow I'$ be the unique morphism $I \rightarrow I'$.

$\langle 1 \rangle 2$. LET: $i^{-1} : I' \rightarrow I$ be the unique morphism $I' \rightarrow I$.

$\langle 1 \rangle 3$. $ii^{-1} = \text{id}_{I'}$

PROOF: There is only one morphism $I' \rightarrow I'$.

$\langle 1 \rangle 4$. $i^{-1}i = \text{id}_I$

PROOF: There is only one morphism $I \rightarrow I$.

\square

5.1.6 Terminal Objects

Definition 5.1.32 (Terminal Object). An object T is *terminal* iff, for any object X , there exists exactly one morphism $X \rightarrow T$.

Proposition 5.1.33. *1 is terminal in Set.*

PROOF: For any set A , the constant function to $*$ is the only function $A \rightarrow 1$. \square

Proposition 5.1.34. *If T and T' are terminal objects, then there exists a unique isomorphism $T \cong T'$.*

PROOF: Dual to Proposition 5.1.31. \square

5.1.7 Zero Objects

Definition 5.1.35 (Zero Object). An object Z is a *zero object* iff it is an initial object and a terminal object.

Definition 5.1.36 (Zero Morphism). Let \mathcal{C} be a category with a zero object Z . Let $A, B \in \mathcal{C}$. The *zero morphism* $A \rightarrow B$ is the unique morphism $A \rightarrow Z \rightarrow B$.

Proposition 5.1.37. *There is no zero object in **Set**.*

PROOF: Since $\emptyset \not\approx 1$. \square

5.1.8 Triads

Definition 5.1.38 (Triad). Let \mathcal{C} be a category. A *triad* consists of objects X, Y, M and morphisms $\alpha : X \rightarrow M, \beta : Y \rightarrow M$. We call M the *codomain* of the triad.

5.1.9 Cotriads

Definition 5.1.39 (Cotriad). Let \mathcal{C} be a category. A *cotriad* consists of objects X, Y, W and morphisms $\xi : W \rightarrow X, \eta : W \rightarrow Y$. We call W the *domain* of the triad.

5.1.10 Pullbacks

Definition 5.1.40 (Pullback). A diagram

$$\begin{array}{ccc} W & \xrightarrow{\xi} & X \\ \eta \downarrow & & \downarrow \alpha \\ Y & \xrightarrow{\beta} & M \end{array}$$

is a *pullback* iff $\alpha\xi = \beta\eta$ and, for every object Z and morphism $f : Z \rightarrow X$ and $g : Z \rightarrow Y$ such that $\alpha f = \beta g$, there exists a unique $h : Z \rightarrow W$ such that $\xi h = f$ and $\eta h = g$.

In this case we also say that η is the *pullback* of β along α .

Proposition 5.1.41. *If $\xi : W \rightarrow X$ and $\eta : W \rightarrow Y$ form a pullback of $\alpha : X \rightarrow M$ and $\beta : Y \rightarrow M$, and $\xi' : W' \rightarrow X$ and $\eta' : W' \rightarrow Y$ also form the pullback of α and β , then there exists a unique isomorphism $\phi : W \cong W'$ such that $\eta'\phi = \eta$ and $\xi'\phi = \xi$.*

PROOF:

$\langle 1 \rangle 1$. LET: $\phi : W \rightarrow W'$ be the unique morphism such that $\eta'\phi = \eta$ and $\xi'\phi = \xi$.

$\langle 1 \rangle 2$. LET: $\phi^{-1} : W' \rightarrow W$ be the unique morphism such that $\eta\phi^{-1} = \eta'$ and $\xi\phi^{-1} = \xi'$.

$\langle 1 \rangle 3$. $\phi\phi^{-1} = \text{id}_{W'}$

PROOF: Each is the unique $x : W' \rightarrow W'$ such that $\eta'x = \eta'$ and $\xi'x = \xi'$.

$\langle 1 \rangle 4$. $\phi^{-1}\phi = \text{id}_W$

PROOF: Each is the unique $x : W \rightarrow W$ such that $\eta x = \eta$ and $\xi x = \xi$.

□

Proposition 5.1.42. *For any morphism $h : A \rightarrow B$, the following diagram is a pullback diagram.*

$$\begin{array}{ccc} A & \xrightarrow{h} & B \\ \parallel & & \parallel \\ A & \xrightarrow{h} & B \end{array}$$

PROOF:

$\langle 1 \rangle 1$. LET: Z be an object.

$\langle 1 \rangle 2$. LET: $f : Z \rightarrow B$ and $g : Z \rightarrow A$ satisfy $\text{id}_B f = hg$

$\langle 1 \rangle 3$. $g : Z \rightarrow A$ is the unique morphism such that $\text{id}_A g = g$ and $hg = f$.

□

Proposition 5.1.43. *The pullback of an isomorphism is an isomorphism.*

PROOF:

$\langle 1 \rangle 1$. LET:

$$\begin{array}{ccc} W & \xrightarrow{\xi} & X \\ \eta \downarrow & & \downarrow \alpha \\ Y & \xrightarrow{\beta} & M \end{array}$$

be a pullback diagram.

$\langle 1 \rangle 2$. ASSUME: β is an isomorphism.

$\langle 1 \rangle 3$. LET: ξ^{-1} be the unique morphism $X \rightarrow W$ such that $\xi\xi^{-1} = \text{id}_X$ and $\eta\xi^{-1} = \beta^{-1}\alpha$.

PROOF: This exists since $\alpha\text{id}_X = \beta\beta^{-1}\alpha = \alpha$.

$\langle 1 \rangle 4$. $\xi^{-1}\xi = \text{id}_W$

PROOF: Each is the unique $x : W \rightarrow W$ such that $\xi x = \xi$ and $\eta x = \eta$.

□

Proposition 5.1.44. *Let $\beta : (Y, y) \rightarrow (M, m)$ and $\alpha : (X, x) \rightarrow (M, m)$ in $\mathcal{C} \setminus A$. Let*

$$\begin{array}{ccc} W & \xrightarrow{\xi} & X \\ \eta \downarrow & & \downarrow \alpha \\ Y & \xrightarrow{\beta} & M \end{array}$$

be a pullback in \mathcal{C} . Let $w : A \rightarrow W$ be the unique morphism such that $\xi w = x$ and $\eta w = y$. Then $\xi : (W, w) \rightarrow (X, x)$ and $\eta : (W, w) \rightarrow (Y, y)$ is the pullback of β and α in $\mathcal{C} \setminus A$.

PROOF:

$\langle 1 \rangle 1$. LET: $(Z, z) \in \mathcal{C}/A$

$\langle 1 \rangle 2$. LET: $f : (Z, z) \rightarrow (X, x)$ and $g : (Z, z) \rightarrow (Y, y)$ satisfy $\alpha f = \beta g$.

$\langle 1 \rangle 3$. LET: $h : Z \rightarrow W$ be the unique morphism such that $\xi h = f$ and $\eta h = g$.

$\langle 1 \rangle 4$. $hz = w$

$\langle 2 \rangle 1$. $\xi hz = \xi w$

PROOF:

$$\xi hz = fz \quad (\langle 1 \rangle 3)$$

$$= x \quad (\langle 1 \rangle 2)$$

$$= \xi w$$

$\langle 2 \rangle 2$. $\eta hz = \eta w$

PROOF: Similar.

$\langle 1 \rangle 5$. $h : (Z, z) \rightarrow (W, w)$

□

Proposition 5.1.45. Let $\beta : (Y, y) \rightarrow (M, m)$ and $\alpha : (X, x) \rightarrow (M, m)$ in \mathcal{C}/A . Let

$$\begin{array}{ccc} W & \xrightarrow{\xi} & X \\ \eta \downarrow & & \downarrow \alpha \\ Y & \xrightarrow{\beta} & M \end{array}$$

be a pullback in \mathcal{C} . Let $w = x\xi : W \rightarrow A$. Then $\xi : (W, w) \rightarrow (X, x)$ and $\eta : (W, w) \rightarrow (Y, y)$ form a pullback of α and β in \mathcal{C}/A .

PROOF:

$\langle 1 \rangle 1$. $\eta : (W, w) \rightarrow (Y, y)$

PROOF:

$$y\eta = m\beta\eta$$

$$= m\alpha\xi$$

$$= x\xi$$

$$= w$$

$\langle 1 \rangle 2$. LET: $(Z, z) \in \mathcal{C}/A$

$\langle 1 \rangle 3$. LET: $f : (Z, z) \rightarrow (X, x)$ and $g : (Z, z) \rightarrow (Y, y)$ satisfy $\alpha f = \beta g$.

$\langle 1 \rangle 4$. LET: $h : Z \rightarrow W$ be the unique morphism such that $\xi h = f$ and $\eta h = g$.

$\langle 1 \rangle 5$. $h : (Z, z) \rightarrow (W, w)$

PROOF:

$$wh = x\xi h$$

$$= xf \quad (\langle 1 \rangle 4)$$

$$= z \quad (\langle 1 \rangle 3)$$

□

Proposition 5.1.46. In **Set**, let $\alpha : X \rightarrow M$ and $\beta : Y \rightarrow M$. Let $W = \{(x, y) \in X \times Y : \alpha(x) = \beta(y)\}$ with inclusion $i : W \rightarrow X \times Y$. Let $\xi = \pi_1 i : W \rightarrow X$ and $\eta = \pi_2 i : W \rightarrow Y$. Then ξ and η form the pullback of α and β .

PROOF:

$\langle 1 \rangle 1.$ $\alpha\xi = \beta\eta$

PROOF: For $w \in W$, if $i(w) = (x, y)$ then $\alpha(\xi(w)) = \alpha(x) = \beta(y) = \beta(\eta(w))$.

$\langle 1 \rangle 2.$ For every set Z and functions $f : Z \rightarrow X$, $g : Z \rightarrow Y$ such that $\alpha f = \beta g$, there exists a unique $h : Z \rightarrow W$ such that $\xi h = f$ and $\eta h = g$

PROOF: For $z \in Z$, let $h(z)$ be the unique element of W such that $i(h(z)) = (f(z), g(z))$.

□

Pullback lemma

5.1.11 Pushouts

Definition 5.1.47 (Pushout). A diagram

$$\begin{array}{ccc} W & \xrightarrow{\xi} & X \\ \eta \downarrow & & \downarrow \alpha \\ Y & \xrightarrow{\beta} & M \end{array} \quad (5.1)$$

is a *pushout* iff $\alpha\xi = \beta\eta$ and, for every object Z and morphism $f : X \rightarrow Z$ and $g : Y \rightarrow Z$ such that $f\xi = g\eta$, there exists a unique $h : M \rightarrow Z$ such that $h\alpha = f$ and $h\beta = g$.

We also say that β is the *pushout* of ξ along η .

Proposition 5.1.48. If $\alpha : X \rightarrow M$ and $\beta : Y \rightarrow M$ form a pushout of $\xi : W \rightarrow X$ and $\eta : W \rightarrow Y$, and $\alpha' : X \rightarrow M'$ and $\beta' : Y \rightarrow M'$ also form a pushout of ξ and η , then there exists a unique isomorphism $\phi : M \cong M'$ such that $\phi\alpha = \alpha'$ and $\phi\beta = \beta'$.

PROOF: Dual to Proposition 5.1.41. □

Proposition 5.1.49. For any morphism $h : A \rightarrow B$, the following diagram is a pushout diagram.

$$\begin{array}{ccc} A & \xrightarrow{h} & B \\ \parallel & & \parallel \\ A & \xrightarrow{h} & B \end{array}$$

PROOF: Dual to Proposition 5.1.42.

Proposition 5.1.50. The diagram (5.1) is a pushout in \mathcal{C} iff it is a pullback in \mathcal{C}^{op} .

PROOF: Immediate from definitions. □

Proposition 5.1.51. The pushout of an isomorphism is an isomorphism.

PROOF: Dual to Proposition 5.1.43. \square

Proposition 5.1.52. *Let $\xi : (W, w) \rightarrow (X, x)$ and $\eta : (W, w) \rightarrow (Y, y)$ in $\mathcal{C} \setminus A$. Let*

$$\begin{array}{ccc} W & \xrightarrow{\xi} & X \\ \eta \downarrow & & \downarrow \alpha \\ Y & \xrightarrow{\beta} & M \end{array}$$

be a pushout in \mathcal{C} . Let $m := \alpha x : A \rightarrow M$. Then $\alpha : (X, x) \rightarrow (M, m)$ and $\beta : (Y, y) \rightarrow (M, m)$ is the pushout of ξ and η in $\mathcal{C} \setminus A$.

PROOF: Dual to Proposition 5.1.45. \square

Proposition 5.1.53. *Let $\xi : (W, w) \rightarrow (X, x)$ and $\eta : (W, w) \rightarrow (Y, y)$ in \mathcal{C}/A . Let*

$$\begin{array}{ccc} W & \xrightarrow{\xi} & X \\ \eta \downarrow & & \downarrow \alpha \\ Y & \xrightarrow{\beta} & M \end{array}$$

be a pushout in \mathcal{C} . Let $m : M \rightarrow A$ be the unique morphism such that $m\alpha = x$ and $m\beta = y$. Then $\alpha : (X, x) \rightarrow (M, m)$ and $\beta : (Y, y) \rightarrow (M, m)$ is the pushout of ξ and η in \mathcal{C}/A .

PROOF: Dual to Proposition 5.1.44. \square

Proposition 5.1.54. *Set has pushouts.*

PROOF:

$\langle 1 \rangle 1$. LET: $\xi : W \rightarrow X$ and $\eta : W \rightarrow Y$.

$\langle 1 \rangle 2$. LET: \sim be the equivalence relation on $X + Y$ generated by $\xi(w) \sim \eta(w)$ for all $w \in W$

$\langle 1 \rangle 3$. LET: $M = (X + Y)/\sim$ with canonical projection $\pi : X + Y \twoheadrightarrow M$.

$\langle 1 \rangle 4$. LET: $\alpha = \pi \circ \kappa_1 : X \rightarrow M$

$\langle 1 \rangle 5$. LET: $\beta = \pi \circ \kappa_2 : Y \rightarrow M$

$\langle 1 \rangle 6$. LET: Z be any set, $f : X \rightarrow Z$ and $g : Y \rightarrow Z$.

$\langle 1 \rangle 7$. ASSUME: $f\xi = g\eta$

$\langle 1 \rangle 8$. LET: $h : X + Y \rightarrow Z$ be the function defined by $h(x) = f(x)$ and $h(y) = g(y)$ for $x \in X$ and $y \in Y$

$\langle 1 \rangle 9$. h respects \sim

PROOF: For $w \in W$ we have

$$h(\xi(w)) = f(\xi(w)) \quad (\langle 1 \rangle 8)$$

$$= g(\eta(w)) \quad (\langle 1 \rangle 7)$$

$$= h(\eta(w)) \quad (\langle 1 \rangle 8)$$

$\langle 1 \rangle 10$. LET: $\bar{h} : M \rightarrow Z$ be the induced function.

$\langle 1 \rangle 11$. $\bar{h}\alpha = f$

PROOF:

$$\begin{aligned}\bar{h}(\alpha(x)) &= \bar{h}(\pi(\kappa_1(x))) \\ &= h(\kappa_1(x)) \\ &= f(x)\end{aligned}$$

$\langle 1 \rangle 12.$ $\bar{h}\beta = g$

PROOF: Similar.

$\langle 1 \rangle 13.$ For all $k : M \rightarrow Z$, if $k\alpha = f$ and $k\beta = g$ then $k = \bar{h}$.

PROOF:

$$\begin{aligned}k(\pi(\kappa_1(x))) &= k(\alpha(x)) \\ &= f(x) \\ k(\pi(\kappa_2(y))) &= k(\beta(y)) \\ &= g(y) \\ \therefore k \circ \pi &= h \\ \therefore k &= \bar{h}\end{aligned}$$

□

Definition 5.1.55. Let $u : A \rightarrowtail X$ be an injection. The *pointed set obtained from X by collapsing (A, u)* , denoted $X/(A, u)$, is the pushout

$$\begin{array}{ccc} A & \longrightarrow & 1 \\ \downarrow u & & \downarrow * \\ X & \longrightarrow & X/(A, u) \end{array}$$

Proposition 5.1.56. In \mathbf{Set}_* , any two morphisms $1 \rightarrow X$ and $1 \rightarrow Y$ have a pushout.

PROOF: The pushout of $a : (1, *) \rightarrow (X, x)$ and $b : (1, *) \rightarrow (Y, y)$ is $(X+Y/\sim, x)$ where \sim is the equivalence relation generated by $x \sim y$. □

Definition 5.1.57 (Wedge). The *wedge* of pointed sets X and Y , $X \vee Y$, is the pushout of the unique morphism $1 \rightarrow X$ and $1 \rightarrow Y$.

Definition 5.1.58 (Smash). Let X and Y be pointed sets. Let $\xi : X \vee Y \rightarrow X$ be the unique morphism such that the following diagram commutes.

$$\begin{array}{ccccc} 1 & \longrightarrow & X & & \\ \downarrow & & \downarrow & \searrow & \\ Y & \longrightarrow & X \vee Y & \xrightarrow{\xi} & X \\ & \searrow 0 & & & \uparrow \\ & & & & \end{array}$$

Let $\eta : X \vee Y \rightarrow Y$ be the unique morphism such that the following diagram

commutes.



Let $\zeta = \langle \xi, \eta \rangle : X \vee Y \rightarrow X \times Y$. The *smash* of X and Y , $X \wedge Y$, is the result of collapsing $X \times Y$ with respect to ζ .

Pushout lemma

5.1.12 Subcategories

Definition 5.1.59 (Subcategory). A *subcategory* \mathcal{C}' of a category \mathcal{C} consists of:

- a subset $\text{Ob}(\mathcal{C}')$ of \mathcal{C}
- for all $A, B \in \text{Ob}(\mathcal{C}')$, a subset $\mathcal{C}'[A, B] \subseteq \mathcal{C}[A, B]$

such that:

- for all $A \in \text{Ob}(\mathcal{C}')$, we have $\text{id}_A \in \mathcal{C}'[A, A]$
- for all $f \in \mathcal{C}'[A, B]$ and $g \in \mathcal{C}'[B, C]$, we have $g \circ f \in \mathcal{C}'[A, C]$.

It is a *full* subcategory iff, for all $A, B \in \text{Ob}(\mathcal{C}')$, we have $\mathcal{C}'[A, B] = \mathcal{C}[A, B]$.

5.1.13 Opposite Category

Definition 5.1.60 (Opposite Category). For any category \mathcal{C} , the *opposite* category \mathcal{C}^{op} is the category with

- $\text{Ob}(\mathcal{C}^{\text{op}}) = \text{Ob}(\mathcal{C})$
- $\mathcal{C}^{\text{op}}[A, B] = \mathcal{C}[B, A]$
- Given $f \in \mathcal{C}^{\text{op}}[A, B]$ and $g \in \mathcal{C}^{\text{op}}[B, C]$, their composite in \mathcal{C}^{op} is $f \circ g$, where \circ is composition in \mathcal{C} .

Proposition 5.1.61. An object is initial in \mathcal{C} iff it is terminal in \mathcal{C}^{op} .

PROOF: Immediate from definitions. \square

Proposition 5.1.62. An object is terminal in \mathcal{C} iff it is initial in \mathcal{C}^{op} .

PROOF: Immediate from definitions. \square

Corollary 5.1.62.1. If T and T' are terminal objects in \mathcal{C} then there exists a unique isomorphism $T \cong T'$.

5.1.14 Groupoids

Definition 5.1.63 (Groupoid). A *groupoid* is a category in which every morphism is an isomorphism.

5.1.15 Concrete Categories

Definition 5.1.64 (Concrete Category). A *concrete category* \mathcal{C} consists of:

- a set $\text{Ob}(\mathcal{C})$ of *objects*
- for any object $A \in \text{Ob}(\mathcal{C})$, a set $|A|$
- for any objects $A, B \in \text{Ob}(\mathcal{C})$, a set of functions $\mathcal{C}[A, B] \subseteq |B|^{|A|}$

such that:

- for any $f \in \mathcal{C}[A, B]$ and $g \in \mathcal{C}[B, C]$, we have $g \circ f \in \mathcal{C}[A, C]$
- for any object A we have $\text{id}_{|A|} \in \mathcal{C}[A, A]$.

5.1.16 Power of Categories

Definition 5.1.65. Let \mathcal{C} be a category and J a set. The category \mathcal{C}^J is the category with:

- objects all J -indexed families of objects of \mathcal{C}
- morphisms $\{X_j\}_{j \in J} \rightarrow \{Y_j\}_{j \in J}$ all families $\{f_j\}_{j \in J}$ where $f_j : X_j \rightarrow Y_j$

5.1.17 Arrow Category

Definition 5.1.66 (Arrow Category). Let \mathcal{C} be a category. The *arrow category* \mathcal{C}^\rightarrow is the category with:

- objects all triples (A, B, f) where $f : A \rightarrow B$ in \mathcal{C}
- morphisms $(A, B, f) \rightarrow (C, D, g)$ all pairs $(u : A \rightarrow C, v : B \rightarrow D)$ such that $vf = gu$.

5.1.18 Slice Category

Definition 5.1.67 (Slice Category). Let \mathcal{C} be a category and $A \in \mathcal{C}$. The *slice category under A* , $\mathcal{C}_{\backslash A}$, is the category with:

- objects all pairs (B, f) where $B \in \mathcal{C}$ and $f : A \rightarrow B$
- morphisms $(B, f) \rightarrow (C, g)$ are morphisms $u : B \rightarrow C$ such that $uf = g$.

We identify this with the subcategory of \mathcal{C}^\rightarrow formed by mapping (B, f) to (A, B, f) and u to (id_A, u) .

Proposition 5.1.68. *If $s : (B, f) \rightarrow (C, g)$ in $\mathcal{C} \setminus A$, then any retraction of s in \mathcal{C} is a retraction of s in $\mathcal{C} \setminus A$.*

PROOF:

$\langle 1 \rangle 1$. LET: $r : C \rightarrow B$ be a retraction of s in \mathcal{C} .

$\langle 1 \rangle 2$. $rg = f$

PROOF: $rg = rsf = f$.

$\langle 1 \rangle 3$. $r : (C, g) \rightarrow (B, f)$ in $\mathcal{C} \setminus A$

$\langle 1 \rangle 4$. $rs = \text{id}_{(B, f)}$

PROOF: Because composition is inherited from \mathcal{C} .

□

Proposition 5.1.69. id_A is the initial object in $\mathcal{C} \setminus A$.

PROOF: For any $(B, f) \in \mathcal{C} \setminus A$, we have f is the only morphism $A \rightarrow B$ such that $f\text{id}_A = f$. □

Proposition 5.1.70. *If A is terminal in \mathcal{C} then id_A is the zero object in $\mathcal{C} \setminus A$.*

PROOF: For any $(B, f) \in \mathcal{C} \setminus A$, the unique morphism $! : B \rightarrow A$ is the unique morphism such that $!f = \text{id}_A$. □

Definition 5.1.71 (Pointed Sets). The *category of pointed sets* is **Set** \ 1.

Definition 5.1.72. Let \mathcal{C} be a category and $A \in \mathcal{C}$. The *slice category over A* , \mathcal{C}/A , is the category with:

- objects all pairs (B, f) with $f : B \rightarrow A$
- morphisms $u : (B, f) \rightarrow (C, g)$ all morphisms $u : B \rightarrow C$ such that $gu = f$.

Proposition 5.1.73. *Let $u : (B, f) \rightarrow (C, g) : \mathcal{C}/A$. Any section of u in \mathcal{C} is a section of u in \mathcal{C}/A .*

PROOF: Dual to Proposition 5.1.68. □

Proposition 5.1.74. id_A is terminal in \mathcal{C}/A .

PROOF: Dual to Proposition 5.1.69. □

Proposition 5.1.75. *If A is initial in \mathcal{C} then id_A is the zero object in \mathcal{C}/A .*

PROOF: Dual to Proposition 5.1.70. □

Definition 5.1.76. Let $A \in \mathcal{C}$. The category of objects *over and under* A , written \mathcal{C}_A^A , is the category with:

- objects all triples (X, u, p) where $u : A \rightarrow X$, $p : X \rightarrow A$ and $pu = \text{id}_A$
- morphism $f : (X, u, p) \rightarrow (Y, v, q)$ all morphisms $f : X \rightarrow Y$ such that $fu = v$ and $qf = p$

Proposition 5.1.77. $(A, \text{id}_A, \text{id}_A)$ is the zero object in \mathcal{C}_A^A .

PROOF: For any object (X, u, p) , we have p is the unique morphism $(X, u, p) \rightarrow (A, \text{id}_A, \text{id}_A)$, and u is the unique morphism $(A, \text{id}_A, \text{id}_A) \rightarrow (X, u, p)$. \square

Definition 5.1.78 (Fibre Collapsing). Let B be a set. Let $u : (A, a) \rightarrow (X, x)$ in \mathbf{Set}/B . Form the pushout

$$\begin{array}{ccc} A & \xrightarrow{a} & B \\ \downarrow u & & \downarrow j \\ X & \xrightarrow{i} & C \end{array}$$

Let $c : C \rightarrow B$ be the unique morphism such that $cj = \text{id}_B$ and $ci = x$. Then $(C, j, c) \in \mathbf{Set}_B^B$ is called the set over and under B obtained from X by *fibre collapsing* with respect to u . If (A, u) is a subset of X , we denote this set over and under B by $X/_B(A, u)$.

Definition 5.1.79 (Fibre Wedge). Let B be a small set. Let $(X, u_X, p_X), (Y, u_Y, p_Y) \in \mathbf{Set}_B^B$. The *fibre wedge* of X and Y is the pushout of u_X and u_Y :

$$\begin{array}{ccc} B & \xrightarrow{u_X} & X \\ \downarrow u_Y & & \downarrow \\ Y & \longrightarrow & X \vee_B Y \end{array}$$

Definition 5.1.80 (Fibre Smash). Let $X, Y \in \mathbf{Set}_B^B$. Let $\xi : X \vee_B Y \rightarrow X$ be the unique morphism such that the following diagram commutes.

$$\begin{array}{ccc} 1 & \longrightarrow & X \\ \downarrow & & \downarrow \\ Y & \longrightarrow & X \vee_B Y \\ & \searrow \xi & \\ & & X \end{array}$$

0

Let $\eta : X \vee_B Y \rightarrow Y$ be the unique morphism such that the following diagram commutes.

$$\begin{array}{ccc} 1 & \longrightarrow & X \\ \downarrow & & \downarrow \\ Y & \longrightarrow & X \vee_B Y \\ & \searrow \eta & \\ & & Y \end{array}$$

0

Let $\zeta = \langle \xi, \eta \rangle : X \vee_B Y \rightarrow X \times Y$. The *fibre smash* of X and Y , $X \wedge_B Y$, is the result of collapsing $X \times Y$ with respect to ζ .

Proposition 5.1.81. *Set has products and coproducts.*

Proposition 5.1.82. *Let \mathcal{C} be a category. Let $\{X_\alpha\}_{\alpha \in I}$ be a family of objects in \mathcal{C} and $Z \in \mathcal{C}$. Let $\coprod_{\alpha \in I} X_\alpha$ be the coproduct of $\{X_\alpha\}_{\alpha \in I}$. Then*

$$\mathcal{C}[\coprod_{\alpha \in I} X_\alpha, Z] \approx \prod_{\alpha \in I} \mathcal{C}[X_\alpha, Z] .$$

Proposition 5.1.83. *Let \mathcal{C} be a category. Let $\{X_\alpha\}_{\alpha \in I}$ be a family of objects in \mathcal{C} and $Z \in \mathcal{C}$. Let $\prod_{\alpha \in I} X_\alpha$ be the product of $\{X_\alpha\}_{\alpha \in I}$. Then*

$$\mathcal{C}[Z, \prod_{\alpha \in I} X_\alpha] \approx \prod_{\alpha \in I} \mathcal{C}[Z, X_\alpha] .$$

Proposition 5.1.84. *A product in \mathcal{C} constitutes a product in \mathcal{C}/A .*

Proposition 5.1.85. *A coproduct in \mathcal{C} constitutes a product in \mathcal{C}/A .*

5.2 Functors

Definition 5.2.1 (Functor). Let \mathcal{C} and \mathcal{D} be categories. A *functor* $F : \mathcal{C} \rightarrow \mathcal{D}$ consists of:

- a function $F : \text{Ob}(\mathcal{C}) \rightarrow \text{Ob}(\mathcal{D})$
- for every morphism $f : A \rightarrow B$ in \mathcal{C} , a morphism $Ff : FA \rightarrow FB$ in \mathcal{D}

such that:

- for all $A \in \text{Ob}(\mathcal{C})$ we have $F\text{id}_A = \text{id}_{FA}$
- for any morphism $f : A \rightarrow B$ and $g : B \rightarrow C$ in \mathcal{C} , we have $F(g \circ f) = Fg \circ Ff$

Proposition 5.2.2. *Functors preserve isomorphisms.*

PROOF:

$\langle 1 \rangle 1$. LET: $F : \mathcal{C} \rightarrow \mathcal{D}$ be a functor.

$\langle 1 \rangle 2$. LET: $f : A \cong B$ in \mathcal{C}

$\langle 1 \rangle 3$. $Ff^{-1} \circ Ff = \text{id}_{FA}$

PROOF:

$$\begin{aligned} Ff^{-1} \circ Ff &= F(f^{-1} \circ f) \\ &= F\text{id}_A \\ &= \text{id}_{FA} \end{aligned}$$

$\langle 1 \rangle 4$. $Ff \circ Ff^{-1} = \text{id}_{FB}$

PROOF:

$$\begin{aligned} Ff \circ Ff^{-1} &= F(f \circ f^{-1}) \\ &= F\text{id}_B \\ &= \text{id}_{FB} \end{aligned}$$

□

Definition 5.2.3 (Identity Functor). For any category \mathcal{C} , the *identity* functor on \mathcal{C} is the functor $I_{\mathcal{C}} : \mathcal{C} \rightarrow \mathcal{C}$ defined by

$$\begin{aligned} I_{\mathcal{C}}A &:= A & (A \in \mathcal{C}) \\ I_{\mathcal{C}}f &:= f & (f : A \rightarrow B \text{ in } \mathcal{C}) \end{aligned}$$

Proposition 5.2.4. Let $F : \mathcal{C} \rightarrow \mathcal{D}$. If $r : A \rightarrow B$ is a retraction of $s : B \rightarrow A$ in \mathcal{C} then Fr is a retraction of Fs .

PROOF:

$$\begin{aligned} Fr \circ Fs &= F(r \circ s) \\ &= F\text{id}_B \\ &= \text{id}_{FB} \end{aligned}$$

□

Corollary 5.2.4.1. Let $F : \mathcal{C} \rightarrow \mathcal{D}$. If $\phi : A \cong B$ is an isomorphism in \mathcal{C} then $F\phi : FA \cong FB$ is an isomorphism in \mathcal{D} with $(F\phi)^{-1} = F\phi^{-1}$.

Definition 5.2.5 (Composition of Functors). Given functors $F : \mathcal{C} \rightarrow \mathcal{D}$ and $G : \mathcal{D} \rightarrow \mathcal{E}$, the *composite* functor $GF : \mathcal{C} \rightarrow \mathcal{E}$ is defined by

$$\begin{aligned} (GF)A &= G(FA) & (A \in \mathcal{C}) \\ (GF)f &= G(Ff) & (f : A \rightarrow B : \mathcal{C}) \end{aligned}$$

Definition 5.2.6 (Category of Categories). Let **Cat** be the category of small categories and functors.

Definition 5.2.7 (Isomorphism of Categories). Let $F : \mathcal{C} \rightarrow \mathcal{D}$ be a functor. Then F is an *isomorphism of categories* iff there exists a functor $F^{-1} : \mathcal{D} \rightarrow \mathcal{C}$, the *inverse* of F , such that $FF^{-1} = I_{\mathcal{D}}$ and $F^{-1}F = I_{\mathcal{C}}$.

Categories \mathcal{C} and \mathcal{D} are *isomorphic*, $\mathcal{C} \cong \mathcal{D}$, iff there exists an isomorphism between them.

Proposition 5.2.8. If A is initial in \mathcal{C} then $\mathcal{C} \setminus A \cong \mathcal{C}$.

PROOF:

⟨1⟩1. Define $F : \mathcal{C} \setminus A \rightarrow \mathcal{C}$ by

$$F(B, f) = B$$

$$F(u : (B, f) \rightarrow (C, g)) = u$$

⟨1⟩2. Define $G : \mathcal{C} \rightarrow \mathcal{C} \setminus A$ by

$$GB = (B, !_B)$$

where $!_B$ is the unique morphism $A \rightarrow B$

$$G(u : B \rightarrow C) = u : (B, !_B) \rightarrow (C, !_C)$$

⟨1⟩3. $FG = \text{id}_{\mathcal{C}}$

⟨1⟩4. $GF = \text{id}_{\mathcal{C} \setminus A}$

PROOF: Since $GF(B, f) = (B, !_B) = (B, f)$ because the morphism $A \rightarrow B$ is unique.

□

Proposition 5.2.9. *If A is terminal in \mathcal{C} then $\mathcal{C}/A \cong \mathcal{C}$.*

PROOF: Dual. \square

Proposition 5.2.10.

$$\mathcal{C}_A^A \cong (\mathcal{C}/A) \backslash (A, \text{id}_A) \cong (\mathcal{C} \backslash A) / (A, \text{id}_A)$$

PROOF:

- $\langle 1 \rangle 1$. Define a functor $F : \mathcal{C}_A^A \rightarrow (\mathcal{C}/A) \backslash (A, \text{id}_A)$.
 $\langle 2 \rangle 1$. Given $A \xrightarrow{u} X \xrightarrow{p} A$ in \mathcal{C}_A^A , let $F(X, u, p) = ((X, p), u)$
 $\langle 2 \rangle 2$. Given $f : (A \xrightarrow{u} X \xrightarrow{p} A) \rightarrow (A \xrightarrow{v} Y \xrightarrow{q} A)$, let $Ff = f$.
 $\langle 1 \rangle 2$. Define a functor $G : (\mathcal{C}/A) \backslash (A, \text{id}_A) \rightarrow \mathcal{C}_A^A$.
 $\langle 1 \rangle 3$. Define a functor $H : \mathcal{C}_A^A \rightarrow (\mathcal{C} \backslash A) / (A, \text{id}_A)$.
 $\langle 1 \rangle 4$. Define a functor $K : (\mathcal{C} \backslash A) / (A, \text{id}_A) \rightarrow \mathcal{C}_A^A$.
 \square

Definition 5.2.11 (Forgetful Functor). For any concrete category \mathcal{C} , define the *forgetful* functor $U : \mathcal{C} \rightarrow \mathbf{Set}$ by:

$$\begin{aligned} UA &= |A| \\ Uf &= f \end{aligned}$$

Definition 5.2.12 (Switching Functor). For any category \mathcal{C} , define the *switching* functor $T : \mathcal{C} \times \mathcal{C} \rightarrow \mathcal{C} \times \mathcal{C}$ by

$$\begin{aligned} T(A, B) &= (B, A) \\ T(f, g) &= (g, f) \end{aligned}$$

Definition 5.2.13 (Reduction). Let $\Phi : \mathbf{Set} \rightarrow \mathbf{Set}$ be a functor. The *reduction* of Φ is the functor $\Phi^* : \mathbf{Set}_* \rightarrow \mathbf{Set}_*$ defined by: $\Phi^*(X, a)$ is the collapse of $\Phi(X)$ with respect to $\Phi(a) : \Phi(1) \rightarrow \Phi(X)$.

Definition 5.2.14. Extend the wedge \vee to a functor $\mathbf{Set}_* \times \mathbf{Set}_* \rightarrow \mathbf{Set}_*$ by defining, given $f : X \rightarrow X'$ and $g : Y \rightarrow Y'$, then $f \vee g$ is the unique morphism that makes the following diagram commute.

$$\begin{array}{ccccc} 1 & \longrightarrow & X & & \\ \downarrow & & \downarrow & \searrow f & \\ Y & \longrightarrow & X \vee Y & & X' \\ & \searrow g & \searrow f \vee g & & \downarrow \\ & & Y' & \longrightarrow & X' \vee Y' \end{array}$$

Definition 5.2.15. Extend smash to a functor $\wedge : \mathbf{Set}_* \times \mathbf{Set}_* \rightarrow \mathbf{Set}_*$ as follows. Given $f : X \rightarrow X'$ and $g : Y \rightarrow Y'$, let $f \wedge g : X \wedge Y \rightarrow X' \wedge Y'$ be the

unique morphism such that the following diagram commutes.

$$\begin{array}{ccccc}
 X \vee Y & \longrightarrow & 1 & & \\
 \downarrow & \searrow & \downarrow & \searrow & \\
 X \times Y & \longrightarrow & X \wedge Y & & \\
 & \searrow & \downarrow & \searrow & \\
 & & X' \vee Y' & \longrightarrow & 1 \\
 f \times g \swarrow & & \downarrow & & \downarrow \\
 & & X' \times Y' & \longrightarrow & X' \wedge Y'
 \end{array}$$

Definition 5.2.16 (Reduction). Let B be a small set. Let $\Phi_B : \mathbf{Set}/B \rightarrow \mathbf{Set}/B$ be a functor. The *reduction* of Φ_B is the functor $\Phi_B^B : \mathbf{Set}_B^B \rightarrow \mathbf{Set}_B^B$ defined as follows.

For $(X, u : B \rightarrow X, p : X \rightarrow B) \in \mathbf{Set}_B^B$, let $\Phi_B^B(X)$ be the set over and under B obtained from $\Phi_B(X)$ by collapsing with respect to $\Phi_B(u) : \Phi_B(B) \rightarrow \Phi_B(X)$.

Definition 5.2.17. Extend \vee_B to a functor $\mathbf{Set}_B^B \times \mathbf{Set}_B^B \rightarrow \mathbf{Set}_B^B$.

Definition 5.2.18. Extend \wedge_B to a functor $\mathbf{Set}_B^B \times \mathbf{Set}_B^B \rightarrow \mathbf{Set}_B^B$.

Definition 5.2.19 (Faithful). A functor $F : \mathcal{C} \rightarrow \mathcal{D}$ is *faithful* iff, for any objects $A, B \in \mathcal{C}$ and morphisms $f, g : A \rightarrow B : \mathcal{C}$, if $Ff = Fg$ then $f = g$.

Definition 5.2.20 (Full). A functor $F : \mathcal{C} \rightarrow \mathcal{D}$ is *full* iff, for any objects $A, B \in \mathcal{C}$ and morphism $g : FA \rightarrow FB : \mathcal{D}$, there exists $f : A \rightarrow B : \mathcal{C}$ such that $Ff = g$.

Definition 5.2.21 (Fully Faithful). A functor $F : \mathcal{C} \rightarrow \mathcal{D}$ is *fully faithful* iff it is full and faithful.

Definition 5.2.22 (Full Embedding). A functor $F : \mathcal{C} \rightarrow \mathcal{D}$ is a *full embedding* iff it is fully faithful and injective on objects.

5.3 Natural Transformations

Definition 5.3.1 (Natural Transformation). Let $F, G : \mathcal{C} \rightarrow \mathcal{D}$. A *natural transformation* $\tau : F \Rightarrow G$ is a family of morphisms $\{\tau_X : FX \rightarrow GX\}_{X \in \mathcal{C}}$ such that, for every morphism $f : X \rightarrow Y : \mathcal{C}$, we have $Gf \circ \tau_X = \tau_Y \circ Ff$.

$$\begin{array}{ccc}
 FX & \xrightarrow{Ff} & FY \\
 \tau_X \downarrow & & \downarrow \tau_Y \\
 GX & \xrightarrow{Gf} & GY
 \end{array}$$

Definition 5.3.2 (Natural Isomorphism). A natural transformation $\tau : F \Rightarrow G : \mathcal{C} \rightarrow \mathcal{D}$ is a *natural isomorphism*, $\tau : F \cong G$, iff for all $X \in \mathcal{C}$, τ_X is an isomorphism $FX \cong GX$.

Functors F and G are *naturally isomorphic*, $F \cong G$, iff there exists a natural isomorphism between them.

Definition 5.3.3 (Inverse). Let $\tau : F \cong G$. The *inverse* natural isomorphism $\tau^{-1} : G \cong F$ is defined by $(\tau^{-1})_X = \tau_X^{-1}$.

5.4 Bifunctors

Definition 5.4.1 (Commutative). A bifunctor $\square : \mathcal{C}^2 \rightarrow \mathcal{C}$ is *commutative* iff $\square \cong \square \circ T$, where $T : \mathcal{C}^2 \rightarrow \mathcal{C}^2$ is the swap functor.

Proposition 5.4.2. $\vee : \mathbf{Set}_* \times \mathbf{Set}_* \rightarrow \mathbf{Set}_*$ is commutative.

PROOF: Since the pushout of f and g is the pushout of g and f . \square

Proposition 5.4.3. $\wedge : \mathbf{Set}_* \times \mathbf{Set}_* \rightarrow \mathbf{Set}_*$ is commutative.

PROOF: In the diagram defining $X \wedge Y$, construct the isomorphism between the version with X and Y and the version with Y with X for every object. \square

Proposition 5.4.4. $\vee_B : \mathbf{Set}_B^B \times \mathbf{Set}_B^B \rightarrow \mathbf{Set}_B^B$ is commutative.

Proposition 5.4.5. $\wedge_B : \mathbf{Set}_B^B \times \mathbf{Set}_B^B \rightarrow \mathbf{Set}_B^B$ is commutative.

Definition 5.4.6 (Associative). A bifunctor \square is *associative* iff $\square \circ (\square \times \text{id}) \cong \square \circ (\text{id} \times \square)$.

Proposition 5.4.7. $\vee : \mathbf{Set}_* \times \mathbf{Set}_* \rightarrow \mathbf{Set}_*$ is associative.

PROOF: Since $X \vee (Y \vee Z)$ and $(X \vee Y) \vee Z$ are both the pushout of the unique morphisms $1 \rightarrow X$, $1 \rightarrow Y$ and $1 \rightarrow Z$. \square

Proposition 5.4.8. $\wedge : \mathbf{Set}_* \times \mathbf{Set}_* \rightarrow \mathbf{Set}_*$ is associative.

PROOF: Draw isomorphisms between the diagrams for $X \wedge (Y \wedge Z)$ and $(X \wedge Y) \wedge Z$. \square

Product and coproduct are commutative and associative.

Proposition 5.4.9. $\vee_B : \mathbf{Set}_B^B \times \mathbf{Set}_B^B \rightarrow \mathbf{Set}_B^B$ is associative.

Proposition 5.4.10. $\wedge_B : \mathbf{Set}_B^B \times \mathbf{Set}_B^B \rightarrow \mathbf{Set}_B^B$ is associative.

Proposition 5.4.11. Let \mathcal{C} be a category with binary coproducts. Let $\square : \mathcal{C} \times \mathcal{C} \rightarrow \mathcal{C}$ be a bifunctor. Then \square distributes over $+$ iff the canonical morphism

$$(X \square Z) + (Y \square Z) \rightarrow (X + Y) \square Z$$

is an isomorphism for all X, Y, Z .

Proposition 5.4.12. *In a category with binary products and binary coproducts, then \times distributes over $+$.*

Proposition 5.4.13. *In $\mathbf{Set}/*$, we have \times does not distribute over \vee .*

Proposition 5.4.14. *In $\mathbf{Set}/*$, we have \wedge distributes over \vee .*

Proposition 5.4.15. *In \mathbf{Set}/B , we have \times_B distributes over $+_B$.*

Proposition 5.4.16. *In \mathbf{Set}/B^B , we have \wedge_B distributes over \vee_B .*

5.5 Functor Categories

Definition 5.5.1 (Functor Category). Given categories \mathcal{C} and \mathcal{D} , define the *functor category* $\mathcal{C}^{\mathcal{D}}$ to be the category with objects the functors from \mathcal{D} to \mathcal{C} and morphisms the natural transformations.

Definition 5.5.2 (Yoneda Embedding). Let \mathcal{C} be a category. The *Yoneda embedding* $Y : \mathcal{C} \rightarrow \mathbf{Set}^{\mathcal{C}^{\text{op}}}$ is the functor that maps an object A to $\mathcal{C}[-, A]$ and morphisms similarly.

Theorem 5.5.3 (Yoneda Lemma). *Let \mathcal{C} be a category. There exists a natural isomorphism*

$$\phi_{XF} : \mathbf{Set}^{\mathcal{C}^{\text{op}}}[\mathcal{C}[-, X], F] \cong FX$$

that maps $\tau : \mathcal{C}[-, X] \Rightarrow F$ to $\tau_X(\text{id}_X)$.

PROOF:

$\langle 1 \rangle 1$. ϕ is natural in X .

PROOF:

$\langle 2 \rangle 1$. LET: $f : X \rightarrow Y : \mathcal{C}$

$\langle 2 \rangle 2$. LET: $\tau : \mathcal{C}[-, X] \Rightarrow F$

$\langle 2 \rangle 3$. $Ff(\phi(\tau)) = \phi(\tau \circ \mathcal{C}[-, f])$

PROOF:

$$\begin{aligned} \phi(\tau \circ \mathcal{C}[-, f]) &= \tau_Y(\text{id}_Y \circ f) \\ &= \tau_Y(f) \\ &= \tau_Y(f \circ \text{id}_X) \\ &= Ff(\tau_X(\text{id}_X)) && (\tau \text{ natural}) \\ &= Ff(\phi(\tau)) \end{aligned}$$

$\langle 1 \rangle 2$. ϕ is natural in F .

$\langle 2 \rangle 1$. LET: $\alpha : F \Rightarrow G : \mathcal{C}^{\text{op}} \rightarrow \mathbf{Set}$

$\langle 2 \rangle 2$. LET: $\tau : \mathcal{C}[-, X] \Rightarrow F$

$\langle 2 \rangle 3$. $\alpha_X(\phi(\tau)) = \phi(\alpha \bullet \tau)$

PROOF: $\phi(\alpha \bullet \tau) = \alpha_X(\tau_X(\text{id}_X)) = \alpha_X(\phi(\tau))$

$\langle 1 \rangle 3$. Each ϕ_{XF} is injective.

$\langle 2 \rangle 1$. LET: $\sigma, \tau : \mathcal{C}[-, X] \Rightarrow F$

$\langle 2 \rangle 2$. ASSUME: $\phi(\sigma) = \phi(\tau)$

$\langle 2 \rangle 3$. LET: $f : Y \rightarrow X$

$\langle 2 \rangle 4$. $\sigma_Y(f) = \tau_Y(f)$

PROOF:

$$\begin{aligned}
 \sigma_Y(f) &= \sigma_Y(\text{id}_X \circ f) \\
 &= Ff(\sigma_X(\text{id}_X)) && (\sigma \text{ is natural}) \\
 &= Ff(\tau_X(\text{id}_X)) && (\langle 2 \rangle 2) \\
 &= \tau_Y(\text{id}_X \circ f) && (\tau \text{ is natural}) \\
 &= \tau_Y(f)
 \end{aligned}$$

$\langle 1 \rangle 4$. Each ϕ_{XF} is surjective.

$\langle 2 \rangle 1$. LET: $X \in \mathcal{C}$ and $F : \mathcal{C} \rightarrow \mathcal{D}$

$\langle 2 \rangle 2$. LET: $a \in FX$

$\langle 2 \rangle 3$. LET: $\tau : \mathcal{C}[-, X] \Rightarrow F$ be given by $\tau_Y(g) = Fg(a)$ for $g : Y \rightarrow X$

$\langle 2 \rangle 4$. τ is natural.

$\langle 3 \rangle 1$. LET: $h : Y \rightarrow Z : \mathcal{C}$

PROVE: $Fh \circ \tau_Z = \tau_Y \circ \mathcal{C}[h, \text{id}_X]$

$\langle 3 \rangle 2$. LET: $g : Z \rightarrow X$

$\langle 3 \rangle 3$. $Fh(\tau_Z(g)) = \tau_Y(g \circ h)$

PROOF:

$$\begin{aligned}
 \tau_Y(g \circ h) &= F(g \circ h)(a) \\
 &= Fh(Fg(a)) \\
 &= Fh(\tau_Z(g))
 \end{aligned}$$

$\langle 2 \rangle 5$. $\phi(\tau) = a$

PROOF:

$$\begin{aligned}
 \phi_X(\tau) &= \tau_X(\text{id}_X) \\
 &= F\text{id}_X(a) \\
 &= a
 \end{aligned}$$

□

Corollary 5.5.3.1. *The Yoneda embedding is fully faithful.*

Corollary 5.5.3.2. *Given objects A and B in \mathcal{C} , we have $A \cong B$ if and only if $\mathcal{C}[-, A] \cong \mathcal{C}[-, B]$.*

Part III

Number Systems

Chapter 6

The Real Numbers

Theorem 6.0.1. *The following hold in the real numbers:*

1. $x + (y + z) = (x + y) + z$
2. $x(yz) = (xy)z$
3. $x + y = y + x$
4. $xy = yx$
5. $x + 0 = x$
6. $x1 = x$
7. $x + (-x) = 0$
8. If $x \neq 0$ then $x \cdot (1/x) = 1$
9. $x(y + z) = xy + xz$
10. If $x > y$ then $x + z > y + z$.
11. If $x > y$ and $z > 0$ then $xz > yz$.
12. \mathbb{R} has the least upper bound property.
13. If $x < y$ then there exists z such that $x < z < y$.

Definition 6.0.2. Given real numbers x and y with $y \neq 0$, we write x/y for xy^{-1} .

Theorem 6.0.3. *For any real numbers x and y , if $x + y = x$ then $y = 0$.*

PROOF:

$\langle 1 \rangle 1.$ LET: $x, y \in \mathbb{R}$

$\langle 1 \rangle 2.$ ASSUME: $x + y = x$

$\langle 1 \rangle 3.$ $y = 0$

PROOF:

$$\begin{aligned}
y &= y + 0 && \text{(Definition of zero)} \\
&= y + (x + (-x)) && \text{(Definition of } -x) \\
&= (y + x) + (-x) && \text{(Associativity of Addition)} \\
&= (x + y) + (-x) && \text{(Commutativity of Addition)} \\
&= x + (-x) && (\langle 1 \rangle 2) \\
&= 0 && \text{(Definition of } -x)
\end{aligned}$$

□

Theorem 6.0.4.

$$\forall x \in \mathbb{R}. 0x = 0$$

PROOF:

 $\langle 1 \rangle 1$. LET: $x \in \mathbb{R}$ $\langle 1 \rangle 2$. $xx + 0x = xx$

PROOF:

$$\begin{aligned}
xx + 0x &= (x + 0)x && \text{(Distributive Law)} \\
&= xx && \text{(Definition of 0)}
\end{aligned}$$

 $\langle 1 \rangle 3$. $0x = 0$ PROOF: Theorem 6.0.3, $\langle 1 \rangle 2$.

□

Theorem 6.0.5.

$$-0 = 0$$

PROOF: Since $0 + 0 = 0$. □**Theorem 6.0.6.**

$$\forall x \in \mathbb{R}. -(-x) = x$$

PROOF: Since $-x + x = 0$. □**Theorem 6.0.7.**

$$\forall x, y \in \mathbb{R}. x(-y) = -(xy)$$

PROOF:

$$\begin{aligned}
x(-y) + xy &= x((-y) + y) && \text{(Distributive Law)} \\
&= x0 && \text{(Definition of } -y) \\
&= 0 && \text{(Theorem 6.0.4) } \square
\end{aligned}$$

Theorem 6.0.8.

$$\forall x \in \mathbb{R}. (-1)x = -x$$

PROOF:

$$\begin{aligned}
(-1)x &= -(1 \cdot x) && \text{(Theorem 6.0.7)} \\
&= -x && \text{(Definition of 1) } \square
\end{aligned}$$

Proposition 6.0.9. *Let X be a linearly ordered set. Let $a, b, c \in X$ with $a < b < c$. Then $[a, c] \cong [0, 1]$ if and only if $[a, b] \cong [0, 1]$ and $[b, c] \cong [0, 1]$.*

PROOF:

$\langle 1 \rangle 1$. For all $x \in (0, 1)$ we have $[0, x] \cong [0, 1]$.

PROOF: The function that maps t to t/x is an order isomorphism.

$\langle 1 \rangle 2$. For all $x \in (0, 1)$ we have $[x, 1] \cong [0, 1]$.

PROOF: The function that maps t to $(t - x)/(1 - x)$ is an order isomorphism.

$\langle 1 \rangle 3$. We have $[0, 2] \cong [0, 1]$.

PROOF: The function that maps t to $t/2$ is an order isomorphism.

□

Proposition 6.0.10. *Let X be a linearly ordered set. Let (a_n) be a strictly increasing sequence in X . Let b be its supremum. Then $[a_0, b] \cong [0, 1]$ if and only if, for all n , we have $[a_n, a_{n+1}] \cong [0, 1]$.*

PROOF:

$\langle 1 \rangle 1$. For all $x, y \in [0, 1]$ with $x < y$ we have $[x, y] \cong [0, 1]$.

PROOF: The function that maps t to $(t - x)/(y - x)$ is an order isomorphism.

$\langle 1 \rangle 2$. We have $[0, 1] \cong [0, +\infty)$.

PROOF: The function that maps t to $1/(1 - t) - 1$ is an order isomorphism.

□

6.1 Subtraction

Definition 6.1.1 (Subtraction). We write $x - y$ for $x + (-y)$.

Theorem 6.1.2.

$$\forall x, y, z \in \mathbb{R}. x(y - z) = xy - xz$$

PROOF:

$$\begin{aligned} x(y - z) &= x(y + (-z)) && \text{(Definition of subtraction)} \\ &= xy + x(-z) && \text{(Distributive Law)} \\ &= xy + (-(xz)) && \text{(Theorem 6.0.7)} \\ &= xy - xz && \text{(Definition of subtraction)} \quad \square \end{aligned}$$

Theorem 6.1.3.

$$\forall x, y \in \mathbb{R}. -(x + y) = -x - y$$

PROOF:

$$\begin{aligned} -(x + y) &= (-1)(x + y) && \text{(Theorem 6.0.8)} \\ &= (-1)x + (-1)y && \text{(Distributive Law)} \\ &= -x + (-y) && \text{(Theorem 6.0.8)} \\ &= -x - y && \text{(Definition of subtraction)} \quad \square \end{aligned}$$

Theorem 6.1.4.

$$\forall x, y \in \mathbb{R}. -(x - y) = -x + y$$

PROOF:

$$\begin{aligned}
 -(x - y) &= -(x + (-y)) && \text{(Definition of subtraction)} \\
 &= -x - (-y) && \text{(Theorem 6.1.3)} \\
 &= -x + (-(-y)) && \text{(Definition of subtraction)} \\
 &= -x + y && \text{(Theorem 6.0.6)} \quad \square
 \end{aligned}$$

Definition 6.1.5 (Reciprocal). Given $x \in \mathbb{R}$ with $x \neq 0$, the *reciprocal* of x , $1/x$, is the unique real number such that $x \cdot 1/x = 1$.

Theorem 6.1.6. For any real numbers x and y , if $x \neq 0$ and $xy = x$ then $y = 1$.

PROOF:

- $\langle 1 \rangle 1$. LET: $x, y \in \mathbb{R}$
 $\langle 1 \rangle 2$. ASSUME: $x \neq 0$
 $\langle 1 \rangle 3$. ASSUME: $xy = x$
 $\langle 1 \rangle 4$. $y = 1$

PROOF:

$$\begin{aligned}
 y &= y1 && \text{(Definition of 1)} \\
 &= y(x \cdot 1/x) && \text{(Definition of } 1/x, \langle 1 \rangle 2) \\
 &= (yx)1/x && \text{(Associativity of Multiplication)} \\
 &= (xy)1/x && \text{(Commutativity of Multiplication)} \\
 &= x \cdot 1/x && (\langle 1 \rangle 3) \\
 &= 1 && \text{(Definition of } 1/x, \langle 1 \rangle 2)
 \end{aligned}$$

\square

Definition 6.1.7 (Quotient). Given real numbers x and y with $y \neq 0$, the *quotient* x/y is defined by

$$x/y = x \cdot 1/y .$$

Theorem 6.1.8. For any real number x , if $x \neq 0$ then $x/x = 1$.

PROOF: Immediate from definitions. \square

Theorem 6.1.9.

$$\forall x \in \mathbb{R}. x/1 = x$$

PROOF:

- $\langle 1 \rangle 1$. LET: $x \in \mathbb{R}$
 $\langle 1 \rangle 2$. $1/1 = 1$
 PROOF: Since $1 \cdot 1 = 1$.
 $\langle 1 \rangle 3$. $x/1 = x$
 PROOF: Since $x/1 = x \cdot 1/1 = x \cdot 1 = x$.

\square

Theorem 6.1.10. For any real numbers x and y , if $x \neq 0$ and $y \neq 0$ then $xy \neq 0$.

PROOF:

$\langle 1 \rangle 1$. LET: $x, y \in \mathbb{R}$

$\langle 1 \rangle 2$. ASSUME: $xy = 0$ and $x \neq 0$

PROVE: $y = 0$

$\langle 1 \rangle 3$. $y = 0$

PROOF:

$$\begin{aligned} y &= 1y && \text{(Definition of 1)} \\ &= (1/x)xy && \text{(Definition of } 1/x, \langle 1 \rangle 2) \\ &= (1/x)0 && (\langle 1 \rangle 2) \\ &= 0 && \text{(Theorem 6.0.4)} \end{aligned}$$

□

Theorem 6.1.11. For any real numbers y and z , if $y \neq 0$ and $z \neq 0$ then $(1/y)(1/z) = 1/(yz)$.

PROOF: Since $yz(1/y)(1/z) = 1 \cdot 1 = 1$. □

Corollary 6.1.11.1. For any real numbers x, y, z, w with $y \neq 0 \neq w$, we have $(x/y)(z/w) = (xz)/(yw)$.

Theorem 6.1.12. For any real numbers x, y, z, w with $y \neq 0 \neq w$, we have

$$\frac{x}{y} + \frac{z}{w} = \frac{xw + yz}{yw}$$

PROOF:

$$\begin{aligned} yw \left(\frac{x}{y} + \frac{z}{w} \right) &= yw \frac{x}{y} + yw \frac{z}{w} \\ &= wx + yz \end{aligned} \quad \square$$

Theorem 6.1.13. For any real number x , if $x \neq 0$ then $1/x \neq 0$.

PROOF: Since $x \cdot 1/x = 1 \neq 0$. □

Theorem 6.1.14. For any real numbers w, z , if $w \neq 0 \neq z$ then $1/(w/z) = z/w$.

PROOF: Since $(z/w)(w/z) = (wz)/(wz) = 1$. □

Theorem 6.1.15. For any real numbers a, x and y , if $y \neq 0$ then $(ax)/y = a(x/y)$

PROOF: Since $ya(x/y) = ax$. □

Theorem 6.1.16. For any real numbers x and y , if $y \neq 0$ then $(-x)/y = x/(-y) = -(x/y)$.

PROOF:

$\langle 1 \rangle 1$. $(-x)/y = -(x/y)$

PROOF: Take $a = -1$ in Theorem 6.1.15.

$\langle 1 \rangle 2$. $x/(-y) = -(x/y)$

PROOF: Since $(-y)(-(x/y)) = y(x/y) = x$.
 \square

Theorem 6.1.17. *For any real numbers x, y, z and w , if $x > y$ and $w > z$ then $x + w > y + z$.*

PROOF: We have $y + z < x + z < x + w$ by Monotonicity of Addition twice. \square

Corollary 6.1.17.1. *For any real numbers x and y , if $x > 0$ and $y > 0$ then $x + y > 0$.*

Theorem 6.1.18. *For any real numbers x and y , if $x > 0$ and $y > 0$ then $xy > 0$.*

PROOF:

$$\begin{aligned} xy &> 0y && \text{(Monotonicity of Multiplication)} \\ &= 0 && \text{(Theorem 6.0.4)} \quad \square \end{aligned}$$

Theorem 6.1.19. *For any real number x , we have $x > 0$ iff $-x < 0$.*

PROOF:

$\langle 1 \rangle 1$. If $0 < x$ then $-x < 0$

PROOF: By Monotonicity of Addition adding $-x$ to both sides.

$\langle 1 \rangle 2$. If $-x < 0$ then $0 < x$

PROOF: By Monotonicity of Addition adding x to both sides.

\square

Theorem 6.1.20. *For any real numbers x and y , we have $x > y$ iff $-x < -y$.*

PROOF:

$\langle 1 \rangle 1$. If $y < x$ then $-x < -y$.

PROOF: By Monotonicity of Addition adding $-x - y$ to both sides.

$\langle 1 \rangle 2$. If $-x < -y$ then $y < x$.

PROOF: By Monotonicity of Addition adding $x + y$ to both sides.

\square

Theorem 6.1.21. *For any real numbers x, y and z , if $x > y$ and $z < 0$ then $xz < yz$.*

PROOF:

$\langle 1 \rangle 1$. LET: x, y and z be real numbers.

$\langle 1 \rangle 2$. ASSUME: $x > y$

$\langle 1 \rangle 3$. ASSUME: $z < 0$

$\langle 1 \rangle 4$. $-z > 0$

PROOF: Theorem 6.1.19, $\langle 1 \rangle 3$.

$\langle 1 \rangle 5$. $x(-z) > y(-z)$

PROOF: $\langle 1 \rangle 2$, $\langle 1 \rangle 4$, Monotonicity of Multiplication.

$\langle 1 \rangle 6$. $-(xz) > -(yz)$

PROOF: Theorem 6.0.7, $\langle 1 \rangle 5$.

$\langle 1 \rangle 7. \quad xz < yz$

PROOF: Theorem 6.1.19, $\langle 1 \rangle 6$.

□

Theorem 6.1.22. *For any real number x , if $x \neq 0$ then $xx > 0$.*

PROOF:

$\langle 1 \rangle 1$. If $x > 0$ then $xx > 0$

PROOF: By Monotonicity of Multiplication.

$\langle 1 \rangle 2$. If $x < 0$ then $xx > 0$

PROOF: Theorem 6.1.21.

□

Theorem 6.1.23.

$$0 < 1$$

PROOF: By Theorem 6.1.22 since $1 = 1 \cdot 1$. □

Definition 6.1.24 (Positive). A real number x is *positive* iff $x > 0$.

We write \mathbb{R}_+ for the set of positive reals.

Theorem 6.1.25. *For any real numbers x and y , we have xy is positive if and only if x and y are both positive or both negative.*

PROOF: By the Monotonicity of Multiplication and Theorem 6.1.21. □

Corollary 6.1.25.1. *For any real number x , if $x > 0$ then $1/x > 0$.*

PROOF: Since $x \cdot 1/x = 1$ is positive. □

Theorem 6.1.26. *For any real numbers x and y , if $x > y > 0$ then $1/x < 1/y$.*

PROOF: If $1/y \leq 1/x$ then $1 < 1$ by Monotonicity of Multiplication. □

Theorem 6.1.27. *For any real numbers x and y , if $x < y$ then $x < (x+y)/2 < y$.*

PROOF: We have $2x < x+y$ and $x+y < 2y$ by Monotonicity of Addition, hence $x < (x+y)/2 < y$ by Monotonicity of Multiplication since $1/2 > 0$. □

Corollary 6.1.27.1. \mathbb{R} is a linear continuum.

Definition 6.1.28 (Negative). A real number x is *negative* iff $x < 0$.

We write $\overline{\mathbb{R}_+}$ for the set of nonnegative reals.

Theorem 6.1.29. *For every positive real number a , there exists a unique positive real \sqrt{a} such that $\sqrt{a}^2 = a$.*

PROOF:

$\langle 1 \rangle 1$. LET: a be a positive real.

$\langle 1 \rangle 2$. For any real numbers x and h , if $0 \leq h < 1$, then

$$(x+h)^2 < x^2 + h(2x+1) .$$

⟨2⟩1. LET: x and h be real numbers.

⟨2⟩2. ASSUME: $0 \leq h < 1$

⟨2⟩3. $(x + h)^2 < x^2 + h(2x + 1)$

PROOF:

$$\begin{aligned} (x + h)^2 &= x^2 + 2hx + h^2 \\ &< x^2 + 2hx + h & (\langle 2 \rangle 2) \\ &= x^2 + h(2x + 1) \end{aligned}$$

⟨1⟩3. For any real numbers x and h , if $h > 0$ then

$$(x - h)^2 > x^2 - 2hx .$$

⟨2⟩1. LET: x and h be real numbers.

⟨2⟩2. ASSUME: $h > 0$

⟨2⟩3. $(x - h)^2 > x^2 - 2hx$

PROOF:

$$\begin{aligned} (x - h)^2 &= x^2 - 2hx + h^2 \\ &> x^2 - 2hx & (\langle 2 \rangle 2) \end{aligned}$$

⟨1⟩4. For any positive real x , if $x^2 < a$ then there exists $h > 0$ such that $(x + h)^2 < a$.

⟨2⟩1. LET: x be a positive real.

⟨2⟩2. ASSUME: $x^2 < a$

⟨2⟩3. LET: $h = \min((a - x^2)/(2x + 1), 1/2)$

⟨2⟩4. $0 < h < 1$

⟨2⟩5. $(x + h)^2 < a$

PROOF:

$$\begin{aligned} (x + h)^2 &< x^2 + h(2x + 1) & (\langle 1 \rangle 2) \\ &\leq a \end{aligned}$$

⟨1⟩5. For any positive real x , if $x^2 > a$ then there exists $h > 0$ such that $(x - h)^2 > a$.

⟨2⟩1. LET: x be a positive real.

⟨2⟩2. ASSUME: $x^2 > a$

⟨2⟩3. LET: $h = (x^2 - a)/2x$

⟨2⟩4. $h > 0$

⟨2⟩5. $(x - h)^2 > a$

PROOF:

$$\begin{aligned} (x - h)^2 &> x^2 - 2hx \\ &= a & (\langle 2 \rangle 3) \end{aligned}$$

⟨1⟩6. LET: $B = \{x \in \mathbb{R} : x^2 < a\}$

⟨1⟩7. B is bounded above.

PROOF: If $a \geq 1$ then a is an upper bound. If $a < 1$ then 1 is an upper bound.

⟨1⟩8. B contains at least one positive real.

PROOF: If $a \geq 1$ then $1 \in B$. If $a < 1$ then $a \in B$.

⟨1⟩9. LET: $b = \sup B$

⟨1⟩10. $b^2 = a$

⟨2⟩1. $b^2 \geq a$

⟨3⟩1. ASSUME: for a contradiction $b^2 < a$

- $\langle 3 \rangle 2$. PICK $h > 0$ such that $(b + h)^2 < a$
 PROOF: $\langle 1 \rangle 4$
 $\langle 3 \rangle 3$. $b + h \in B$
 $\langle 3 \rangle 4$. Q.E.D.
 PROOF: This contradicts $\langle 1 \rangle 9$.
 $\langle 2 \rangle 2$. $b^2 \leq a$
 $\langle 3 \rangle 1$. ASSUME: for a contradiction $b^2 > a$
 $\langle 3 \rangle 2$. PICK $h > 0$ such that $(b - h)^2 > a$
 PROOF: $\langle 1 \rangle 5$
 $\langle 3 \rangle 3$. PICK $x \in B$ such that $b - h < x$
 PROOF: $\langle 1 \rangle 9$
 $\langle 3 \rangle 4$. $(b - h)^2 < x^2 < a$
 $\langle 3 \rangle 5$. Q.E.D.
 PROOF: This contradicts $\langle 3 \rangle 2$
 $\langle 1 \rangle 11$. For any positive reals b and c , if $b^2 = c^2$ then $b = c$.
 $\langle 2 \rangle 1$. LET: b and c be positive reals.
 $\langle 2 \rangle 2$. ASSUME: $b^2 = c^2$
 $\langle 2 \rangle 3$. $b^2 - c^2 = 0$
 $\langle 2 \rangle 4$. $(b - c)(b + c) = 0$
 $\langle 2 \rangle 5$. $b - c = 0$ or $b + c = 0$
 $\langle 2 \rangle 6$. $b + c \neq 0$
 PROOF: Since $b + c > 0$
 $\langle 2 \rangle 7$. $b - c = 0$
 $\langle 2 \rangle 8$. $b = c$
 \square

Theorem 6.1.30. *The set of real numbers is uncountable.*

Definition 6.1.31. We write \mathbb{R}^ω for the set of sequences in \mathbb{R}^ω that are eventually zero.

Definition 6.1.32 (Hilbert Cube). The *Hilbert cube* is $\prod_{n=0}^\infty [0, 1/(n+1)]$.

6.2 The Ordered Square

Definition 6.2.1 (Ordered Square). The *ordered square* I_o^2 is the set $[0, 1]^2$ under the dictionary order.

Proposition 6.2.2. *The ordered square is a linear continuum.*

PROOF:

- $\langle 1 \rangle 1$. I_o^2 has the least upper bound property.
 $\langle 2 \rangle 1$. LET: S be a nonempty subset of I_o^2 .
 $\langle 2 \rangle 2$. LET: a be the supremum of $\pi_1(S)$
 $\langle 2 \rangle 3$. CASE: $a \in \pi_1(S)$
 $\langle 3 \rangle 1$. LET: b be the supremum of $\{y \in [0, 1] : (a, y) \in S\}$
 $\langle 3 \rangle 2$. (a, b) is the supremum of S .

$\langle 2 \rangle 4$. CASE: $a \notin \pi_1(S)$

PROOF: $(a, 0)$ is the supremum of S .

$\langle 1 \rangle 2$. I_o^2 is dense.

$\langle 2 \rangle 1$. LET: $(x_1, y_1), (x_2, y_2) \in I_o^2$ with $(x_1, y_1) < (x_2, y_2)$

PROVE: There exists $(x_3, y_3) \in I_o^2$ such that $(x_1, y_1) < (x_3, y_3) < (x_2, y_2)$

$\langle 2 \rangle 2$. CASE: $x_1 < x_2$

$\langle 3 \rangle 1$. PICK x_3 such that $x_1 < x_3 < x_2$

$\langle 3 \rangle 2$. $(x_1, y_1) < (x_3, 0) < (x_2, y_2)$

$\langle 2 \rangle 3$. CASE: $x_1 = x_2$ and $y_1 < y_2$

$\langle 3 \rangle 1$. PICK y_3 such that $y_1 < y_3 < y_2$

$\langle 3 \rangle 2$. $(x_1, y_1) < (x_1, y_3) < (x_2, y_2)$

□

6.3 Punctured Euclidean Space

Definition 6.3.1 (Punctured Euclidean Space). Let n be a positive integer. The *punctured Euclidean space* is $\mathbb{R}^n - \{\vec{0}\}$.

6.4 Topologist's Sine Curve

Definition 6.4.1 (Topologist's Sine Curve). The *topologist's sine curve* is

$$(\{0\} \times [-1, 1]) \cup \{(x, \sin 1/x) : 0 < x \leq 1\}.$$

6.5 The Long Line

Definition 6.5.1 (Long Line). The *long line* is $S_\Omega \times [0, 1]$ in the dictionary order.

Proposition 6.5.2. For any $a \in S_\Omega$ with $a \neq 0$ we have $[(0, 0), (a, 0)) \cong [0, 1]$.

PROOF: By transfinite induction on a using Propositions 6.0.9 and 6.0.10. □

Chapter 7

Integers and Rationals

7.1 Positive Integers

Definition 7.1.1 (Inductive). A set of real numbers A is *inductive* iff $1 \in A$ and $\forall x \in A. x + 1 \in A$.

Definition 7.1.2 (Positive Integer). The set \mathbb{Z}_+ of *positive integers* is the intersection of the set of inductive sets.

Proposition 7.1.3. *Every positive integer is positive.*

PROOF: The set of positive reals is inductive. \square

Proposition 7.1.4. *1 is the least element of \mathbb{Z}_+ .*

PROOF: Since $\{x \in \mathbb{R} : x \geq 1\}$ is inductive. \square

Proposition 7.1.5. *\mathbb{Z}_+ is inductive.*

PROOF: 1 is an element of every inductive set, and for all $x \in \mathbb{R}$, if x is an element of every inductive set then so is $x + 1$. \square

Theorem 7.1.6 (Principle of Induction). *If A is an inductive set of positive integers then $A = \mathbb{Z}_+$.*

PROOF: Immediate from definitions. \square

Theorem 7.1.7 (Well-Ordering Property). *\mathbb{Z}_+ is well ordered.*

PROOF: Construct the obvious order isomorphism $\omega \cong \mathbb{Z}_+$. \square

Theorem 7.1.8 (Archimedean Ordering Property). *The set \mathbb{Z}_+ is unbounded above.*

PROOF:

$\langle 1 \rangle$ 1. ASSUME: for a contradiction \mathbb{Z}_+ is bounded above.

⟨1⟩2. LET:

$$s = \sup \mathbb{Z}_+$$

⟨1⟩3. PICK $n \in \mathbb{Z}_+$ such that $s - 1 < n$

⟨1⟩4. $s < n + 1$

⟨1⟩5. Q.E.D.

PROOF: ⟨1⟩2 and ⟨1⟩4 form a contradiction.

□

7.1.1 Exponentiation

Definition 7.1.9. For a a real number and n a positive integer, define the real number a^n recursively as follows:

$$\begin{aligned} a^1 &= a \\ a^{n+1} &= a^n a \end{aligned}$$

Theorem 7.1.10. For all $a \in \mathbb{R}$ and $m, n \in \mathbb{Z}_+$, we have

$$a^n a^m = a^{n+m}$$

PROOF:

⟨1⟩1. LET: $P(m)$ be the property $\forall a \in \mathbb{R}. \forall n \in \mathbb{Z}_+. a^n a^m = a^{n+m}$

⟨1⟩2. $P(1)$

PROOF: $a^n a^1 = a^n a = a^{n+1}$.

⟨1⟩3. $\forall m \in \mathbb{Z}_+. P(m) \Rightarrow P(m+1)$

⟨2⟩1. LET: m be a positive integer.

⟨2⟩2. ASSUME: $P(m)$

⟨2⟩3. LET: $a \in \mathbb{R}$

⟨2⟩4. LET: $n \in \mathbb{Z}_+$

⟨2⟩5. $a^n a^{m+1} = a^{n+m+1}$

PROOF:

$$\begin{aligned} a^n a^{m+1} &= a^n a^m a \\ &= a^{n+m} a && (\langle 2 \rangle 2) \\ &= a^{n+m+1} \end{aligned}$$

⟨1⟩4. Q.E.D.

PROOF: By induction.

□

Theorem 7.1.11. For all $a \in \mathbb{R}$ and $m, n \in \mathbb{Z}_+$,

$$(a^n)^m = a^{nm}.$$

PROOF:

⟨1⟩1. LET: $P(m)$ be the property $\forall a \in \mathbb{R}. \forall n \in \mathbb{Z}_+. (a^n)^m = a^{nm}$.

⟨1⟩2. $P(1)$

PROOF: $(a^n)^1 = a^n = a^{n \cdot 1}$

⟨1⟩3. $\forall m \in \mathbb{Z}_+. P(m) \Rightarrow P(m+1)$

PROOF:

$$\begin{aligned} (a^n)^{m+1} &= (a^n)^m a^n \\ &= a^{nm} a^n \\ &= a^{nm+n} && (\text{Theorem 7.1.10}) \\ &= a^{n(m+1)} \end{aligned}$$

□

Theorem 7.1.12. *For any real numbers a and b and positive integer m ,*

$$a^m b^m = (ab)^m .$$

PROOF: Induction on m . □

7.2 Integers

Definition 7.2.1 (Integer). The set \mathbb{Z} of *integers* is

$$\mathbb{Z} = \mathbb{Z}_+ \cup \{0\} \cup \{-x : x \in \mathbb{Z}_+\} .$$

Proposition 7.2.2. *The sum, difference and product of two integers is an integer.*

PROOF: Easy. □

Example 7.2.3. $1/2$ is not an integer.

Proposition 7.2.4. *For any integer n , there is no integer a such that $n < a < n+1$.*

PROOF:

⟨1⟩1. For any positive integer n , there is no integer a such that $n < a < n+1$.

⟨2⟩1. There is no integer a such that $1 < a < 2$.

⟨3⟩1. There is no positive integer a such that $1 < a < 2$.

⟨4⟩1. We do not have $1 < 1 < 2$.

⟨4⟩2. For any positive integer n , we do not have $1 < n+1 < 2$.

PROOF: Since $n \geq 1$ so $n+1 \geq 2$.

⟨3⟩2. We do not have $1 < 0 < 2$.

⟨3⟩3. For any positive integer a , we do not have $1 < -a < 2$.

PROOF: Since $-a < 0 < 1$.

⟨2⟩2. For any positive integer n , if there is no integer a such that $n < a < n+1$, then there is no integer a such that $n+1 < a < n+2$.

PROOF: If $n+1 < a < n+2$ then $n < a-1 < n+1$.

⟨1⟩2. There is no integer a such that $0 < a < 1$.

PROOF: If $0 < a < 1$ then $1 < a+1 < 2$.

⟨1⟩3. For any positive integer n , there is no integer a such that $-n < a < -n+1$.

PROOF: If $-n < a < -n+1$ then $n-1 < -a < n$.

□

Theorem 7.2.5. *Every nonempty subset of \mathbb{Z} bounded above has a largest element.*

PROOF:

⟨1⟩1. LET: S be a nonempty subset of \mathbb{Z} bounded above.

⟨1⟩2. LET: u be an upper bound for S .

⟨1⟩3. PICK an integer $n > u$

PROOF: Archimedean property.

⟨1⟩4. LET: k be the least positive integer such that $n - k \in S$.

⟨2⟩1. PICK $m \in S$

⟨2⟩2. $n - m$ is a positive integer.

⟨2⟩3. There exists a positive integer k such that $n - k \in S$.

⟨1⟩5. $n - k$ is the greatest element in S .

⟨2⟩1. LET: $m \in S$

⟨2⟩2. $n - m \geq k$

⟨2⟩3. $m \leq n - k$

□

Theorem 7.2.6. *For any real number x , if x is not an integer then there exists a unique integer n such that $n < x < n + 1$.*

PROOF:

⟨1⟩1. $\{n \in \mathbb{Z} : n < x\}$ is a nonempty set of integers bounded above.

⟨2⟩1. PICK $m > -x$

PROOF: Archimedean property.

⟨2⟩2. $-m < x$

⟨2⟩3. $\{n \in \mathbb{Z} : n < x\}$ is nonempty.

⟨1⟩2. LET: n be the greatest integer such that $n < x$

⟨1⟩3. $x < n + 1$

⟨1⟩4. If n' is an integer with $n' < x < n' + 1$ then $n' = n$.

PROOF: We have $n' < n + 1$ so $n' \leq n$, and $n < n' + 1$ so $n \leq n'$.

□

Definition 7.2.7 (Even). An integer n is *even* iff $n/2$ is an integer; otherwise, n is *odd*.

Theorem 7.2.8. *If the integer m is odd then there exists an integer n such that $m = 2n + 1$.*

PROOF:

⟨1⟩1. LET: n be the integer such that $n < m/2 < n + 1$

PROOF: Theorem 7.2.6.

⟨1⟩2. $2n < m < 2n + 2$

⟨1⟩3. $m = 2n + 1$

□

Theorem 7.2.9. *The product of two odd integers is odd.*

PROOF: $(2m + 1)(2n + 1) = 2(2mn + m + n) + 1$. \square

Corollary 7.2.9.1. *If p is an odd integer and n is a positive integer then p^n is an odd integer.*

Definition 7.2.10 (Exponentiation). Extend the definition of exponentiation so a^n is defined for:

- all real numbers a and non-negative integers n
- all non-zero real numbers a and integers n

as follows:

$$\begin{aligned} a^0 &= 1 \\ a^{-n} &= 1/a^n \end{aligned} \quad (n \text{ a positive integer})$$

Theorem 7.2.11 (Laws of Exponents). *For all non-zero reals a and b and integers m and n ,*

$$\begin{aligned} a^n a^m &= a^{n+m} \\ (a^n)^m &= a^{nm} \\ a^m b^m &= (ab)^m \end{aligned}$$

PROOF: Easy. \square

Theorem 7.2.12. \mathbb{Z} is countable.

PROOF: The function that maps an integer n to $2n$ if $n \geq 0$ and $-1 - 2n$ if $n < 0$ is a bijection $\mathbb{Z} \approx \mathbb{N}$. \square

7.3 Rational Numbers

Definition 7.3.1 (Rational Number). The set \mathbb{Q} of *rational numbers* is the set of all real numbers that are the quotient of two integers. A real that is not rational is *irrational*.

Theorem 7.3.2. $\sqrt{2}$ is irrational.

PROOF:

- $\langle 1 \rangle$ 1. For any positive rational a , there exist positive integers m and n not both even such that $a = m/n$.
- $\langle 2 \rangle$ 1. LET: a be a positive rational.
- $\langle 2 \rangle$ 2. LET: n be the least positive integer such that na is a positive integer.
- $\langle 2 \rangle$ 3. LET: $m = na$
- $\langle 2 \rangle$ 4. ASSUME: for a contradiction m and n are both even.
- $\langle 2 \rangle$ 5. $m/2 = (n/2)a$
- $\langle 2 \rangle$ 6. Q.E.D.

PROOF: This contradicts the leastness of n ($\langle 2 \rangle 2$).

$\langle 1 \rangle 2$. ASSUME: for a contradiction $\sqrt{2}$ is rational.

$\langle 1 \rangle 3$. PICK positive integers m and n not both even such that $\sqrt{2} = m/n$.

$\langle 1 \rangle 4$. $m^2 = 2n^2$

$\langle 1 \rangle 5$. m^2 is even.

$\langle 1 \rangle 6$. m is even.

PROOF: Theorem 7.2.9.

$\langle 1 \rangle 7$. LET: $k = m/2$

$\langle 1 \rangle 8$. $4k^2 = 2n^2$

$\langle 1 \rangle 9$. $n^2 = 2k^2$

$\langle 1 \rangle 10$. n^2 is even.

$\langle 1 \rangle 11$. n is even.

PROOF: Theorem 7.2.9.

$\langle 1 \rangle 12$. Q.E.D.

PROOF: $\langle 1 \rangle 3$, $\langle 1 \rangle 6$ and $\langle 1 \rangle 11$ form a contradiction.

□

Theorem 7.3.3. \mathbb{Q} is countably infinite.

PROOF: The function $\mathbb{Z} \times \mathbb{N} \rightarrow \mathbb{Q}$ that maps (m, n) to $m/(n+1)$ is a surjection.

□

7.4 Algebraic Numbers

Definition 7.4.1 (Algebraic Number). A real number r is *algebraic* iff there exists a natural number n and rational numbers a_0, a_1, \dots, a_{n-1} such that

$$r^n + a_{n-1}r^{n-1} + \dots + a_1r + a_0 = 0$$

Otherwise, r is *transcendental*.

Proposition 7.4.2. The set of algebraic numbers is countably infinite.

PROOF: There are countably many finite sequences of rational numbers, and each corresponding polynomial has only finitely many roots. □

Corollary 7.4.2.1. The set of transcendental numbers is uncountable.

Part IV

Algebra

Chapter 8

Monoid Theory

Definition 8.0.1 (Monoid). A *monoid* is a category with one object.

Definition 8.0.2. Let \mathcal{C} be a category and $X \in \mathcal{C}$. The monoid $\text{End}_{\mathcal{C}}(X)$ is the set of all morphisms $X \rightarrow X$ under composition.

Proposition 8.0.3. *For any functor $F : \mathcal{C} \rightarrow \mathcal{D}$ and $X \in \mathcal{C}$, we have that $F : \text{End}_{\mathcal{C}}(X) \rightarrow \text{End}_{\mathcal{D}}(FX)$ is a monoid homomorphism.*

PROOF: Since $F\text{id}_X = \text{id}_{FX}$ and $F(g \circ f) = Fg \circ Ff$. \square

Chapter 9

Group Theory

9.1 Category of Small Groups

Definition 9.1.1. Let **Grp** be the category of small groups and group homomorphisms.

Definition 9.1.2. We identify any group G with the category with one object whose morphisms are the elements of G with composition given by the multiplication in G .

Proposition 9.1.3. *The trivial group is a zero object in **Grp**.*

PROOF: Easy. \square

The zero morphism $G \rightarrow H$ maps every element in G to e .

Definition 9.1.4. Let \mathcal{C} be a category and $X \in \mathcal{C}$. We write $\text{Aut}_{\mathcal{C}}(X)$ for the set of all isomorphisms $X \cong X$ under composition.

Proposition 9.1.5. *Let $F : \mathcal{C} \rightarrow \mathcal{D}$ be a functor and $X \in \mathcal{C}$. Then $F : \text{Aut}_{\mathcal{C}}(X) \rightarrow \text{Aut}_{\mathcal{D}}(FX)$ is a group homomorphism.*

PROOF: Since $F \text{id}_X = \text{id}_{FX}$, $F(g \circ f) = Fg \circ Ff$, and $Ff^{-1} = (Ff)^{-1}$. \square

Proposition 9.1.6. **Grp** has products.

Definition 9.1.7 (Free Product). The product of a family of groups in **Grp** is called the *free product*.

Proposition 9.1.8. **Ab** has products given by direct sums.

Definition 9.1.9 (Left Coset). Let G be a group and H a subgroup of G . The *left cosets* of H are the sets of the form

$$xH := \{xh : h \in H\}$$

We write G/H for the set of left cosets of H in G .

Proposition 9.1.10. *Let G be a group and H a subgroup of G . Then G/H is a partition of G .*

PROOF:

$\langle 1 \rangle 1$. $\bigcup (G/H) = G$

PROOF: Since $x = xe$ and so $x \in xH$.

$\langle 1 \rangle 2$. Any two distinct left cosets of H are disjoint.

PROOF: Since if $z \in xH$ and $z \in yH$ then $xH = yH = zH$.

□

Definition 9.1.11. Let G be a group. Let A and B be subsets of G . Then

$$AB := \{ab : a \in A, b \in B\} .$$

Definition 9.1.12. Let G be a group. Let A be a subset of G . Then

$$A^{-1} := \{a^{-1} : a \in A\} .$$

Chapter 10

Ring Theory

Definition 10.0.1. Let **Ring** be the concrete category of rings and ring homomorphisms.

Definition 10.0.2 (Spectrum). Let R be a commutative ring. The *spectrum* of R , $\text{spec } R$, is the set of all prime ideals of R .

Definition 10.0.3 (Zariski Topology). Let R be a commutative ring. The *Zariski topology* on $\text{spec } R$ is the topology where the closed sets are the sets of the form

$$VE := \{p \in \text{spec } R : E \subseteq p\}$$

for any $E \in \mathcal{P}R$.

We prove this is a topology.

PROOF:

$\langle 1 \rangle 1$. LET: $\mathcal{C} = \{VE : E \in \mathcal{P}R\}$

$\langle 1 \rangle 2$. For all $\mathcal{A} \subseteq \mathcal{C}$ we have $\bigcap \mathcal{A} \in \mathcal{C}$

$\langle 2 \rangle 1$. LET: $\mathcal{A} \subseteq \mathcal{C}$

$\langle 2 \rangle 2$. LET: $E = \bigcup \{E' \in \mathcal{P}R : VE' \in \mathcal{A}\}$

PROVE: $VE = \bigcap \mathcal{A}$

$\langle 2 \rangle 3$. For all $p \in \text{spec } R$, if $E \subseteq p$ then $p \in \bigcap \mathcal{A}$

$\langle 3 \rangle 1$. LET: $p \in \text{spec } R$

$\langle 3 \rangle 2$. ASSUME: $E \subseteq p$

$\langle 3 \rangle 3$. LET: $E' \in \mathcal{P}R$ with $VE' \in \mathcal{A}$

$\langle 3 \rangle 4$. $E' \subseteq E$

$\langle 3 \rangle 5$. $E' \subseteq p$

$\langle 3 \rangle 6$. $p \in VE'$

$\langle 2 \rangle 4$. For all $p \in \text{spec } R$, if $p \in \bigcap \mathcal{A}$ then $E \subseteq p$

$\langle 3 \rangle 1$. LET: $p \in \bigcap \mathcal{A}$

$\langle 3 \rangle 2$. For all $E' \in \mathcal{P}R$ with $VE' \in \mathcal{A}$ we have $E' \subseteq p$

$\langle 3 \rangle 3$. $E \subseteq p$

$\langle 1 \rangle 3$. For all $C, D \in \mathcal{C}$ we have $C \cup D \in \mathcal{C}$.

PROOF: Since $VE \cup VE' = V(E \cap E')$

$\langle 1 \rangle 4. \emptyset \in \mathcal{C}$

$\langle 2 \rangle 1. VR = \emptyset$

PROOF: If $p \in VR$ then $R \subseteq p$ contradicting the fact that p is a prime ideal.

□

Definition 10.0.4. For any ring R , let $R - \mathbf{Mod}$ be the category of small R -modules and R -module homomorphisms.

Proposition 10.0.5. $R - \mathbf{Mod}$ has products and coproducts.

Chapter 11

Field Theory

Proposition 11.0.1. *Field does not have binary products.*

PROOF: There cannot be a field K with field homomorphisms $K \rightarrow \mathbb{Z}_2$ and $K \rightarrow \mathbb{Z}_3$, because its characteristic would be both 2 and 3. \square

Chapter 12

Linear Algebra

Definition 12.0.1 (Span). Let V be a vector space and $A \subseteq V$. The *span* of A is the set of all linear combinations of elements of A .

Definition 12.0.2 (Independent). Let V be a vector space and $A \subseteq V$. Then A is *linearly independent* iff, whenever

$$\alpha_1 v_1 + \cdots + \alpha_n v_n = 0$$

where $v_1, \dots, v_n \in A$, then

$$\alpha_1 = \cdots = \alpha_n = 0 \text{ .}$$

Proposition 12.0.3. *Let V be a vector space, $A \subseteq V$ and $v \in V$. If A is linearly independent and $v \notin \text{span } A$, then $A \cup \{v\}$ is independent.*

PROOF:

$\langle 1 \rangle 1$. LET: $\alpha_1 v_1 + \cdots + \alpha_n v_n + \beta v = 0$ where $v_1, \dots, v_n \in A$

$\langle 1 \rangle 2$. $\beta = 0$

PROOF: Otherwise $v = (\alpha_1/\beta)v_1 + \cdots + (\alpha_n/\beta)v_n \in \text{span } A$.

$\langle 1 \rangle 3$. $\alpha_1 = \cdots = \alpha_n = 0$

PROOF: Since A is linearly independent.

□

Theorem 12.0.4. *Every vector space has a basis.*

PROOF:

$\langle 1 \rangle 1$. LET: V be a vector space.

$\langle 1 \rangle 2$. PICK a maximal linearly independent set \mathcal{B} .

PROOF: By Tukey's Lemma.

$\langle 1 \rangle 3$. $\text{span } \mathcal{B} = V$

PROOF: Proposition 12.0.3.

□

Definition 12.0.5. For any field K , we write \mathbf{Vect}_K for $K - \mathbf{Mod}$.

Dual space functor $\mathbf{Vect}_K^{\text{op}} \rightarrow \mathbf{Vect}_K$.

12.1 Inner Product Spaces

Definition 12.1.1 (Inner Product). Let V be a complex vector space. An *inner product* on V is a function $\langle \cdot | \cdot \rangle : V^2 \rightarrow \mathbb{C}$ such that, for all $|\phi\rangle, |\psi\rangle, |\psi_1\rangle, |\psi_2\rangle \in V$ and $c_1, c_2 \in \mathbb{C}$,

1. $\langle \phi | c_1\psi_1 + c_2\psi_2 \rangle = c_1\langle \phi | \psi_1 \rangle + c_2\langle \phi | \psi_2 \rangle$
2. $\langle \psi | \phi \rangle = \overline{\langle \phi | \psi \rangle}$
3. $\langle \psi | \psi \rangle \geq 0$
4. If $\langle \psi | \psi \rangle = 0$ then $|\psi\rangle = 0$.

An *inner product space* is a complex vector space with an inner product.

Example 12.1.2. The function $\langle \cdot | \cdot \rangle : (\mathbb{C}^n)^2 \rightarrow \mathbb{C}$ defined by

$$\langle (a_1, \dots, a_n) | (b_1, \dots, b_n) \rangle = \overline{a_1}b_1 + \dots + \overline{a_n}b_n$$

is an inner product on \mathbb{C}^n .

Definition 12.1.3 (Normalised). Let V be an inner product space and $|\psi\rangle \in V$. Then $|\psi\rangle$ is *normalised* iff $\langle \psi | \psi \rangle = 1$.

Definition 12.1.4 (Orthogonal). Let V be an inner product space and $|\phi\rangle, |\psi\rangle \in V$. Then $|\phi\rangle$ and $|\psi\rangle$ are *orthogonal* iff $\langle \phi | \psi \rangle = 0$.

Definition 12.1.5 (Orthonormal). Let V be an inner product space and $S \subseteq V$. Then S is *orthonormal* iff:

- Every element of S is normalised.
- Any two distinct elements of S are orthogonal.

Definition 12.1.6 (Hermitian). Let V be an inner product space. A linear operator $T : V \rightarrow V$ is *Hermitian* iff

$$\langle \psi | T | \phi \rangle = \overline{\langle \phi | T | \psi \rangle}$$

for all $|\phi\rangle, |\psi\rangle \in V$.

Proposition 12.1.7. *Every eigenvalue of a Hermitian operator is real.*

PROOF:

$\langle 1 \rangle 1$. LET: $T : V \rightarrow V$ be Hermitian.

$\langle 1 \rangle 2$. LET: $|\phi\rangle$ be an eigenvector with eigenvalue α .

$\langle 1 \rangle 3$. $\langle \phi | T | \phi \rangle = \alpha \langle \phi | \phi \rangle$

$\langle 1 \rangle 4$. $\langle \phi | T | \phi \rangle = \overline{\alpha} \langle \phi | \phi \rangle$

PROOF:

$$\begin{aligned} \langle \phi | T | \phi \rangle &= \overline{\langle \phi | T | \phi \rangle} \\ &= \overline{\alpha \langle \phi | \phi \rangle} \\ &= \overline{\alpha} \langle \phi | \phi \rangle \end{aligned}$$

⟨1⟩5. $\alpha = \bar{\alpha}$
 \square

Definition 12.1.8 (Hermitian Conjugate). Let V be an inner product space and $T : V \rightarrow V$ a linear operator. The *Hermitian conjugate* $T^\dagger : V \rightarrow V$ is the linear operator such that, for all $|\phi\rangle, |\psi\rangle \in V$, we have

$$\langle\phi|T^\dagger|\psi\rangle = \overline{\langle\psi|T|\phi\rangle}.$$

Proposition 12.1.9.

$$(cT)^\dagger = \bar{c}T^\dagger$$

PROOF:

$$\begin{aligned}\langle\phi|\bar{c}T^\dagger|\psi\rangle &= \bar{c}\langle\phi|T^\dagger|\psi\rangle \\ &= \bar{c}\overline{\langle\psi|T|\phi\rangle} \\ &= \overline{\langle\psi|cT|\phi\rangle}\end{aligned}\quad \square$$

Proposition 12.1.10.

$$(ST)^\dagger = T^\dagger S^\dagger$$

PROOF:

$$\begin{aligned}\langle\phi|T^\dagger S^\dagger|\psi\rangle &= \overline{\langle S^\dagger|\psi|T|\phi\rangle} \\ &= \langle T|\phi|S^\dagger|\psi\rangle \\ &= \overline{\langle\psi|ST|\phi\rangle}\end{aligned}\quad \square$$

Proposition 12.1.11. T is Hermitian iff $T = T^\dagger$.

PROOF: Immediate from definitions. \square

Proposition 12.1.12. If M is the matrix of T then \overline{M}^T is the matrix of T^\dagger .

Definition 12.1.13 (Unitary). Let V be an inner product space and $T : V \rightarrow V$ a linear operator. Then T is *unitary* iff $T^\dagger T = I$.

Proposition 12.1.14. If α is an eigenvalue of a unitary operator then $|\alpha| = 1$.

PROOF:

⟨1⟩1. LET: $T : V \rightarrow V$ be unitary.

⟨1⟩2. LET: $|\phi\rangle$ be an eigenstate with eigenvalue α .

⟨1⟩3. $|\alpha|^2\langle\phi|\phi\rangle = \langle\phi|\phi\rangle$

PROOF:

$$\begin{aligned}\langle\phi|\phi\rangle &= \langle\phi|T^\dagger T|\phi\rangle \\ &= \alpha\langle\phi|T^\dagger|\phi\rangle \\ &= \alpha\overline{\langle\phi|T|\phi\rangle} \\ &= \alpha\bar{\alpha}\overline{\langle\phi|\phi\rangle} \\ &= |\alpha|^2\langle\phi|\phi\rangle\end{aligned}$$

⟨1⟩4. $|\alpha| = 1$

□

Definition 12.1.15 (Bra Vector). Let V be an inner product space and $|\phi\rangle \in V$. The *bra vector* or *Hermitian conjugate* $\langle\phi|$ is the linear functional $\langle\phi| : V \rightarrow \mathbb{C}$ that maps $|\psi\rangle$ to $\langle\phi|\psi\rangle$.

Proposition 12.1.16. *The hermitian conjugate of $c|\phi\rangle$ is $\bar{c}\langle\phi|$.*

PROOF: Since $\langle c|\phi\rangle|\psi\rangle = \bar{c}\langle\phi|\psi\rangle$. □

Proposition 12.1.17. *The Hermitian conjugate of $T|\phi\rangle$ is $\langle\phi|T^\dagger$, the linear functional that maps $|\psi\rangle$ to $\langle\phi|T^\dagger|\psi\rangle$.*

PROOF:

$$\begin{aligned}\langle T|\phi\rangle|\psi\rangle &= \overline{\langle\psi|T|\phi\rangle} \\ &= \langle\phi|T^\dagger|\psi\rangle\end{aligned}\quad \square$$

Definition 12.1.18 (Outer Product). Let $|\phi\rangle, |\psi\rangle \in V$. The *outer product* $|\psi\rangle\langle\phi| : V \rightarrow \mathbb{C}$ is the linear functional defined by

$$(|\psi\rangle\langle\phi|)|\chi\rangle = \langle\phi|\chi\rangle|\psi\rangle \quad .$$

Proposition 12.1.19. *Let $\{|\psi_1\rangle, |\psi_2\rangle, \dots\}$ be a countable orthonormal basis. Then*

$$\sum_{n=1}^{\infty} |\psi_n\rangle\langle\psi_n| = I \quad .$$

Part V

Analysis

Chapter 13

Real Analysis

13.1 Hermite Polynomials

Definition 13.1.1 (Hermite Polynomials). For $n \in \mathbb{N}$, define a sequence of natural numbers a_n, a_{n-2}, \dots by

$$a_n = 2$$
$$a_{k-2} = -\frac{k(k-1)}{2(n-k+2)}a_k$$

with the final entry being a_1^n if n is odd and a_0 if n is even.

The n th *Hermite polynomial* H_n is the polynomial

$$H_n(x) = \sum_k a_k x^k .$$

Example 13.1.2.

$$\begin{aligned}H_0(x) &= 1 \\H_1(x) &= 2x \\H_2(x) &= 4x^2 - 2 \\H_3(x) &= 8x^3 - 12x \\H_4(x) &= 16x^4 - 48x^2 + 12 \\H_5(x) &= 32x^5 - 160x^3 + 120x\end{aligned}$$

Proposition 13.1.3.

$$H_{n+1}(x) = 2xH_n(x) - 2nH_{n-1}(x)$$

Proposition 13.1.4 (Rodrigues Formula).

$$H_n(x) = (-1)^n e^{x^2} \frac{d^n}{dx^n} e^{-x^2}$$

Proposition 13.1.5.

$$\frac{d}{dx}H_n(x) = 2nH_{n-1}(x)$$

Proposition 13.1.6.

$$\sum_{n=0}^{\infty} \frac{z^n}{n!} H_n(x) = e^{-z^2 + 2zx}$$

13.2 Fourier Transforms

Definition 13.2.1 (Fourier Transform). The *Fourier transform* of a function f is

$$F(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} f(t) e^{-ixt} dt .$$

Definition 13.2.2 (Fourier Transform). The *inverse Fourier transform* of a function F is

$$f(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} F(t) e^{ixt} dt .$$

Theorem 13.2.3 (Plancherel's Theorem). *F is the Fourier transform of f if and only if f is the inverse Fourier transform of F .*

Part VI

Topology

Chapter 14

Topological Spaces

14.1 Topological Spaces

Definition 14.1.1 (Topological Space). Let X be a set and $\mathcal{T} \subseteq \mathcal{P}X$. Then we say (X, \mathcal{T}) is a *topological space* iff:

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

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

Example 14.1.2 (Discrete Topology). For any set X , the power set $\mathcal{P}X$ is called the *discrete* topology on X .

Example 14.1.3 (Indiscrete Topology). For any set X , the *indiscrete* or *trivial* topology on X is $\{\emptyset, X\}$.

Example 14.1.4 (Cofinite Topology). For any set X , the *cofinite* topology is $\mathcal{T} = \{\emptyset\} \cup \{X - U : U \subseteq X \text{ is finite}\}$.

We prove this is a topology.

Example 14.1.5 (Cocountable Topology). For any set X , the *cocountable* topology is $\{X - U : U \subseteq X \text{ is countable}\}$.

Example 14.1.6 (Sierpiński Two-Point Space). The *Sierpiński two-point space* is $\{0, 1\}$ under the topology $\{\emptyset, \{1\}, \{0, 1\}\}$.

Proposition 14.1.7. *Let X be a topological space and $U \subseteq X$. Then U is open if and only if, for all $x \in U$, there exists an open set V such that $x \in V \subseteq U$.*

PROOF:

$\langle 1 \rangle 1$. If U is open then, for all $x \in U$, there exists an open set V such that $x \in V \subseteq U$.

PROOF: Take $V = U$.

$\langle 1 \rangle 2$. If, for all $x \in U$, there exists an open set V such that $x \in V \subseteq U$, then U is open.

PROOF: Since then U is the union of all the open subsets of U .

□

Proposition 14.1.8. *The intersection of a set of topologies on a set X is a topology on X .*

PROOF:

$\langle 1 \rangle 1$. LET: \mathcal{T} be a set of topologies on X .

$\langle 1 \rangle 2$. For all $\mathcal{U} \subseteq \bigcap \mathcal{T}$ we have $\bigcup \mathcal{U} \in \bigcap \mathcal{T}$.

$\langle 2 \rangle 1$. LET: $\mathcal{U} \subseteq \bigcap \mathcal{T}$

$\langle 2 \rangle 2$. LET: $T \in \mathcal{T}$

$\langle 2 \rangle 3$. $\mathcal{U} \subseteq T$

$\langle 2 \rangle 4$. $\bigcup \mathcal{U} \in T$

$\langle 1 \rangle 3$. For all $U, V \in \bigcap \mathcal{T}$ we have $U \cap V \in \bigcap \mathcal{T}$.

$\langle 2 \rangle 1$. LET: $U, V \in \bigcap \mathcal{T}$

$\langle 2 \rangle 2$. LET: $T \in \mathcal{T}$

$\langle 2 \rangle 3$. $U, V \in T$

$\langle 2 \rangle 4$. $U \cap V \in T$

$\langle 1 \rangle 4$. $X \in \bigcap \mathcal{T}$.

□

Definition 14.1.9 (Finer, Coarser). Let \mathcal{T} and \mathcal{T}' be topologies on the set X . Then \mathcal{T} is *coarser*, *smaller* or *weaker* than \mathcal{T}' , or \mathcal{T}' is *finer*, *larger* or *stronger* than \mathcal{T} , iff $\mathcal{T} \subseteq \mathcal{T}'$.

14.2 Closed Sets

Definition 14.2.1 (Closed Set). Let X be a topological space and $A \subseteq X$. Then A is *closed* iff $X - A$ is open.

Proposition 14.2.2. *A set B is open if and only if $X - B$ is closed.*

PROOF: We have B is open iff $X - (X - B)$ is open iff $X - B$ is closed. □

Theorem 14.2.3. *Let X be a set. Let $\mathcal{C} \subseteq \mathcal{P}X$. Then there exists a topology on X such that \mathcal{C} is the set of closed sets if and only if:*

$$1. \emptyset \in \mathcal{C}$$

$$2. \forall \mathcal{A} \subseteq \mathcal{C}. \bigcap \mathcal{A} \in \mathcal{C}$$

$$3. \forall C, D \in \mathcal{C}. C \cup D \in \mathcal{C}$$

In this case, the topology is unique, and is $\{X - C : C \in \mathcal{C}\}$.

PROOF:

$\langle 1 \rangle 1$. In any topology on X we have \emptyset is closed.

PROOF: Since $X - \emptyset = X$ is open.

$\langle 1 \rangle 2$. In any topology on X , the intersection of a set \mathcal{A} of closed sets is closed.

PROOF: Since $X - \bigcap \mathcal{A} = \bigcup_{A \in \mathcal{A}} (X - A)$ is open.

$\langle 1 \rangle 3$. In any topology on X , the union of two closed sets is closed.

PROOF: For any closed sets C and D , we have $X - (C \cup D) = (X - C) \cap (X - D)$ is open.

$\langle 1 \rangle 4$. If \mathcal{C} is a set satisfying 1–3, then $\{X - C : C \in \mathcal{C}\}$ is a topology on X with respect to which \mathcal{C} is the set of closed sets.

$\langle 2 \rangle 1$. LET: \mathcal{C} be a set satisfying 1–3.

$\langle 2 \rangle 2$. LET: $\mathcal{T} = \{X - C : C \in \mathcal{C}\}$

$\langle 2 \rangle 3$. For all $U \in \mathcal{T}$ we have $X - U \in \mathcal{C}$.

$\langle 2 \rangle 4$. \mathcal{T} is a topology on X .

$\langle 3 \rangle 1$. For all $\mathcal{U} \subseteq \mathcal{T}$ we have $\bigcup \mathcal{U} \in \mathcal{T}$.

$\langle 4 \rangle 1$. LET: $\mathcal{U} \subseteq \mathcal{T}$

$\langle 4 \rangle 2$. For all $U \in \mathcal{U}$ we have $X - U \in \mathcal{C}$.

$\langle 4 \rangle 3$. $X - \bigcup \mathcal{U} \in \mathcal{C}$

PROOF:

$$\begin{aligned} X - \bigcup \mathcal{U} &= \bigcap_{U \in \mathcal{U}} (X - U) \\ &\in \mathcal{C} \end{aligned}$$

$\langle 4 \rangle 4$. $\bigcup \mathcal{U} \in \mathcal{T}$

$\langle 3 \rangle 2$. For all $U, V \in \mathcal{T}$ we have $U \cap V \in \mathcal{T}$.

$\langle 3 \rangle 3$. $X \in \mathcal{T}$

$\langle 2 \rangle 5$. For any set C we have $C \in \mathcal{C}$ iff C is closed with respect to \mathcal{T} .

$\langle 1 \rangle 5$. If \mathcal{T} is any topology on X then $\mathcal{T} = \{X - C : C \text{ is closed in } \mathcal{T}\}$.

PROOF: Proposition 14.2.2.

□

14.3 Neighbourhoods

Definition 14.3.1 (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 14.3.2. *A set B is open if and only if it is a neighbourhood of each of its points.*

PROOF: This is Proposition 14.1.7. □

Proposition 14.3.3. *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 $\mathcal{O} = \{U : \forall x \in U. U \in \mathcal{N}_x\}$.

PROOF: Straightforward. \square

14.4 Interior

Definition 14.4.1 (Interior). The interior of B is the union of all the open sets included in B .

14.5 Closure

Definition 14.5.1 (Closure). Let X be a topological space and $B \subseteq X$. The closure of B , \overline{B} , is the intersection of all the closed sets that include B .

Proposition 14.5.2. A set C is closed if and only if $C = \overline{C}$.

PROOF: Easy. \square

Corollary 14.5.2.1. A set B is open iff $X - B = \overline{X - B}$.

Proposition 14.5.3 (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 $\mathcal{O} = \{U : X - U = \overline{X - U}\}$.

PROOF: Straightforward. \square

14.6 Bases

Definition 14.6.1 (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} . The elements of \mathcal{B} are called *basic open neighbourhoods* of their elements.

Example 14.6.2. Let X be a set. The set of all one-element subsets of X is a basis for the discrete topology on X .

Proposition 14.6.3. Let X be a topological space. Let \mathcal{B} be a basis for the topology on X . Then the topology on X is the coarsest topology that includes \mathcal{B} .

Proposition 14.6.4. Let X and Y be topological spaces. Let \mathcal{B} be a basis for the topology on X and \mathcal{C} a basis for the topology on Y . Then

$$\{B \times C : B \in \mathcal{B}, C \in \mathcal{C}\}$$

is a basis for the product topology on $X \times Y$.

Theorem 14.6.5. There are infinitely many primes.

Furstenberg's proof:

PROOF:

$\langle 1 \rangle 1$. For $a \in \mathbb{Z} - \{0\}$ and $b \in \mathbb{Z}$,

LET: $S(a, b) := \{an + b : n \in \mathbb{N}\}$

$\langle 1 \rangle 2$. LET: \mathcal{T} be the topology generated by the basis $\{S(a, b) : a \in \mathbb{Z} - \{0\}, b \in \mathbb{Z}\}$

$\langle 2 \rangle 1$. For every $n \in \mathbb{Z}$, there exist a, b such that $n \in S(a, b)$.

PROOF: $n \in S(n, 0)$

$\langle 2 \rangle 2$. If $n \in S(a_1, b_1) \cap S(a_2, b_2)$ then there exist a_3, b_3 such that $n \in S(a_3, b_3) \subseteq S(a_1, b_1) \cap S(a_2, b_2)$

$\langle 3 \rangle 1$. LET: $d = \text{lcm}(a_1, a_2)$

PROVE: $S(d, n) \subseteq S(a_1, b_1) \cap S(a_2, b_2)$

$\langle 3 \rangle 2$. LET: $d = a_1k = a_2l$

$\langle 3 \rangle 3$. LET: $n = a_1c + b_1 = a_2d + b_2$

$\langle 3 \rangle 4$. LET: $z \in \mathbb{Z}$

PROVE: $dz + n \in S(a_1, b_1) \cap S(a_2, b_2)$

$\langle 3 \rangle 5$. $dz + n \in S(a_1, b_1)$

PROOF:

$$\begin{aligned} dz + n &= a_1kz + a_1c + b_1 \\ &= a_1(kz + c) + b_1 \end{aligned}$$

$\langle 3 \rangle 6$. $dz + n \in S(a_2, b_2)$

PROOF: Similar.

$\langle 1 \rangle 3$. For all $a \in \mathbb{Z} - \{0\}$ and $b \in \mathbb{Z}$ we have $S(a, b)$ is closed.

$\langle 2 \rangle 1$. LET: $a \in \mathbb{Z} - \{0\}$ and $b \in \mathbb{Z}$

$\langle 2 \rangle 2$. LET: $n \in \mathbb{Z} - S(a, b)$

$\langle 2 \rangle 3$. $n \in S(a, n) \subseteq \mathbb{Z} - S(a, b)$

$\langle 3 \rangle 1$. LET: $x \in S(a, n)$

- $\langle 3 \rangle 2$. ASSUME: for a contradiction $x \in S(a, b)$
 $\langle 3 \rangle 3$. PICK m such that $x = am + b$
 $\langle 3 \rangle 4$. PICK l such that $x = al + n$
 $\langle 3 \rangle 5$. $n = a(m - l) + b$
 $\langle 3 \rangle 6$. $n \in S(a, b)$
 $\langle 3 \rangle 7$. Q.E.D.

PROOF: This contradicts $\langle 2 \rangle 2$.

$\langle 1 \rangle 4$.

$$\mathbb{Z} - \{1, -1\} = \bigcup_{p \text{ prime}} S(p, 0)$$

PROOF: Since every integer except 1 and -1 is divisible by a prime.

- $\langle 1 \rangle 5$. No nonempty finite set is open.
 $\langle 2 \rangle 1$. LET: U be a nonempty open set
 $\langle 2 \rangle 2$. PICK $n \in U$
 $\langle 2 \rangle 3$. There exist a, b such that $n \in S(a, b) \subseteq U$
 $\langle 2 \rangle 4$. U is infinite.
 $\langle 1 \rangle 6$. $\mathbb{Z} - \{1, -1\}$ is not closed.
 $\langle 1 \rangle 7$. $\bigcup_{p \text{ prime}} S(p, 0)$ is not closed.
 $\langle 1 \rangle 8$. The union of finitely many closed sets is closed.
 $\langle 1 \rangle 9$. There are infinitely many primes.

□

14.7 Order Topology

Definition 14.7.1 (Order Topology). Let X be a linearly ordered set. The *order topology* on X is the topology generated by the open interval (a, b) as well as the open rays $(a, +\infty)$ and $(-\infty, b)$ for $a, b \in X$.

The *standard topology* on \mathbb{R} is the order topology.

Proposition 14.7.2. *Let X be a linearly ordered set. Then the order topology is generated by the basis consisting of:*

- all open intervals (a, b)
- all intervals of the form $[\perp, b)$ where \perp is the least element of X , if any
- all intervals of the form $(a, \top]$ where \top is the greatest element of X , if any.

Proposition 14.7.3. *Let X be a linearly ordered set. The open rays in X form a subbasis for the order topology.*

Definition 14.7.4 (Lower Limit Topology). The *lower limit topology*, *Sorgenfrey topology*, *uphill topology* or *half-open topology* is the topology on \mathbb{R} generated by the basis consisting of all half-open intervals $[a, b)$.

We write \mathbb{R}_l for \mathbb{R} under the lower limit topology.

Definition 14.7.5 (K -topology). Let $K = \{1/n : n \in \mathbb{Z}_+\}$. The K -topology on \mathbb{R} is the topology generated by the basis consisting of all open intervals (a, b) and all sets of the form $(a, b) - K$.

We write \mathbb{R}_K for \mathbb{R} under the K -topology.

Proposition 14.7.6. *Let X be a linearly ordered set under the order topology. Let $Y \subseteq X$ be convex. Then the order topology on Y is the same as the subspace topology.*

PROOF:

$\langle 1 \rangle 1$. The order topology is coarser than the subspace topology.

$\langle 2 \rangle 1$. For all $a \in Y$, the open ray $\{y \in Y : a < y\}$ is open in the subspace topology.

PROOF: It is $(a, +\infty) \cap Y$.

$\langle 2 \rangle 2$. For all $a \in Y$, the open ray $\{y \in Y : y < a\}$ is open in the subspace topology.

PROOF: It is $(-\infty, a) \cap Y$.

$\langle 1 \rangle 2$. The subspace topology is coarser than the order topology.

$\langle 2 \rangle 1$. For all $a \in X$, the set $(-\infty, a) \cap Y$ is open in the order topology.

$\langle 3 \rangle 1$. CASE: $a \in Y$

PROOF: Then $(-\infty, a) \cap Y = \{y \in Y : y < a\}$ is an open ray in Y .

$\langle 3 \rangle 2$. CASE: a is an upper bound for Y

PROOF: Then $(-\infty, a) \cap Y = Y$.

$\langle 3 \rangle 3$. CASE: a is a lower bound for Y

PROOF: Then $(-\infty, a) \cap Y = \emptyset$.

$\langle 3 \rangle 4$. Q.E.D.

PROOF: These are the only three cases because Y is convex.

$\langle 2 \rangle 2$. For all $a \in X$, the set $(a, +\infty) \cap Y$ is open in the order topology.

PROOF: Similar.

□

Example 14.7.7. We cannot remove the hypothesis that the set Y is convex.

Let $X = \mathbb{R}$ and $Y = [0, 1) \cup \{2\}$. Then $\{2\}$ is open in the subspace topology but not in the order topology on Y .

Proposition 14.7.8. *Let X be a topological space. Let \mathcal{B} be a basis for the topology on X and $U \subseteq X$. Then U is open if and only if, for all $x \in U$, there exists $B \in \mathcal{B}$ such that $x \in B \subseteq U$.*

Proposition 14.7.9. *Let X be a topological space and $\mathcal{B} \subseteq \mathcal{P}X$. Assume that, for every open set U and element $x \in U$, there exists $B \in \mathcal{B}$ such that $x \in B \subseteq U$. Then \mathcal{B} is a basis for the topology on X .*

Proposition 14.7.10. *Let X be a topological space and $\mathcal{B} \subseteq \mathcal{P}X$. Then \mathcal{B} is a basis for a topology on X if and only if:*

1. $\bigcup \mathcal{B} = X$

2. For all $A, B \in \mathcal{B}$ and $x \in A \cap B$, there exists $C \in \mathcal{B}$ such that $x \in C \subseteq A \cap B$.

In this case, the topology is unique and is the set of all unions of subsets of \mathcal{B} . We call it the topology generated by \mathcal{B} .

Proposition 14.7.11. *Let \mathcal{B} and \mathcal{B}' be bases for the topologies \mathcal{T} and \mathcal{T}' , respectively, on X . Then \mathcal{T}' is finer than \mathcal{T} if and only if, for every $B \in \mathcal{B}$ and $x \in B$, there exists $B' \in \mathcal{B}'$ such that $x \in B' \subseteq B$.*

Corollary 14.7.11.1. *The topologies of \mathbb{R}_l and \mathbb{R}_K are strictly finer than the standard topology on \mathbb{R} but are not comparable to one another.*

Proposition 14.7.12. *In a linearly ordered set under the order topology, every closed interval and closed ray is closed.*

PROOF:

$\langle 1 \rangle 1$. LET: X be a linearly ordered set under the order topology.

$\langle 1 \rangle 2$. Every closed interval in X is closed.

PROOF: Since $X - [a, b] = (-\infty, a) \cup (b, +\infty)$.

$\langle 1 \rangle 3$. Every closed ray in X is closed.

PROOF: Since $X - [a, +\infty) = (-\infty, a)$ and $X - (-\infty, a] = (a, +\infty)$.

□

14.7.1 Subspaces

Proposition 14.7.13. *Let X be a topological space. Let Y be a subspace of X . Let \mathcal{B} be a basis for the topology on X . Then $\{B \cap Y : B \in \mathcal{B}\}$ is a basis for the topology on Y .*

PROOF:

$\langle 1 \rangle 1$. For all $B \in \mathcal{B}$ we have $B \cap Y$ is open in Y .

PROOF: Since B is open in X .

$\langle 1 \rangle 2$. For any open set V in Y and $y \in V$, there exists $B \in \mathcal{B}$ such that $y \in B \cap Y \subseteq V$.

$\langle 2 \rangle 1$. LET: V be open in Y .

$\langle 2 \rangle 2$. LET: $y \in V$

$\langle 2 \rangle 3$. PICK U open in X such that $V = U \cap Y$.

$\langle 2 \rangle 4$. PICK $B \in \mathcal{B}$ such that $y \in B \subseteq U$.

$\langle 2 \rangle 5$. $y \in B \cap Y \subseteq V$

□

Proposition 14.7.14. *Let X be a topological space and Y a subspace of X . Let $A \subseteq Y$. Then A is closed in Y if and only if there exists a closed set B in X such that $A = B \cap Y$.*

PROOF:

A is closed in $Y \Leftrightarrow Y - A$ is open in Y

$\Leftrightarrow \exists U$ open in $X. Y - A = U \cap Y$

$\Leftrightarrow \exists C$ closed in $X. Y - A = Y - C$

$\Leftrightarrow \exists C$ closed in $X. A = Y \cap C$

□

14.7.2 Product Topology

Proposition 14.7.15. *Let $\{X_i\}_{i \in I}$ be a family of topological spaces. For all $i \in I$, let \mathcal{B}_i be a basis for the topology on X_i . Then $\mathcal{B} = \{\prod_{i \in I} B_i : \text{for finitely many } i \in I \text{ we have } B_i \in \mathcal{B}_i, \text{ and } B_i = X_i \text{ for all other } i\}$ is a basis for the product topology on $\prod_{i \in I} X_i$.*

PROOF:

$\langle 1 \rangle 1$. Every $B \in \mathcal{B}$ is open in the product topology.

PROOF: Since every element of \mathcal{B}_i is open in X_i .

$\langle 1 \rangle 2$. For any open set U in the product topology and $x \in U$, there exists $B \in \mathcal{B}$ such that $x \in B \subseteq U$.

$\langle 2 \rangle 1$. LET: U be a set open in the box topology.

$\langle 2 \rangle 2$. LET: $x \in U$

$\langle 2 \rangle 3$. PICK a family $\{U_i\}_{i \in I}$ where U_i is open in X_i for $i = i_1, \dots, i_n$, and $U_i = X_i$ for all other i , such that $x \in \prod_{i \in I} U_i \subseteq U$

$\langle 2 \rangle 4$. For $i = i_1, \dots, i_n$, choose $B_i \in \mathcal{B}_i$ such that $x_i \in B_i \subseteq U_i$. Let $B_i = X_i$ for all other i .

$\langle 2 \rangle 5$. $\prod_{i \in I} B_i \in \mathcal{B}$

$\langle 2 \rangle 6$. $x \in \prod_{i \in I} B_i \subseteq \prod_{i \in I} U_i \subseteq U$

□

14.8 Subbases

Definition 14.8.1 (Subbasis). Let X be a topological space. A *subbasis* for the topology on X is a set \mathcal{S} of open sets such that every open set is a union of finite intersections of \mathcal{S} .

Proposition 14.8.2. *Let X be a set and $\mathcal{S} \subseteq X$. Then \mathcal{S} is a subbasis for a topology on X if and only if $\bigcup \mathcal{S} = X$, in which case the topology is unique and is the set of all unions of finite intersections of elements of \mathcal{S} .*

Proposition 14.8.3. *Let X be a topological space. Let \mathcal{S} be a subbasis for the topology on X . Then the topology on X is the coarsest topology that includes \mathcal{S} .*

Proposition 14.8.4. *Let X and Y be topological spaces. Then*

$$\mathcal{S} = \{\pi_1^{-1}(U) : U \text{ is open in } X\} \cup \{\pi_2^{-1}(V) : V \text{ is open in } Y\}$$

is a subbasis for the product topology on $X \times Y$.

PROOF:

$\langle 1 \rangle 1$. Every element of \mathcal{S} is open.

PROOF: Since $\pi_1^{-1}(U) = U \times Y$ and $\pi_2^{-1}(V) = X \times V$.

$\langle 1 \rangle 2$. Every open set is a union of finite intersections of elements of \mathcal{S} .

PROOF: Since, for U open in X and V open in Y , we have $U \times V = \pi_1^{-1}(U) \cap \pi_2^{-1}(V)$.

□

Definition 14.8.5 (Space with Basepoint). A *space with basepoint* is a pair (X, x) where X is a topological space and $x \in X$.

14.9 Neighbourhood Bases

Definition 14.9.1 (Neighbourhood Basis). Let X be a topological space and $x_0 \in X$. A *neighbourhood basis* of x_0 is a set \mathcal{U} of neighbourhoods of x_0 such that every neighbourhood of x_0 includes an element of \mathcal{U} .

14.10 First Countable Spaces

Definition 14.10.1 (First Countable). A topological space is *first countable* iff every point has a countable neighbourhood basis.

Proposition 14.10.2. \mathbb{R}_l is first countable.

PROOF: For any $x \in \mathbb{R}$ we have $\{[x, x + 1/n) : n \in \mathbb{Z}_+\}$ is a countable local basis.
□

Proposition 14.10.3. The ordered square is first countable.

PROOF:

⟨1⟩1. Every point (a, b) with $0 < b < 1$ has a countable local basis.

PROOF: The set of all intervals $((a, q), (a, r))$ where q and r are rational and $0 \leq q < b < r \leq 1$ is a countable local basis.

⟨1⟩2. Every point $(a, 0)$ has a countable local basis with $a > 0$.

PROOF: The set of all intervals $((q, 0), (a, r))$ where q and r are rational with $0 \leq q < a$ and $0 < r \leq 1$ is a countable local basis.

⟨1⟩3. Every point $(a, 1)$ has a countable local basis with $a < 1$.

PROOF: The set of all intervals $((a, q), (r, 1))$ with q and r rational and $0 \leq q < 1, a < r \leq 1$ is a countable local basis.

⟨1⟩4. $(0, 0)$ has a countable local basis.

PROOF: The set of all intervals $[(0, 0), (0, r))$ with r rational and $0 < r \leq 1$ is a countable local basis.

⟨1⟩5. $(1, 1)$ has a countable local basis.

PROOF: The set of all intervals $((1, q), (1, 1])$ with q rational and $0 \leq q < 1$ is a countable local basis.
□

14.11 Second Countable Spaces

Definition 14.11.1 (Second Countable). A topological space is *second countable* iff it has a countable basis.

Every second countable space is first countable.

A subspace of a first countable space is first countable.

A subspace of a second countable space is second countable.

\mathbb{R}^n is second countable.

An uncountable discrete space is first countable but not second countable.

Proposition 14.11.2. *Let $\{X_\lambda\}_{\lambda \in \Lambda}$ be a family of topological spaces such that no X_λ is indiscrete. If Λ is uncountable, then $\prod_{\lambda \in \Lambda} X_\lambda$ is not first countable.*

PROOF:

$\langle 1 \rangle 1$. For all $\lambda \in \Lambda$, PICK U_λ open in X_λ such that $\emptyset \neq U_\lambda \neq X_\lambda$.

$\langle 1 \rangle 2$. For all $\lambda \in \Lambda$, PICK $x_\lambda \in U_\lambda$.

$\langle 1 \rangle 3$. ASSUME: for a contradiction B is a countable neighbourhood basis for $(x_\lambda)_{\lambda \in \Lambda}$.

$\langle 1 \rangle 4$. PICK $\lambda \in \Lambda$ such that, for all $U \in B$, we have $\pi_\lambda(U) = X_\lambda$

$\langle 1 \rangle 5$. There is no $U \in B$ such that $U \subseteq \pi_\lambda^{-1}(U_\lambda)$

$\langle 1 \rangle 6$. Q.E.D.

PROOF: This is a contradiction.

□

Proposition 14.11.3. *The long line cannot be embedded in \mathbb{R}^n for any n .*

PROOF: Since the long line is not second countable but \mathbb{R}^n is. □

14.12 Interior

Definition 14.12.1 (Interior). Let X be a topological space. Let $A \subseteq X$. The *interior* of A , A° , is the union of all the open sets included in A .

14.13 Closure

Definition 14.13.1 (Closure). Let X be a topological space. Let $A \subseteq X$. The *closure* of A , \bar{A} , is the intersection of all the closed sets that include A .

Proposition 14.13.2. *Let X be a topological space, $A \subseteq X$ and $x \in X$. Then $x \in \bar{A}$ if and only if every open set that contains x intersects A .*

PROOF:

$x \in \bar{A} \Leftrightarrow$ for every closed set C , if $A \subseteq C$ then $x \in C$

\Leftrightarrow for every open set U , if $A \subseteq X - U$ then $x \in X - U$

\Leftrightarrow for every open set U , if $A \cap U = \emptyset$ then $x \notin U$

\Leftrightarrow for every open set U , if $x \in U$ then A intersects U □

Proposition 14.13.3. *Let X be a topological space. Let $A \subseteq B \subseteq X$. Then $\bar{A} \subseteq \bar{B}$.*

PROOF: Since every closed set that includes B is a closed set that includes A . □

Proposition 14.13.4. *Let X be a topological space. Let $A, B \subseteq X$. Then $\overline{A \cup B} = \bar{A} \cup \bar{B}$.*

PROOF:

$\langle 1 \rangle 1$. $\overline{A \cup B} \subseteq \bar{A} \cup \bar{B}$

PROOF: Since $\overline{A \cup B}$ is a closed set that includes $A \cup B$.

$\langle 1 \rangle 2$. $\overline{A \cup B} \subseteq \overline{A \cup B}$

PROOF: Since $A \subseteq \overline{A \cup B}$ and $B \subseteq \overline{A \cup B}$ by Proposition 14.13.3.

□

Proposition 14.13.5. *Let X be a topological space. Let $\mathcal{A} \subseteq \mathcal{P}X$. Then*

$$\bigcup \{\overline{A} : A \in \mathcal{A}\} \subseteq \overline{\bigcup \mathcal{A}}.$$

PROOF: For all $A \in \mathcal{A}$ we have $\overline{A} \subseteq \overline{\bigcup \mathcal{A}}$ by Proposition 14.13.3. □

Example 14.13.6. The converse does not always hold. In \mathbb{R} , let $\mathcal{A} = \{\{x\} : 0 < x < 1\}$. Then $\bigcup \{\overline{A} : A \in \mathcal{A}\} = (0, 1)$ but $\overline{\bigcup \mathcal{A}} = [0, 1]$.

Proposition 14.13.7. *Let X be a topological space. Let $\mathcal{A} \subseteq \mathcal{P}X$. Then $\overline{\bigcap \mathcal{A}} \subseteq \bigcap \{\overline{A} : A \in \mathcal{A}\}$.*

PROOF: Since $\overline{\bigcap \mathcal{A}} \subseteq \overline{A}$ for all $A \in \mathcal{A}$ by Proposition 14.13.3. □

Example 14.13.8. The converse does not always hold. In \mathbb{R} , if A is the set of all rational numbers and B is the set of all irrational numbers then $\bigcap A \cap B = \emptyset$ but $\bigcap A \cap \bigcap B = \mathbb{R}$.

14.13.1 Bases

Proposition 14.13.9. *Let X be a topological space, $A \subseteq X$ and $x \in X$. Let \mathcal{B} be a basis for the topology on X . Then $x \in \overline{A}$ if and only if, for all $B \in \mathcal{B}$, if $x \in B$ then B intersects A .*

PROOF:

$\langle 1 \rangle 1$. If $x \in \overline{A}$ then, for all $B \in \mathcal{B}$, if $x \in B$ then B intersects A .

PROOF: Proposition 14.13.2 since every element of \mathcal{B} is open.

$\langle 1 \rangle 2$. If, for all $B \in \mathcal{B}$, if $x \in B$ then B intersects A , then $x \in \overline{A}$.

$\langle 2 \rangle 1$. ASSUME: For all $B \in \mathcal{B}$, if $x \in B$ then B intersects A .

$\langle 2 \rangle 2$. LET: U be an open set that contains x .

$\langle 2 \rangle 3$. PICK $B \in \mathcal{B}$ such that $x \in B \subseteq U$.

$\langle 2 \rangle 4$. B intersects A .

PROOF: $\langle 2 \rangle 1$

$\langle 2 \rangle 5$. U intersects A .

□

14.13.2 Subspaces

Proposition 14.13.10. *Let X be a topological space. Let Y be a subspace of X . Let $A \subseteq Y$. Let \overline{A} be the closure of A in X . Then the closure of A in Y is $\overline{A} \cap Y$.*

PROOF:

⟨1⟩1. $\overline{A} \cap Y$ is the closed in Y .

PROOF: Since \overline{A} is closed in X .

⟨1⟩2. For any closed set B in Y , if $A \subseteq B$ then $\overline{A} \cap Y \subseteq B$.

⟨2⟩1. LET: B be closed in Y .

⟨2⟩2. ASSUME: $A \subseteq B$

⟨2⟩3. PICK C closed in X such that $B = C \cap Y$.

⟨2⟩4. $A \subseteq C$

⟨2⟩5. $\overline{A} \subseteq C$

⟨2⟩6. $\overline{A} \cap Y \subseteq B$

□

14.13.3 Product Topology

Proposition 14.13.11. *Let X and Y be topological spaces. Let $A \subseteq X$ and $B \subseteq Y$. Then $\overline{A \times B} = \overline{A} \times \overline{B}$.*

PROOF:

⟨1⟩1. $\overline{A \times B} \subseteq \overline{A} \times \overline{B}$

PROOF: Since $\overline{A \times B}$ is a closed set that includes $A \times B$ by Proposition 15.8.2.

⟨1⟩2. $\overline{A} \times \overline{B} \subseteq \overline{A \times B}$

⟨2⟩1. LET: $x \in \overline{A}$ and $y \in \overline{B}$.

⟨2⟩2. LET: U be an open set that contains (x, y) .

⟨2⟩3. PICK open sets V in X and W in Y such that $(x, y) \in V \times W \subseteq U$.

⟨2⟩4. V intersects A and W intersects B .

⟨2⟩5. U intersects $A \times B$.

□

14.13.4 Interior

Proposition 14.13.12. *Let X be a topological space and $A \subseteq X$. Then*

$$X - A^\circ = \overline{X - A}$$

PROOF:

$$\begin{aligned} X - A^\circ &= X - \bigcup \{U \text{ open in } X : U \subseteq A\} \\ &= \bigcap \{X - U : U \text{ open in } X, U \subseteq A\} \quad (\text{De Morgan's Law}) \\ &= \bigcap \{C : C \text{ closed in } X, X - A \subseteq C\} \\ &= \overline{X - A} \end{aligned} \quad \square$$

Proposition 14.13.13. *Let X be a topological space and $A \subseteq X$. Then*

$$X - \overline{A} = (X - A)^\circ$$

PROOF: Dual. □

14.14 Boundary

Definition 14.14.1 (Boundary). Let X be a topological space. Let $A \subseteq X$. The *boundary* of A is

$$\partial A := \overline{A} \cap \overline{X - A}.$$

Proposition 14.14.2. Let X be a topological space. Let $A \subseteq X$. Then

$$A^\circ \cap \partial A = \emptyset.$$

PROOF:

- $\langle 1 \rangle 1.$ $A^\circ \subseteq A$
- $\langle 1 \rangle 2.$ $X - A \subseteq X - A^\circ$
- $\langle 1 \rangle 3.$ $\overline{X - A} \subseteq \overline{X - A^\circ}$
- $\langle 1 \rangle 4.$ $\partial A \subseteq X - A^\circ$

□

Proposition 14.14.3. Let X be a topological space. Let $A \subseteq X$. Then

$$\overline{A} = A^\circ \cup \partial A$$

- $\langle 1 \rangle 1.$ $A^\circ \subseteq \overline{A}$

PROOF: Since $A^\circ \subseteq A \subseteq \overline{A}$.

- $\langle 1 \rangle 2.$ $\partial A \subseteq \overline{A}$

PROOF: Definition of ∂A .

- $\langle 1 \rangle 3.$ $\overline{A} \subseteq A^\circ \cup \partial A$

- $\langle 2 \rangle 1.$ LET: $x \in \overline{A}$

- $\langle 2 \rangle 2.$ ASSUME: $x \notin A^\circ$

PROVE: $x \in \partial A$

- $\langle 2 \rangle 3.$ $x \in \overline{X - A}$

PROOF: Since $\overline{X - A} = X - A^\circ$.

- $\langle 2 \rangle 4.$ $x \in \partial A$

PROOF: Since $\partial A = \overline{A} \cap \overline{X - A}$.

□

Proposition 14.14.4. Let X be a topological space. Let $A \subseteq X$. Then $\partial A = \emptyset$ if and only if A is both open and closed.

PROOF:

- $\langle 1 \rangle 1.$ If $\partial A = \emptyset$ then A is open and closed.

- $\langle 2 \rangle 1.$ ASSUME: $\partial A = \emptyset$

- $\langle 2 \rangle 2.$ $\overline{A} = A^\circ$

PROOF: Proposition 14.14.3.

- $\langle 2 \rangle 3.$ $\overline{A} = A = A^\circ$

- $\langle 1 \rangle 2.$ If A is open and closed then $\partial A = \emptyset$.

PROOF: If A is open and closed then

$$\begin{aligned} \partial A &= \overline{A} \cap \overline{X - A} \\ &= \overline{A} \cap (X - A^\circ) \\ &= A \cap (X - A) \\ &= \emptyset \end{aligned}$$

□

Proposition 14.14.5. *Let X be a topological space. Let $U \subseteq X$. Then U is open if and only if $\partial U = \overline{U} - U$.*

PROOF:

⟨1⟩1. If U is open then $\partial U = \overline{U} - U$

PROOF: If U is open then

$$\begin{aligned}\partial U &= \overline{U} \cap \overline{X - U} \\ &= \overline{U} \cap (X - U^\circ) \\ &= \overline{U} - U^\circ \\ &= \overline{U} - U\end{aligned}$$

⟨1⟩2. If $\partial U = \overline{U} - U$ then U is open.

⟨2⟩1. ASSUME: $\partial U = \overline{U} - U$

⟨2⟩2. $\overline{U} - U^\circ = \overline{U} - U$

⟨2⟩3. $U \subseteq U^\circ$

⟨2⟩4. $U = U^\circ$

□

14.15 Limit Points

Definition 14.15.1 (Limit Point). Let X be a topological space, $x \in X$ and $A \subseteq X$. Then x is a *limit point*, *cluster point* or *point of accumulation* of A iff every neighbourhood of x intersects $A - \{x\}$.

Proposition 14.15.2. *Let X be a topological space. Let $A \subseteq X$. Let A' be the set of limit points of A . Then*

$$\overline{A} = A \cup A'$$

PROOF:

⟨1⟩1. $\overline{A} \subseteq A \cup A'$

⟨2⟩1. LET: $x \in \overline{A}$

⟨2⟩2. ASSUME: $x \notin A$

PROVE: $x \in A'$

⟨2⟩3. LET: U be a neighbourhood of x .

⟨2⟩4. PICK $y \in U \cap A$

PROOF: Proposition 14.13.2.

⟨2⟩5. $y \neq x$

⟨1⟩2. $A \subseteq \overline{A}$

PROOF: Immediate from the definition of \overline{A} .

⟨1⟩3. $A' \subseteq \overline{A}$

PROOF: From Proposition 14.13.2.

□

Corollary 14.15.2.1. *A set is closed if and only if it contains all its limit points.*

14.16 Isolated Points

Definition 14.16.1 (Isolated Point). Let X be a topological space. Let $a \in X$. Then a is an *isolated point* iff $\{a\}$ is open.

Chapter 15

Continuous Functions

Definition 15.0.1 (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 15.0.2. *The composite of two continuous functions is continuous.*

PROOF:

$\langle 1 \rangle 1$. LET: $f : X \rightarrow Y$ and $g : Y \rightarrow Z$ be continuous.

$\langle 1 \rangle 2$. LET: U be open in Z .

$\langle 1 \rangle 3$. $g^{-1}(U)$ is open in Y .

$\langle 1 \rangle 4$. $\inf f(g^{-1}(U))$ is open in X .

□

Proposition 15.0.3. 1. id_X is continuous

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

3. 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.

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

Proposition 15.0.4. Let X and Y be topological spaces. Let $f : X \rightarrow Y$. Then the following are equivalent.

1. f is continuous.

2. For all $A \subseteq X$ we have $f(\overline{A}) \subseteq \overline{f(A)}$.

3. For every closed B in Y , we have $f^{-1}(B)$ is closed in X .

PROOF:

$\langle 1 \rangle 1$. $1 \Rightarrow 2$

$\langle 2 \rangle 1$. ASSUME: f is continuous.

- $\langle 2 \rangle 2$. LET: $A \subseteq X$
 $\langle 2 \rangle 3$. LET: $x \in \bar{A}$
 PROVE: $f(x) \in \overline{f(A)}$
 $\langle 2 \rangle 4$. LET: V be a neighbourhood of $f(x)$.
 PROVE: V intersects $f(A)$.
 $\langle 2 \rangle 5$. $f^{-1}(V)$ is a neighbourhood of x .
 $\langle 2 \rangle 6$. PICK $y \in f^{-1}(V) \cap A$
 $\langle 2 \rangle 7$. $f(y) \in V \cap f(A)$
 $\langle 1 \rangle 2$. $2 \Rightarrow 3$
 $\langle 2 \rangle 1$. ASSUME: 2
 $\langle 2 \rangle 2$. LET: B be closed in Y
 $\langle 2 \rangle 3$. LET: $A = f^{-1}(B)$
 PROVE: $\bar{A} = A$
 $\langle 2 \rangle 4$. $f(A) \subseteq B$
 $\langle 2 \rangle 5$. $\bar{A} \subseteq A$
 $\langle 3 \rangle 1$. LET: $x \in \bar{A}$
 $\langle 3 \rangle 2$. $f(x) \in B$
 PROOF:

$$f(x) \in f(\bar{A})$$

$$\subseteq \overline{f(A)} \quad (\langle 2 \rangle 1)$$

$$\subseteq \bar{B} \quad (\langle 2 \rangle 4)$$

$$= B \quad (\langle 2 \rangle 2)$$
 $\langle 1 \rangle 3$. $3 \Rightarrow 1$
 $\langle 2 \rangle 1$. ASSUME: 3
 $\langle 2 \rangle 2$. LET: V be open in Y .
 $\langle 2 \rangle 3$. $f^{-1}(Y - V)$ is closed in X .
 $\langle 2 \rangle 4$. $X - f^{-1}(V)$ is closed in X .
 $\langle 2 \rangle 5$. $f^{-1}(V)$ is open in X .

□

Proposition 15.0.5. *Let X and Y be topological spaces. Any constant function $X \rightarrow Y$ is continuous.*

PROOF:

- $\langle 1 \rangle 1$. LET: $b \in Y$
 $\langle 1 \rangle 2$. LET: $f : X \rightarrow Y$ be the constant function with value b .
 $\langle 1 \rangle 3$. LET: $V \subseteq Y$ be open.
 $\langle 1 \rangle 4$. $f^{-1}(V)$ is either \emptyset or X .
 $\langle 1 \rangle 5$. $f^{-1}(V)$ is open.

□

Proposition 15.0.6. *Let X and Y be topological spaces. Let $f : X \rightarrow Y$. Let \mathcal{B} be a basis for Y . Then f is continuous if and only if, for all $B \in \mathcal{B}$, we have $f^{-1}(B)$ is open in X .*

PROOF:

⟨1⟩1. If f is continuous then, for all $B \in \mathcal{B}$, we have $f^{-1}(B)$ is open in X .

PROOF: Since every element of \mathcal{B} is open in Y .

⟨1⟩2. If, for all $B \in \mathcal{B}$, we have $f^{-1}(B)$ is open in X , then f is continuous.

⟨2⟩1. ASSUME: For all $B \in \mathcal{B}$, we have $f^{-1}(B)$ is open in X .

⟨2⟩2. LET: U be open in Y .

⟨2⟩3. LET: $x \in f^{-1}(U)$

⟨2⟩4. PICK $B \in \mathcal{B}$ such that $f(x) \in B \subseteq U$.

⟨2⟩5. $x \in f^{-1}(B) \subseteq f^{-1}(U)$

□

Proposition 15.0.7. *Let X and Y be topological spaces. Let $f : X \rightarrow Y$. Let \mathcal{S} be a subbasis for the topology on Y . Then f is continuous if and only if, for all $V \in \mathcal{S}$, we have $f^{-1}(V)$ is open in X .*

PROOF:

⟨1⟩1. If f is continuous then, for all $V \in \mathcal{S}$, we have $f^{-1}(V)$ is open in X .

PROOF: Immediate from definitions.

⟨1⟩2. If, for all $V \in \mathcal{S}$, we have $f^{-1}(V)$ is open in X , then f is continuous.

⟨2⟩1. ASSUME: For all $V \in \mathcal{S}$, we have $f^{-1}(V)$ is open in X .

⟨2⟩2. For all $V_1, \dots, V_n \in \mathcal{S}$ we have $f^{-1}(V_1 \cap \dots \cap V_n)$ is open in X .

PROOF: Since $f^{-1}(V_1 \cap \dots \cap V_n) = f^{-1}(V_1) \cap \dots \cap f^{-1}(V_n)$.

⟨2⟩3. Q.E.D.

PROOF: By Proposition 15.0.6 since the set of all finite intersections of elements of \mathcal{S} forms a basis for the topology on Y .

□

Proposition 15.0.8. *Let $f : \mathbb{R} \rightarrow \mathbb{R}$. Then f is continuous if and only if, for all $x \in \mathbb{R}$ and $\epsilon > 0$, there exists $\delta > 0$ such that, for all $y \in \mathbb{R}$, if $|y - x| < \delta$ then $|f(y) - f(x)| < \epsilon$.*

PROOF:

⟨1⟩1. If f is continuous then, for all $x \in \mathbb{R}$ and $\epsilon > 0$, there exists $\delta > 0$ such that, for all $y \in \mathbb{R}$, if $|y - x| < \delta$ then $|f(y) - f(x)| < \epsilon$.

⟨2⟩1. ASSUME: f is continuous.

⟨2⟩2. LET: $x \in \mathbb{R}$

⟨2⟩3. LET: $\epsilon > 0$

⟨2⟩4. $f^{-1}((f(x) - \epsilon, f(x) + \epsilon))$ is open in X .

⟨2⟩5. PICK a, b such that $x \in (a, b) \subseteq f^{-1}((f(x) - \epsilon, f(x) + \epsilon))$.

⟨2⟩6. LET: $\delta = \min(x - a, b - x)$

⟨2⟩7. LET: $y \in \mathbb{R}$

⟨2⟩8. ASSUME: $|y - x| < \delta$

⟨2⟩9. $y \in (a, b)$

⟨2⟩10. $f(y) \in (f(x) - \epsilon, f(x) + \epsilon)$

⟨2⟩11. $|f(y) - f(x)| < \epsilon$

⟨1⟩2. If, for all $x \in \mathbb{R}$ and $\epsilon > 0$, there exists $\delta > 0$ such that, for all $y \in \mathbb{R}$, if $|y - x| < \delta$ then $|f(y) - f(x)| < \epsilon$, then f is continuous.

⟨2⟩1. ASSUME: For all $x \in \mathbb{R}$ and $\epsilon > 0$, there exists $\delta > 0$ such that, for all $y \in \mathbb{R}$, if $|y - x| < \delta$ then $|f(y) - f(x)| < \epsilon$.

- ⟨2⟩2. For all $a \in \mathbb{R}$ we have $f^{-1}((a, +\infty))$ is open.
 ⟨3⟩1. LET: $a \in \mathbb{R}$
 ⟨3⟩2. LET: $x \in f^{-1}((a, +\infty))$
 ⟨3⟩3. LET: $\epsilon = f(x) - a$
 ⟨3⟩4. PICK $\delta > 0$ such that, for all $y \in \mathbb{R}$, if $|y - x| < \delta$ then $|f(y) - f(x)| < \epsilon$
 ⟨3⟩5. $x \in (x - \delta, x + \delta) \subseteq f^{-1}((a, +\infty))$
 ⟨2⟩3. For all $a \in \mathbb{R}$ we have $f^{-1}((-\infty, a))$ is open.
 PROOF: Similar.
 ⟨2⟩4. Q.E.D.
 PROOF: Proposition 15.0.8.

□

Definition 15.0.9 (Continuity at a Point). Let X and Y be topological spaces. Let $f : X \rightarrow Y$. Let $a \in X$. Then f is *continuous at a* iff, for every neighbourhood V of $f(a)$, there exists a neighbourhood U of a such that $f(U) \subseteq V$.

Proposition 15.0.10. *Let X and Y be topological spaces. Let $f : X \rightarrow Y$. Then f is continuous if and only if f is continuous at every point in X .*

- ⟨1⟩1. If f is continuous then f is continuous at every point in X .
 ⟨2⟩1. ASSUME: f is continuous.
 ⟨2⟩2. LET: $a \in X$
 ⟨2⟩3. LET: V be a neighbourhood of $f(a)$
 ⟨2⟩4. LET: $U = f^{-1}(V)$
 ⟨2⟩5. U is a neighbourhood of a .
 ⟨2⟩6. $f(U) \subseteq V$
 ⟨1⟩2. If f is continuous at every point in X then f is continuous.
 ⟨2⟩1. ASSUME: f is continuous at every point in X .
 ⟨2⟩2. LET: V be open in Y .
 ⟨2⟩3. LET: $x \in f^{-1}(V)$
 ⟨2⟩4. V is a neighbourhood of $f(x)$
 ⟨2⟩5. PICK a neighbourhood U of x such that $f(U) \subseteq V$
 ⟨2⟩6. $x \in U \subseteq f^{-1}(V)$

□

Definition 15.0.11 (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.

Proposition 15.0.12. *Let X and Y be topological spaces. Let $f : X \rightarrow Y$. Then f is a homeomorphism iff f is bijective and, for all $U \subseteq X$, we have $f(U)$ is open if and only if U is open.*

PROOF: Immediate from definitions. □

Definition 15.0.13 (Topological Property). A property P of topological spaces is a *topological* property iff, for any topological spaces X and Y , if $P[X]$ and $X \cong Y$ then $P[Y]$.

Definition 15.0.14 (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.

Definition 15.0.15. Let **Top** be the category of small topological spaces and continuous functions.

Proposition 15.0.16. \emptyset is initial in **Top**.

Proposition 15.0.17. 1 is terminal in **Top**.

Forgetful functor **Top** \rightarrow **Set**.

Basepoint preserving continuous functor.

Proposition 15.0.18. Let (X, \mathcal{T}) be a topological space. Let S be the Sierpiński two-point space. Define $\Phi : \mathcal{T} \rightarrow \mathbf{Top}[X, S]$ by $\Phi(U)(x) = 1$ iff $x \in U$. Then Φ is a bijection.

PROOF:

$\langle 1 \rangle 1$. For all $U \in \mathcal{T}$ we have $\Phi(U)$ is continuous.

$\langle 2 \rangle 1$. LET: $U \in \mathcal{T}$

$\langle 2 \rangle 2$. $\Phi(U)(\{1\})$ is open.

PROOF: Since $\Phi(U)(\{1\}) = U$.

$\langle 1 \rangle 2$. Φ is injective.

PROOF: If $\Phi(U) = \Phi(V)$ then we have $\forall x(x \in U \Leftrightarrow \Phi(U)(x) = 1 \Leftrightarrow \Phi(V)(x) = 1 \Leftrightarrow x \in V)$.

$\langle 1 \rangle 3$. Φ is surjective.

PROOF: Given $f : X \rightarrow S$ continuous we have $\Phi(f^{-1}(1)) = f$.

□

15.0.1 Order Topology

Proposition 15.0.19. Let X and Y be linearly ordered sets under the order topology. Let $f : X \rightarrow Y$ be strictly monotone and surjective. Then f is a homeomorphism.

PROOF:

$\langle 1 \rangle 1$. f is continuous.

$\langle 2 \rangle 1$. For all $b \in Y$ we have $f^{-1}((b, +\infty))$ is open in X .

$\langle 3 \rangle 1$. LET: $b \in Y$

$\langle 3 \rangle 2$. LET: a be the element of X such that $f(a) = b$.

$\langle 3 \rangle 3$. $f^{-1}((b, +\infty)) = (a, +\infty)$

$\langle 2 \rangle 2$. For all $b \in Y$ we have $f^{-1}((-\infty, b))$ is open in X .

PROOF: Similar.

$\langle 1 \rangle 2$. f^{-1} is continuous.

PROOF: Similar.

□

Corollary 15.0.19.1. For n a positive integer, the n th root function $\overline{\mathbb{R}_+} \rightarrow \overline{\mathbb{R}_+}$ is continuous.

15.0.2 Paths

Definition 15.0.20 (Path). A *path* in a topological space X is a continuous function $[0, 1] \rightarrow X$.

Definition 15.0.21 (Constant Path). Let X be a topological space and $a \in X$. The *constant* path at a is the path $p : [0, 1] \rightarrow X$ with $p(t) = a$ for all $t \in [0, 1]$.

Definition 15.0.22 (Reverse Path). Let X be a topological space and $p : [0, 1] \rightarrow X$. The *reverse* of p is the path $q : [0, 1] \rightarrow X$ with $q(t) = p(1 - t)$ for all $t \in [0, 1]$.

Definition 15.0.23 (Concatenation). Let X be a topological space and $p, q : [0, 1] \rightarrow X$ be paths in X with $p(1) = q(0)$. The *concatenation* of p and q is the path $r : [0, 1] \rightarrow X$ with

$$r(t) = \begin{cases} p(2t) & \text{if } 0 \leq t \leq 1/2 \\ q(2t - 1) & \text{if } 1/2 \leq t \leq 1 \end{cases}$$

15.0.3 Loops

Definition 15.0.24 (Loop). A *loop* in a topological space X is a path $\alpha : [0, 1] \rightarrow X$ such that $\alpha(0) = \alpha(1)$.

15.1 Convergence

Definition 15.1.1 (Convergence). Let X be a topological space. Let (x_n) be a sequence in X . A point $a \in X$ is a *limit* of the sequence iff, for every neighbourhood U of a , there exists n_0 such that $\forall n \geq n_0, x_n \in U$.

Proposition 15.1.2. If $f : X \rightarrow Y$ is continuous and $x_n \rightarrow l$ in X then $f(x_n) \rightarrow f(l)$ in Y .

Example 15.1.3. The converse does not hold.

Let X be the set of all continuous functions $[0, 1] \rightarrow [-1, 1]$ under the product topology. Let $i : X \rightarrow L^2([0, 1])$ be the inclusion.

If $f_n \rightarrow f$ then $i(f_n) \rightarrow i(f)$ — Lebesgue convergence theorem.

We prove that i is not continuous.

Assume for a contradiction i is continuous. Choose a neighbourhood K of 0 in X such that $\forall \phi \in K, \int \phi^2 < 1/2$. Let $K = \prod_{\lambda \in [0, 1]} U_\lambda$ where $U_\lambda = [-1, 1]$ except for $\lambda = \lambda_1, \dots, \lambda_n$. Let ϕ be the function that is 0 at $\lambda_1, \dots, \lambda_n$ and 1 everywhere else. Then $\phi \in K$ but $\int \phi^2 = 1$.

Proposition 15.1.4. The converse does hold for first countable spaces. If $f : X \rightarrow Y$ where X is first countable, and Y is a topological space, and whenever $x_n \rightarrow x$ then $f(x_n) \rightarrow f(x)$, then f is continuous.

Proposition 15.1.5. If (s_n) is an increasing sequence of real numbers bounded above, then (s_n) converges.

PROOF:

⟨1⟩1. LET: s be the supremum of $\{s_n : n \in \mathbb{N}\}$.

PROVE: $s_n \rightarrow s$ as $n \rightarrow \infty$.

⟨1⟩2. LET: $\epsilon > 0$

⟨1⟩3. PICK N such that $s_N > s - \epsilon$.

⟨1⟩4. $\forall n \geq N. s - \epsilon \leq s_n \leq s$

⟨1⟩5. $\forall n \geq N. |s_n - s| < \epsilon$

□

15.1.1 Closure

Proposition 15.1.6. *Let X be a topological space. Let $A \subseteq X$. Let (a_n) be a sequence in A and $l \in X$. If $a_n \rightarrow l$ as $n \rightarrow \infty$, then $l \in \overline{A}$.*

PROOF:

⟨1⟩1. LET: U be a neighbourhood of l .

⟨1⟩2. PICK N such that $\forall n \in N. a_n \in U$

⟨1⟩3. $a_N \in A \cap U$

□

15.1.2 Continuous Functions

Proposition 15.1.7. *Let X and Y be topological spaces. Let $f : X \rightarrow Y$ be continuous. Let $x_n \rightarrow x$ as $n \rightarrow \infty$ in X . Then $f(x_n) \rightarrow f(x)$ as $n \rightarrow \infty$ in Y .*

PROOF:

⟨1⟩1. LET: V be a neighbourhood of $f(x)$.

⟨1⟩2. PICK N such that $\forall n \geq N. x_n \in f^{-1}(V)$

⟨1⟩3. $\forall n \geq N. f(x_n) \in V$

□

15.1.3 Infinite Series

Definition 15.1.8 (Series). Let (a_n) be a sequence of real numbers. We say that the infinite series $\sum_{n=0}^{\infty} a_n$ *converges* to s , and write

$$\sum_{n=0}^{\infty} a_n = s$$

iff $\sum_{n=0}^N a_n \rightarrow s$ as $N \rightarrow \infty$.

15.2 Strong Continuity

Definition 15.2.1 (Strong Continuity). Let X and Y be topological spaces. Let $f : X \rightarrow Y$. Then f is *strongly continuous* iff, for every $V \subseteq Y$, we have V is open in Y if and only if $f^{-1}(V)$ is open in X .

Proposition 15.2.2. *Let X and Y be topological spaces. Let $f : X \rightarrow Y$. Then f is strongly continuous if and only if, for all $C \subseteq Y$, we have C is closed in Y if and only if $f^{-1}(C)$ is closed in X .*

PROOF:

$$\begin{aligned} f \text{ is continuous} &\Leftrightarrow \forall V \subseteq Y (V \text{ is open in } Y \Leftrightarrow f^{-1}(V) \text{ is open in } X) \\ &\Leftrightarrow \forall C \subseteq Y (Y - C \text{ is open in } Y \Leftrightarrow f^{-1}(Y - C) \text{ is open in } X) \\ &\Leftrightarrow \forall C \subseteq Y (C \text{ is closed in } Y \Leftrightarrow f^{-1}(C) \text{ is closed in } X) \quad \square \end{aligned}$$

15.3 Subspaces

Definition 15.3.1 (Subspace). Let X be a topological space, Y a set, and $f : Y \rightarrow X$. The *subspace topology* on Y induced by f is $\mathcal{T} = \{f^{-1}(U) : U \text{ is open in } X\}$.

We prove this is a topology.

PROOF:

- $\langle 1 \rangle 1$. For all $\mathcal{U} \subseteq \mathcal{T}$ we have $\bigcup \mathcal{U} \in \mathcal{T}$
 PROOF: Since $\bigcup \mathcal{U} = f^{-1}(\bigcup \{V : f^{-1}(V) \in \mathcal{U}\})$.
 - $\langle 1 \rangle 2$. For all $U, V \in \mathcal{T}$ we have $U \cap V \in \mathcal{T}$
 PROOF: Since $f^{-1}(U) \cap f^{-1}(V) = f^{-1}(U \cap V)$.
 - $\langle 1 \rangle 3$. $Y \in \mathcal{T}$
 PROOF: Since $Y = f^{-1}(X)$.
-

Proposition 15.3.2. *Let X be a topological space, Y a set and $f : Y \rightarrow X$ a function. Then the subspace topology on Y is the coarsest topology such that f is continuous.*

PROOF: Immediate from definition. □

Proposition 15.3.3 (Local Formulation of Continuity). *Let X and Y be topological spaces. Let $f : X \rightarrow Y$. Let \mathcal{U} be a set of open subspaces of X such that $X = \bigcup \mathcal{U}$. If $f|_U : U \rightarrow Y$ is continuous for all $U \in \mathcal{U}$, then f is continuous.*

PROOF:

- $\langle 1 \rangle 1$. LET: $x \in X$
 PROVE: f is continuous at x .
 - $\langle 1 \rangle 2$. LET: V be a neighbourhood of $f(x)$.
 - $\langle 1 \rangle 3$. PICK $U \in \mathcal{U}$ such that $x \in U$.
 - $\langle 1 \rangle 4$. PICK W open in U such that $x \in W$ and $f(W) \subseteq V$.
 - $\langle 1 \rangle 5$. W is open in X .
-

Theorem 15.3.4. *Let X be a topological space and (Y, i) a subset of X . Then the subspace topology on Y is the unique topology such that, for every topological space Z and function $f : Z \rightarrow Y$, we have f is continuous if and only if $i \circ f : Z \rightarrow X$ is continuous.*

PROOF:

- ⟨1⟩1. If we give Y the subspace topology then, for every topological space Z and function $f : Z \rightarrow Y$, we have f is continuous if and only if $i \circ f$ is continuous.
- ⟨2⟩1. Given Y the subspace topology.
- ⟨2⟩2. LET: Z be a topological space.
- ⟨2⟩3. LET: $f : Z \rightarrow Y$
- ⟨2⟩4. If f is continuous then $i \circ f$ is continuous.
PROOF: Since i is continuous.
- ⟨2⟩5. If $i \circ f$ is continuous then f is continuous.
- ⟨3⟩1. ASSUME: $i \circ f$ is continuous.
- ⟨3⟩2. LET: U be open in Y .
- ⟨3⟩3. $f^{-1}(i^{-1}(i(U)))$ is open in Z .
- ⟨3⟩4. $f^{-1}(U)$ is open in Z .
- ⟨1⟩2. If, for every topological space Z and function $f : Z \rightarrow Y$, we have f is continuous if and only if $i \circ f$ is continuous.
- ⟨2⟩1. ASSUME: For every topological space Z and function $f : Z \rightarrow Y$, we have f is continuous if and only if $i \circ f$ is continuous.
- ⟨2⟩2. i is continuous.
- ⟨2⟩3. For every open set U in X , we have $i^{-1}(X)$ is open in Y
- ⟨2⟩4. LET: Z be the set Y under the subspace topology and $f : Z \rightarrow Y$ the identity function.
- ⟨2⟩5. $i \circ f$ is continuous.
- ⟨2⟩6. f is continuous.
- ⟨2⟩7. Every set open in Y is open in Z .

□

Proposition 15.3.5. *Let X be a topological space, Y a subspace of X and $U \subseteq Y$. If Y is open in X and U is open in Y then U is open in X .*

PROOF:

- ⟨1⟩1. PICK V open in X such that $U = V \cap Y$
- ⟨1⟩2. U is open in X .

PROOF: It is the intersection of two open sets in X .

□

Proposition 15.3.6. *Let X be a topological space. Let Y be a subspace of X . Let $C \subseteq Y$. If Y is closed in X and C is closed in Y then C is closed in X .*

PROOF: Similar. □

Proposition 15.3.7. *Let Y be a subspace of X and $A \subseteq Y$. Then the subspace topology on A as a subspace of Y is the same as the subspace topology on A as a subspace of X .*

PROOF:

- ⟨1⟩1. LET: \mathcal{T}_Y be the subspace topology on A as a subspace of Y .
- ⟨1⟩2. LET: \mathcal{T}_X be the subspace topology on A as a subspace of X .

- ⟨1⟩3. LET: $U \subseteq A$
 ⟨1⟩4. $U \in \mathcal{T}_Y \Leftrightarrow U \in \mathcal{T}_X$

PROOF:

$$\begin{aligned}
 U \in \mathcal{T}_Y &\Leftrightarrow \exists V \text{ open in } Y. U = V \cap A \\
 &\Leftrightarrow \exists V. \exists W \text{ open in } X. (V = Y \cap W \wedge U = V \cap A) \\
 &\Leftrightarrow \exists W \text{ open in } X. U = Y \cap W \cap A \\
 &\Leftrightarrow \exists W \text{ open in } X. U = W \cap A \\
 &\Leftrightarrow U \in \mathcal{T}_X
 \end{aligned}$$

□

Proposition 15.3.8. *Let X be a topological space. Let \mathcal{B} be a basis for the topology on X . Let $Y \subseteq X$. Then $\mathcal{B}' = \{B \cap Y : B \in \mathcal{B}\}$ is a basis for the topology on Y .*

PROOF:

- ⟨1⟩1. Every element of \mathcal{B}' is open.
 PROOF: For all $B \in \mathcal{B}$, we have B is open in X , so $B \cap Y$ is open in Y .
 ⟨1⟩2. For any open set V in Y and $y \in V$, there exists $B' \in \mathcal{B}'$ such that
 $y \in B' \subseteq V$
 ⟨2⟩1. LET: V be open in Y .
 ⟨2⟩2. LET: $y \in V$
 ⟨2⟩3. PICK U open in X such that $V = U \cap Y$.
 ⟨2⟩4. PICK $B \in \mathcal{B}$ such that $y \in B \subseteq U$
 ⟨2⟩5. $B \cap Y \in \mathcal{B}'$ and $y \in B \cap Y \subseteq V$

□

Proposition 15.3.9. *Let X be a topological space and Y a subspace of X . Let $A \subseteq Y$. If A is closed in Y and Y is closed in X then A is closed in X .*

PROOF:

- ⟨1⟩1. PICK C closed in X such that $A = C \cap Y$.
 ⟨1⟩2. A is closed in X .
 PROOF: It is the intersection of two closed sets in X .

□

15.3.1 Product Topology

Proposition 15.3.10. *Let $\{X_i\}_{i \in I}$ be a family of topological spaces. Let Y_i be a subspace of X_i for all $i \in I$. Then the product topology on $\prod_{i \in I} Y_i$ is the same as the subspace topology on $\prod_{i \in I} Y_i$ as a subspace of $\prod_{i \in I} X_i$.*

PROOF:

- ⟨1⟩1. Given $\prod_{i \in I} Y_i$ the subspace topology.
 ⟨1⟩2. LET: $\iota : \prod_{i \in I} Y_i$ be the inclusion.
 ⟨1⟩3. LET: Z be any topological space.
 ⟨1⟩4. LET: $f : Z \rightarrow \prod_{i \in I} Y_i$
 ⟨1⟩5. f is continuous if and only if, for all $i \in I$, we have $\pi_i \circ f$ is continuous.

PROOF:

f is continuous $\Leftrightarrow \iota \circ f : Z \rightarrow \prod_{i \in I} X_i$ is continuous (Theorem 15.3.4)

$\Leftrightarrow \forall i \in I. \pi_i \circ \iota \circ f : Z \rightarrow X_i$ is continuous (Theorem 15.8.4)

$\Leftrightarrow \forall i \in I. \iota_i \circ \pi_i \circ f : Z \rightarrow X_i$ is continuous

$\Leftrightarrow \forall i \in I. \pi_i \circ f : Z \rightarrow Y_i$ is continuous (Theorem 15.3.4)

where ι_i is the inclusion $Y_i \rightarrow X_i$.

□

15.4 Embedding

Definition 15.4.1 (Embedding). Let X and Y be topological spaces and $f : X \rightarrow Y$. Then f is an *embedding* iff f is injective and the topology on X is the subspace induced by f .

Proposition 15.4.2. *Every embedding is continuous.*

PROOF: Theorem 15.3.4. □

Proposition 15.4.3. *Let X and Y be topological spaces. Let $b \in Y$. The function $\kappa : X \rightarrow X \times Y$ that maps x to (x, b) is an embedding.*

PROOF:

⟨1⟩1. For all U open in X , we have $U = \kappa^{-1}(V)$ for some V open in $X \times Y$.

PROOF: Take $V = U \times Y$.

⟨1⟩2. For all V open in $X \times Y$ we have $\kappa^{-1}(V)$ is open in X .

PROOF: Since $\pi_1 \circ \kappa = \text{id}_X$ and $\pi_2 \circ \kappa$ (which is the constant function with value b) are both continuous, hence κ is continuous.

□

15.5 Open Maps

Definition 15.5.1 (Open Map). Let X and Y be topological spaces and $f : X \rightarrow Y$. Then f is an *open map* iff, for all U open in X , we have $f(U)$ is open in Y .

Proposition 15.5.2. *Let X and Y be topological spaces. The projections $\pi_1 : X \times Y \rightarrow X$ and $\pi_2 : X \times Y \rightarrow Y$ are open maps.*

PROOF:

⟨1⟩1. π_1 is an open map.

⟨2⟩1. LET: U be open in $X \times Y$.

⟨2⟩2. LET: $x \in \pi_1(U)$

⟨2⟩3. PICK y such that $(x, y) \in U$

⟨2⟩4. PICK V and W open in X and Y respectively such that $(x, y) \in V \times W \subseteq U$

- $\langle 2 \rangle 5.$ $x \in V \subseteq \pi_1(U)$
 $\langle 1 \rangle 2.$ π_2 is an open map.

PROOF: Similar.

□

15.5.1 Subspaces

Proposition 15.5.3. *Let X and Y be topological spaces. Let $p : X \rightarrow Y$ be an open map. Let A be an open set in X . Then $p \upharpoonright A : A \rightarrow p(A)$ is an open map.*

PROOF:

- $\langle 1 \rangle 1.$ LET: U be open in A .
 $\langle 1 \rangle 2.$ U is open in X .

PROOF: Proposition 15.3.5.

- $\langle 1 \rangle 3.$ $p(U)$ is open in Y .
 $\langle 1 \rangle 4.$ $p(U)$ is open in $p(A)$.

PROOF: Since $p(U) = p(U) \cap p(A)$.

□

15.6 Locally Finite

Definition 15.6.1 (Locally Finite). Let X be a topological space. Let $\{A_i\}_{i \in I}$ be a family of subsets of X . Then $\{A_i\}_{i \in I}$ is *locally finite* iff, for every $x \in X$, there exist only finitely many $i \in I$ such that $x \in A_i$.

Theorem 15.6.2 (Pasting Lemma). *Let X and Y be topological spaces. Let $f : X \rightarrow Y$. Let $\{A_i\}_{i \in I}$ be a locally finite family of closed subspaces of X such that $X = \bigcup_{i \in I} A_i$. If $f \upharpoonright A_i : A_i \rightarrow Y$ is continuous for all $i \in I$, then f is continuous.*

PROOF:

- $\langle 1 \rangle 1.$ LET: B be closed in Y .
 $\langle 1 \rangle 2.$ LET: $A = f^{-1}(B)$
 PROVE: A is closed in X .
 $\langle 1 \rangle 3.$ $A = \bigcup_{i \in I} f \upharpoonright A_i^{-1}(B)$
 $\langle 1 \rangle 4.$ LET: $x \in X - A$
 PROVE: There exists a neighbourhood U' of x such that $U' \subseteq X - A$.
 $\langle 1 \rangle 5.$ PICK a neighbourhood U of x such that U intersects A_i for only finitely many $i \in I$.
 $\langle 1 \rangle 6.$ LET: i_1, \dots, i_n be the elements of I such that U intersects A_{i_1}, \dots, A_{i_n} .
 $\langle 1 \rangle 7.$ For $j = 1, \dots, n$,
 LET: $S_j = f \upharpoonright A_{i_j}^{-1}(B)$
 $\langle 1 \rangle 8.$ For $j = 1, \dots, n$, we have S_j is closed in X .
 $\langle 1 \rangle 9.$ For $j = 1, \dots, n$, we have $x \notin S_j$.
 $\langle 1 \rangle 10.$ LET: $U' = U \cap \bigcap_{j=1}^n (X - S_j)$
 $\langle 1 \rangle 11.$ U' is a neighbourhood of x .

⟨1⟩12. $U' \subseteq X - A$

□

15.7 Closed Maps

Definition 15.7.1 (Closed Map). Let X and Y be topological spaces. Let $f : X \rightarrow Y$. Then f is a *closed map* iff, for every closed set C in X , we have $f(C)$ is closed in Y .

15.8 Product Topology

Definition 15.8.1 (Product Topology). Let $\{X_\lambda\}_{\lambda \in \Lambda}$ be a family of topological spaces. The *product topology* on $\prod_{\lambda \in \Lambda} X_\lambda$ is the coarsest topology such that every projection onto X_λ is continuous.

15.8.1 Closed Sets

Proposition 15.8.2. Let X and Y be topological spaces. Let A be a closed set in X and B a closed set in Y . Then $A \times B$ is closed in $X \times Y$.

PROOF: Since $(X \times Y) - (A \times B) = ((X - A) \times Y) \cup (X \times (Y - B))$. □

Proposition 15.8.3. Let $\{X_\alpha\}_{\alpha \in A}$ be a family of topological spaces. The product topology on $\prod_{\alpha \in A} X_\alpha$ is the topology generated by the basis $\mathcal{B} = \{\prod_{\alpha \in A} U_\alpha : \text{for all } \alpha \in A, U_\alpha \text{ is open in } X_\alpha \text{ and } U_\alpha = X_\alpha \text{ for all but finitely many } \alpha \in A\}$.

PROOF:

⟨1⟩1. \mathcal{B} is a basis for a topology.

⟨1⟩2. LET: \mathcal{T} be the topology generated by \mathcal{B} .

⟨1⟩3. LET: \mathcal{T}_p be the product topology.

⟨1⟩4. $\mathcal{T} \subseteq \mathcal{T}_p$

⟨2⟩1. LET: $B \in \mathcal{B}$

⟨2⟩2. LET: $B = \prod_{\alpha \in A} U_\alpha$ with each U_α open in X_α and $U_\alpha = X_\alpha$ except for $\alpha = \alpha_1, \dots, \alpha_n$

⟨2⟩3. $B = \pi_{\alpha_1}^{-1}(U_{\alpha_1}) \cap \dots \cap \pi_{\alpha_n}^{-1}(U_{\alpha_n})$

⟨2⟩4. $B \in \mathcal{T}_p$

⟨1⟩5. $\mathcal{T}_p \subseteq \mathcal{T}$

⟨2⟩1. For every $\alpha \in A$ we have π_α is continuous.

PROOF: Since $\pi^{-1}(U)$ is open for every U open in X_α .

□

Theorem 15.8.4. Let $\{X_\alpha\}_{\alpha \in A}$ be a family of topological spaces. Then the product topology on $\prod_{\alpha \in A} X_\alpha$ is the unique topology such that, for every topological space Z and function $f : Z \rightarrow \prod_{\alpha \in A} X_\alpha$, we have f is continuous if and only if, for all $\alpha \in A$, we have $\pi_\alpha \circ f : Z \rightarrow X_\alpha$ is continuous.

PROOF:

- (1)1. If we give $\prod_{\alpha \in A} X_\alpha$ the product topology, then for every topological space Z and function $f : Z \rightarrow \prod_{\alpha \in A} X_\alpha$, we have f is continuous if and only if, for all $\alpha \in A$, we have $\pi_\alpha \circ f$ is continuous.
 (2)1. Give $\prod_{\alpha \in A} X_\alpha$ the product topology.
 (2)2. LET: Z be a topological space.
 (2)3. LET: $f : Z \rightarrow \prod_{\alpha \in A} X_\alpha$
 (2)4. If f is continuous then, for all $\alpha \in A$, we have $\pi_\alpha \circ f$ is continuous.
 PROOF: Since the composite of two continuous functions is continuous.
 (2)5. If, for all $\alpha \in A$, we have $\pi_\alpha \circ f$ is continuous, then f is continuous.
 (3)1. ASSUME: For all $\alpha \in A$ we have $\pi_\alpha \circ f$ is continuous.
 (3)2. LET: $\{U_\alpha\}_{\alpha \in A}$ be a family with U_α open in X_α such that $U_\alpha = X_\alpha$ for all α except $\alpha = \alpha_1, \dots, \alpha_n$.
 (3)3. For all α we have $f^{-1}(\pi_\alpha^{-1}(U_\alpha))$ is open in Z .
 (3)4. $f^{-1}(\prod_\alpha U_\alpha)$ is open in Z
 PROOF: Since $f^{-1}(\prod_\alpha U_\alpha) = f^{-1}(\pi_{\alpha_1}^{-1}(U_{\alpha_1})) \cap \dots \cap f^{-1}(\pi_{\alpha_n}^{-1}(U_{\alpha_n}))$.
 (1)2. If \mathcal{T} is a topology on $\prod_{\alpha \in A} X_\alpha$ such that, for every topological space Z and function $f : Z \rightarrow \prod_{\alpha \in A} X_\alpha$, we have f is continuous if and only if, for all $\alpha \in A$, we have $\pi_\alpha \circ f$ is continuous, then \mathcal{T} is the product topology.
 (2)1. ASSUME: \mathcal{T} is a topology on $\prod_{\alpha \in A} X_\alpha$ such that, for every topological space Z and function $f : Z \rightarrow \prod_{\alpha \in A} X_\alpha$, we have f is continuous if and only if, for all $\alpha \in A$, we have $\pi_\alpha \circ f$ is continuous.
 (2)2. LET: \mathcal{T}_p be the product topology.
 (2)3. $\mathcal{T} \subseteq \mathcal{T}_p$
 (3)1. LET: $Z = (\prod_\alpha X_\alpha, \mathcal{T}_p)$
 (3)2. LET: $f : Z \rightarrow \prod_\alpha X_\alpha$ be the identity function
 (3)3. For all α we have $\pi_\alpha \circ f$ is continuous.
 (3)4. f is continuous.
 PROOF: (2)1
 (3)5. Every set open in \mathcal{T} is open in \mathcal{T}_p
 (2)4. $\mathcal{T}_p \subseteq \mathcal{T}$
 (3)1. $\text{id}_{\prod_\alpha X_\alpha}$ is continuous.
 (3)2. For all α we have π_α is continuous.
 PROOF: (2)1
 (3)3. $\mathcal{T}_p \subseteq \mathcal{T}$
 PROOF: Since \mathcal{T}_p is the coarsest topology such that every π_α is continuous.

□

Example 15.8.5. It is not true that, for any function $f : \prod_{\alpha \in A} X_\alpha \rightarrow Y$, if f is continuous in every variable separately then f is continuous.

Define $f : \mathbb{R}^2 \rightarrow \mathbb{R}$ by

$$f(x, y) = \begin{cases} \frac{xy}{x^2+y^2} & \text{if } (x, y) \neq (0, 0) \\ 0 & \text{if } x = y = 0 \end{cases}$$

Then f is continuous in x and in y , but is not continuous.

Proposition 15.8.6. *Let $\{X_i\}_{i \in I}$ be a nonempty family of topological spaces. The product topology on $\prod_{i \in I} X_i$ is the topology generated by the subbasis $\{\pi_i^{-1}(U) : i \in I, U \text{ is open in } X_i\}$.*

PROOF:

$\langle 1 \rangle 1.$ $\{\pi_i^{-1}(U) : i \in I, U \text{ is open in } X_i\}$ is a subbasis for a topology on $\prod_{i \in I} X_i$.

$\langle 2 \rangle 1.$ PICK $i_0 \in I$

$\langle 2 \rangle 2.$ $\prod_{i \in I} X_i = \pi_{i_0}^{-1}(X_{i_0})$

$\langle 1 \rangle 2.$ The topology generated by this subbasis is the product topology.

PROOF: Since the basis in Proposition 15.8.3 is the set of all finite intersections of elements of this subbasis.

□

15.8.2 Closure

Proposition 15.8.7. *Let $\{X_i\}_{i \in I}$ be a family of topological spaces. Let $A_i \subseteq X_i$ for all $i \in I$. Then*

$$\prod_{i \in I} \overline{A_i} = \overline{\prod_{i \in I} A_i}.$$

PROOF:

$\langle 1 \rangle 1.$ $\prod_{i \in I} \overline{A_i} \subseteq \overline{\prod_{i \in I} A_i}$

$\langle 2 \rangle 1.$ LET: $x \in \prod_{i \in I} \overline{A_i}$

$\langle 2 \rangle 2.$ For any family $\{U_i\}_{i \in I}$ where each U_i is open in X_i , and $U_i = X_i$ for all but finitely many $i \in I$, if $x \in \prod_{i \in I} U_i$ then $\prod_{i \in I} U_i$ intersects $\prod_{i \in I} A_i$.

$\langle 3 \rangle 1.$ LET: $\{U_i\}_{i \in I}$ be a family where each U_i is open in X_i , and $U_i = X_i$ for all but finitely many i .

$\langle 3 \rangle 2.$ ASSUME: $x \in \prod_{i \in I} \overline{A_i}$

$\langle 3 \rangle 3.$ For all $i \in I$ we have U_i intersects A_i

PROOF: Since $\pi_i(x) \in \overline{A_i}$ and U_i is a neighbourhood of $\pi_i(x)$.

$\langle 3 \rangle 4.$ $\prod_{i \in I} U_i$ intersects $\prod_{i \in I} A_i$

$\langle 2 \rangle 3.$ $x \in \prod_{i \in I} \overline{A_i}$

PROOF: Proposition 14.13.9.

$\langle 1 \rangle 2.$ $\overline{\prod_{i \in I} A_i} \subseteq \prod_{i \in I} \overline{A_i}$

$\langle 2 \rangle 1.$ LET: $x \in \overline{\prod_{i \in I} A_i}$

$\langle 2 \rangle 2.$ LET: $i \in I$

PROVE: $\pi_i(x) \in \overline{A_i}$

$\langle 2 \rangle 3.$ LET: U be a neighbourhood of $\pi_i(x)$ in X_i

$\langle 2 \rangle 4.$ $\pi_i^{-1}(U)$ is a neighbourhood of x in $\prod_{i \in I} X_i$

$\langle 2 \rangle 5.$ PICK $y \in \pi_i^{-1}(U) \cap \prod_{i \in I} A_i$

$\langle 2 \rangle 6.$ $\pi_i(y) \in U \cap A_i$

□

15.8.3 Convergence

Proposition 15.8.8. *Let $\{X_i\}_{i \in I}$ be a family of topological spaces. Let (x_n) be a sequence of points in $\prod_{i \in I} X_i$ and $l \in \prod_{i \in I} X_i$. Then $x_n \rightarrow l$ as $n \rightarrow \infty$ if and*

only if, for all $i \in I$, we have $\pi_i(x_n) \rightarrow \pi_i(l)$ as $n \rightarrow \infty$.

PROOF:

$\langle 1 \rangle 1$. If $x_n \rightarrow l$ as $n \rightarrow \infty$ then, for all $i \in I$, we have $\pi_i(x_n) \rightarrow \pi_i(l)$ as $n \rightarrow \infty$.

PROOF: Proposition 15.1.2.

$\langle 1 \rangle 2$. If, for all $i \in I$, we have $\pi_i(x_n) \rightarrow \pi_i(l)$ as $n \rightarrow \infty$, then $x_n \rightarrow l$ as $n \rightarrow \infty$.

$\langle 2 \rangle 1$. ASSUME: For all $i \in I$ we have $\pi_i(x_n) \rightarrow \pi_i(l)$ as $n \rightarrow \infty$.

$\langle 2 \rangle 2$. LET: U be a neighbourhood of l .

$\langle 2 \rangle 3$. PICK $i_1, \dots, i_n \in I$ and open sets U_j in X_{i_j} for $j = 1, \dots, n$ such that $l \in \pi_{i_1}^{-1}(U_1) \cap \dots \cap \pi_{i_n}^{-1}(U_n) \subseteq U$

$\langle 2 \rangle 4$. For $j = 1, \dots, n$ we have $\pi_{i_j}(l) \in U_j$

$\langle 2 \rangle 5$. PICK N such that, for all $m \geq N$, we have $\pi_{i_j}(x_m) \in U_j$

$\langle 2 \rangle 6$. $\forall m \geq N. x_m \in U$

□

15.9 Topological Disjoint Union

Definition 15.9.1 (Coproduct Topology). Let $\{X_\alpha\}_{\alpha \in A}$ be a family of topological spaces. The *coproduct topology* on $\coprod_{\alpha \in A} X_\alpha$ is

$$\mathcal{T} = \left\{ \coprod_{\alpha \in A} U_\alpha : \{U_\alpha\}_{\alpha \in A} \text{ is a family with } U_\alpha \text{ open in } X_\alpha \text{ for all } \alpha \right\}.$$

We prove this is a topology.

PROOF:

$\langle 1 \rangle 1$. For all $\mathcal{U} \subseteq \mathcal{T}$ we have $\bigcup \mathcal{U} \in \mathcal{T}$

PROOF:

$$\bigcup_{i \in I} \coprod_{\alpha \in A} U_{i\alpha} = \coprod_{\alpha \in A} \bigcup_{i \in I} U_{i\alpha}$$

$\langle 1 \rangle 2$. For all $U, V \in \mathcal{T}$ we have $U \cap V \in \mathcal{T}$

PROOF:

$$\coprod_{\alpha \in A} U_\alpha \cap \coprod_{\alpha \in A} V_\alpha = \coprod_{\alpha \in A} (U_\alpha \cap V_\alpha)$$

$\langle 1 \rangle 3$. $\coprod_{\alpha \in A} X_\alpha \in \mathcal{T}$

PROOF: Since every X_α is open in X_α .

□

Proposition 15.9.2. The coproduct topology is the finest topology on $\coprod_{\alpha \in A} X_\alpha$ such that every injection $\kappa_\alpha : X_\alpha \rightarrow \coprod_{\alpha \in A} X_\alpha$ is continuous.

PROOF:

$\langle 1 \rangle 1$. LET: $P = \coprod_{\alpha \in A} X_\alpha$

$\langle 1 \rangle 2$. LET: \mathcal{T}_c be the coproduct topology.

$\langle 1 \rangle 3$. LET: \mathcal{T} be any topology on P

$\langle 1 \rangle 4$. For all $\alpha \in A$, the injection $\kappa_\alpha : X_\alpha \rightarrow (P, \mathcal{T}_c)$ is continuous.

- ⟨2⟩1. LET: $\alpha \in A$
 - ⟨2⟩2. LET: $\{U_\alpha\}_{\alpha \in A}$ be a family with each U_α open in X_α .
 - ⟨2⟩3. For all $\alpha \in A$, we have $\kappa_\alpha^{-1}(\coprod_{\alpha \in A} U_\alpha)$ is open in X_α .
 PROOF: Since $\kappa_\alpha^{-1}(\coprod_{\alpha \in A} U_\alpha) = U_\alpha$.
 - ⟨1⟩5. If, for all $\alpha \in A$, the injection $\kappa_\alpha : X_\alpha \rightarrow (P, \mathcal{T})$ is continuous, then $\mathcal{T} \subseteq \mathcal{T}_c$.
 - ⟨2⟩1. ASSUME: For all $\alpha \in A$, the injection $\kappa_\alpha : X_\alpha \rightarrow (P, \mathcal{T})$ is continuous.
 - ⟨2⟩2. LET: $U \in \mathcal{T}$
 - ⟨2⟩3. For all $\alpha \in A$, we have $\kappa_\alpha^{-1}(U)$ is open in X_α .
 - ⟨2⟩4. $U = \coprod_{\alpha \in A} \kappa_\alpha^{-1}(U) \in \mathcal{T}_c$
-

Theorem 15.9.3. *Let $\{X_\alpha\}_{\alpha \in A}$ be a family of topological spaces. The coproduct topology is the unique topology on $\coprod_{\alpha \in A} X_\alpha$ such that, for every topological space Z and function $f : \coprod_{\alpha \in A} X_\alpha \rightarrow Z$, we have f is continuous if and only if $\forall \alpha \in A, f \circ \kappa_\alpha$ is continuous.*

PROOF:

- ⟨1⟩1. LET: $X = \coprod_{\alpha \in A} X_\alpha$
- ⟨1⟩2. LET: \mathcal{T}_c be the coproduct topology.
- ⟨1⟩3. For every topological space Z and function $f : (X, \mathcal{T}_c) \rightarrow Z$, we have f is continuous if and only if $\forall \alpha \in A, f \circ \kappa_\alpha$ is continuous.
- ⟨2⟩1. LET: Z be a topological space.
- ⟨2⟩2. LET: $f : X \rightarrow Z$
- ⟨2⟩3. If f is continuous then $\forall \alpha \in A, f \circ \kappa_\alpha$ is continuous.
 PROOF: Because the composite of two continuous functions is continuous.
- ⟨2⟩4. If $\forall \alpha \in A, f \circ \kappa_\alpha$ is continuous then f is continuous.
 - ⟨3⟩1. ASSUME: $\forall \alpha \in A, f \circ \kappa_\alpha$ is continuous.
 - ⟨3⟩2. LET: U be open in Z
 - ⟨3⟩3. For all $\alpha \in A$ we have $\kappa_\alpha^{-1}(f^{-1}(U))$ is open in X_α
 - ⟨3⟩4. $f^{-1}(U) = \coprod_{\alpha \in A} \kappa_\alpha^{-1}(f^{-1}(U))$
 - ⟨3⟩5. $f^{-1}(U)$ is open in X
- ⟨1⟩4. For any topology \mathcal{T} on X , if for every topological space Z and function $f : (X, \mathcal{T}) \rightarrow Z$, we have f is continuous if and only if $\forall \alpha \in A, f \circ \kappa_\alpha$ is continuous, then $\mathcal{T} = \mathcal{T}_c$.
- ⟨2⟩1. LET: \mathcal{T} be a topology on X .
- ⟨2⟩2. ASSUME: For every topological space Z and function $f : (X, \mathcal{T}) \rightarrow Z$, we have f is continuous if and only if $\forall \alpha \in A, f \circ \kappa_\alpha$ is continuous.
- ⟨2⟩3. $\mathcal{T} \subseteq \mathcal{T}_c$
 - ⟨3⟩1. For all $\alpha \in A$ we have $\kappa_\alpha : X_\alpha \rightarrow (X, \mathcal{T})$ is continuous.
 PROOF: From ⟨2⟩1 since id_X is continuous.
 - ⟨3⟩2. $\mathcal{T} \subseteq \mathcal{T}_c$
 PROOF: Proposition 15.9.2.
- ⟨2⟩4. $\mathcal{T}_c \subseteq \mathcal{T}$
 - ⟨3⟩1. LET: $f : (X, \mathcal{T}) \rightarrow (X, \mathcal{T}_c)$ be the identity function.
 - ⟨3⟩2. $f \circ \kappa_\alpha$ is continuous for all α .

⟨3⟩3. f is continuous.

PROOF: ⟨2⟩1

⟨3⟩4. $\mathcal{T}_c \subseteq \mathcal{T}$

□

15.10 Quotient Spaces

Definition 15.10.1 (Quotient Topology). Let X be a topological space, S a set, and $\pi : X \twoheadrightarrow S$ be a surjection. The *quotient topology* on S induced by π is $\mathcal{T} = \{U \in \mathcal{P}S : \pi^{-1}(U) \text{ is open in } X\}$.

We prove this is a topology.

PROOF:

⟨1⟩1. For all $\mathcal{U} \subseteq \mathcal{T}$ we have $\bigcup \mathcal{U} \in \mathcal{T}$.

PROOF: Since $\pi^{-1}(\bigcup \mathcal{U}) = \bigcup \{\pi^{-1}(U) : U \in \mathcal{U}\}$.

⟨1⟩2. For all $U, V \in \mathcal{T}$ we have $U \cap V \in \mathcal{T}$.

PROOF: Since $\pi^{-1}(U \cap V) = \pi^{-1}(U) \cap \pi^{-1}(V)$.

⟨1⟩3. $X \in \mathcal{T}$

PROOF: Since $X = \pi^{-1}(Y)$.

□

Proposition 15.10.2. *Let X be a topological space, S a set and $\pi : X \twoheadrightarrow S$ a surjection. Then the quotient topology on S is the finest topology such that π is continuous.*

PROOF: Immediate from definitions. □

Theorem 15.10.3. *Let X be a topological space, let S be a set, and let $\pi : X \twoheadrightarrow S$ be surjective. Then the quotient topology on S is the unique topology such that, for every topological space Z and function $f : S \rightarrow Z$, we have f is continuous if and only if $f \circ \pi$ is continuous.*

PROOF:

⟨1⟩1. If S is given the quotient topology, then for every topological space Z and function $f : S \rightarrow Z$, we have f is continuous if and only if $f \circ \pi$ is continuous.

⟨2⟩1. Give S the quotient topology.

⟨2⟩2. LET: Z be a topological space.

⟨2⟩3. LET: $f : S \rightarrow Z$

⟨2⟩4. If f is continuous then $f \circ \pi$ is continuous.

PROOF: The composite of two continuous functions is continuous.

⟨2⟩5. If $f \circ \pi$ is continuous then f is continuous.

⟨3⟩1. ASSUME: $f \circ \pi$ is continuous.

⟨3⟩2. LET: U be open in Z .

⟨3⟩3. $\pi^{-1}(f^{-1}(U))$ is open in X .

⟨3⟩4. $f^{-1}(U)$ is open in S .

- $\langle 1 \rangle 2$. If S is given a topology such that, for every topological space Z and function $f : S \rightarrow Z$, we have f is continuous if and only if $f \circ \pi$ is continuous, then that topology is the quotient topology.
 $\langle 2 \rangle 1$. Give S a topology such that, for every topological space Z and function $f : S \rightarrow Z$, we have f is continuous if and only if $f \circ \pi$ is continuous.
 $\langle 2 \rangle 2$. LET: $U \subseteq S$
 $\langle 2 \rangle 3$. If $\pi^{-1}(U)$ is open in X then U is open in S .
 $\langle 3 \rangle 1$. LET: Z be S under the quotient topology induced by π .
 $\langle 3 \rangle 2$. LET: $f : S \rightarrow Z$ be the identity function.
 $\langle 3 \rangle 3$. $f \circ \pi$ is continuous.
 $\langle 3 \rangle 4$. f is continuous.
PROOF: $\langle 2 \rangle 1$
 $\langle 3 \rangle 5$. U is open in Z .
 $\langle 3 \rangle 6$. U is open in X .
 $\langle 2 \rangle 4$. If U is open in S then $\pi^{-1}(U)$ is open in X .
PROOF: Since π is continuous (taking $Z = S$ and $f = \text{id}_S$ in $\langle 2 \rangle 1$).

□

15.10.1 Quotient Maps

Definition 15.10.4 (Quotient Map). Let X and S be topological spaces and $\pi : X \rightarrow S$. Then π is a *quotient map* iff π is surjective and the topology on S is the quotient topology induced by π .

Proposition 15.10.5. Let X and Y be topological spaces. Let $f : X \rightarrow Y$. Then f is a quotient map if and only if f is surjective and strongly continuous.

PROOF: Immediate from definition. □

Proposition 15.10.6. Let X and Y be topological spaces. Let $p : X \rightarrow Y$ be surjective. Then the following are equivalent.

1. p is a quotient map.
2. p is continuous and maps saturated open sets to open sets.
3. p is continuous and maps saturated closed sets to closed sets.

PROOF:

- $\langle 1 \rangle 1$. $1 \Rightarrow 2$
 $\langle 2 \rangle 1$. ASSUME: p is a quotient map.
 $\langle 2 \rangle 2$. p is continuous.
 $\langle 2 \rangle 3$. p maps saturated open sets to open sets.
 $\langle 3 \rangle 1$. LET: $U \subseteq X$ be a saturated open set.
 $\langle 3 \rangle 2$. $p^{-1}(p(U)) = U$
 $\langle 3 \rangle 3$. $p^{-1}(p(U))$ is open in X .
 $\langle 3 \rangle 4$. $p(U)$ is open in Y .
 $\langle 1 \rangle 2$. $2 \Rightarrow 3$

- ⟨2⟩1. ASSUME: p is continuous and maps saturated open sets to open sets.
- ⟨2⟩2. LET: C be a saturated closed set in X .
- ⟨2⟩3. $X - C$ is a saturated open set.
- ⟨2⟩4. $Y - p(C)$ is open.
- ⟨2⟩5. $p(C)$ is closed.
- ⟨1⟩3. $3 \Rightarrow 1$
- ⟨2⟩1. ASSUME: p is continuous and maps closed sets to closed sets.
- ⟨2⟩2. LET: $C \subseteq Y$
- ⟨2⟩3. ASSUME: $p^{-1}(C)$ is closed in X .
PROVE: C is closed in Y .
- ⟨2⟩4. $p^{-1}(C)$ is saturated.
- ⟨2⟩5. $p(p^{-1}(C))$ is closed.
- ⟨2⟩6. C is closed.

□

Corollary 15.10.6.1. *Let X and Y be topological spaces. Let $p : X \rightarrow Y$ be continuous and surjective. If p is either an open map or a closed map, then p is a quotient map.*

Example 15.10.7. The converse does not hold.

Let $A = \{(x, y) \in \mathbb{R}^2 : x \geq 0 \vee y = 0\}$. Then the first projection $\pi_1 : A \rightarrow \mathbb{R}$ is a quotient map that is neither an open map nor a closed map.

PROOF:

- ⟨1⟩1. π_1 is a quotient map.
- ⟨2⟩1. LET: $U \subseteq \mathbb{R}$
- ⟨2⟩2. If U is open then $\pi_1^{-1}(U)$ is open.
PROOF: Since $\pi_1^{-1}(U) = (U \times \mathbb{R}) \cap A$.
- ⟨2⟩3. If $\pi_1^{-1}(U)$ is open then U is open.
- ⟨3⟩1. ASSUME: $\pi_1^{-1}(U)$ is open.
- ⟨3⟩2. LET: $x \in U$
- ⟨3⟩3. $(x, 0) \in \pi_1^{-1}(U)$
- ⟨3⟩4. PICK open neighbourhoods V of x and W of 0 such that $V \times W \subseteq \pi_1^{-1}(U)$
- ⟨3⟩5. $V \subseteq U$
PROOF: For all $x' \in V$ we have $(x', 0) \in V \times W \subseteq \pi_1^{-1}(U)$.
- ⟨1⟩2. π_1 is not an open map.
PROOF: $\pi_1(((-1, 1) \times (1, 2)) \cap A) = [0, 1)$ which is not open in \mathbb{R} .
- ⟨1⟩3. π_1 is not a closed map.
PROOF: $\pi_1(\{(x, 1/x) \in \mathbb{R}^2 : x > 0\}) = (0, +\infty)$ is not closed in \mathbb{R} .

□

Corollary 15.10.7.1. *Let $\{X_i\}_{i \in I}$ and $\{Y_i\}_{i \in I}$ be families of topological spaces and $p_i : X_i \rightarrow Y_i$ for all $i \in I$.*

- 1. *If every p_i is an open quotient map, then $\prod_{i \in I} p_i : \prod_{i \in I} X_i \rightarrow \prod_{i \in I} Y_i$ is an open quotient map.*

2. If every p_i is a closed quotient map, then $\prod_{i \in I} p_i : \prod_{i \in I} X_i \twoheadrightarrow \prod_{i \in I} Y_i$ is a closed quotient map.

Example 15.10.8. The product of two quotient maps is not necessarily a quotient map.

Let Y be the quotient space of \mathbb{R}_K obtained by collapsing the set K to a point. Let $p : \mathbb{R}_K \twoheadrightarrow Y$ be the quotient map. Then $q \times q : \mathbb{R}_K^2 \rightarrow Y^2$ is not a quotient map.

PROOF:

$\langle 1 \rangle 1$. LET: $\Delta = \{(y, y) : y \in Y\}$

$\langle 1 \rangle 2$. Y is not Hausdorff.

$\langle 2 \rangle 1$. LET: $*_K \in Y$ be the point such that $q(K) = \{*_K\}$

$\langle 2 \rangle 2$. ASSUME: for a contradiction U and V are disjoint neighbourhoods of 0 and $*_K$

$\langle 2 \rangle 3$. $q^{-1}(U)$ and $q^{-1}(V)$ are disjoint open sets with $0 \in q^{-1}(U)$ and $K \subseteq q^{-1}(V)$

$\langle 2 \rangle 4$. Q.E.D.

PROOF: This is a contradiction.

$\langle 1 \rangle 3$. Δ is not closed in Y^2 .

$\langle 1 \rangle 4$. $(q \times q)^{-1}(\Delta)$ is closed in \mathbb{R}_K^2 .

PROOF: It is $\{(x, x) : x \in \mathbb{R}\} \cup K^2$.

□

Proposition 15.10.9. Let $\pi : X \twoheadrightarrow S$ be a quotient map. Let Z be a topological space. Let $f : X \rightarrow Z$ be continuous. Then there exists a continuous map $g : S \rightarrow Z$ such that $f = g \circ \pi$ if and only if, for all $s \in S$, we have f is constant on $\pi^{-1}(s)$.

PROOF: From Theorem 15.10.3. □

Proposition 15.10.10. Let Z be a topological space. Define $\pi : [0, 1] \rightarrow S^1$ by $\pi(t) = (\cos 2\pi t, \sin 2\pi t)$. Given any continuous function $f : S^1 \rightarrow Z$, we have $f \circ \pi$ is a loop in Z . This defines a bijection between $\mathbf{Top}[S^1, Z]$ and the set of loops in Z .

PROOF: Since π is a quotient map. □

Definition 15.10.11 (Projective Space). The *projective space* \mathbb{RP}^n is the quotient of $\mathbb{R}^{n+1} - \{0\}$ by \sim where $x \sim \lambda x$ for all $x \in \mathbb{R}^{n+1} - \{0\}$ and $\lambda \in \mathbb{R}$.

Definition 15.10.12 (Torus). The *torus* T is the quotient of $[0, 1]^2$ by \sim where $(x, 0) \sim (x, 1)$ and $(0, y) \sim (1, y)$.

Definition 15.10.13 (Möbius Band). The *Möbius band* is the quotient of $[0, 1]^2$ by \sim where $(0, y) \sim (1, 1 - y)$.

Definition 15.10.14 (Klein Bottle). The *Klein bottle* is the quotient of $[0, 1]^2$ by \sim where $(x, 0) \sim (x, 1)$ and $(0, y) \sim (1, 1 - y)$.

Proposition 15.10.15. \mathbb{RP}^2 is the quotient of $[0, 1]^2$ by \sim where $(x, 0) \sim (1 - x, 1)$ and $(0, y) \sim (1, 1 - y)$.

PROOF: TODO

Example 15.10.16. Let $\{X_i\}_{i \in I}$ be a family of topological spaces and $\{Y_i\}_{i \in I}$ a family of sets. Let $q_i : X_i \twoheadrightarrow Y_i$ be a surjective function for all $i \in I$. Give each Y_i the quotient topology. It is not true in general that the product topology on $\prod_{i \in I} Y_i$ is the same as the quotient topology induced by $\prod_{i \in I} q_i : \prod_{i \in I} X_i \twoheadrightarrow \prod_{i \in I} Y_i$.

PROOF:

$\langle 1 \rangle 1$. LET: $X^* = \mathbb{R} - \mathbb{Z}_+ + \{b\}$ be the quotient space obtained from \mathbb{R} by identifying the subset \mathbb{Z}_+ to the point b .

$\langle 1 \rangle 2$. LET: $p : \mathbb{R} \rightarrow X^*$ be the quotient map.

PROVE: $p \times \text{id}_{\mathbb{Q}} : \mathbb{R} \times \mathbb{Q} \rightarrow X^* \times \mathbb{Q}$ is not a quotient map.

$\langle 1 \rangle 3$. For $n \in \mathbb{Z}_+$,

LET: $c_n = \sqrt{2}/n$

$\langle 1 \rangle 4$. For $n \in \mathbb{Z}_+$,

LET: $U_n = \{(x, y) \in \mathbb{Q} \times \mathbb{R} : n - 1/4 < x < n + 1/4 \text{ and } ((y > x + c_n - n \text{ and } y > -x + c_n + n) \text{ or } (y < x + c_n - n \text{ and } y < -x + c_n + n))\}$

$\langle 1 \rangle 5$. For all $n \in \mathbb{Z}_+$, U_n is open in $\mathbb{R} \times \mathbb{Q}$

$\langle 1 \rangle 6$. For all $n \in \mathbb{Z}_+$ we have $\{n\} \times \mathbb{Q} \subseteq U_n$

$\langle 1 \rangle 7$. LET: $U = \bigcup_{n \in \mathbb{Z}_+} U_n$

$\langle 1 \rangle 8$. U is open in $\mathbb{R} \times \mathbb{Q}$.

$\langle 1 \rangle 9$. U is saturated with respect to $p \times \text{id}_{\mathbb{Q}}$.

$\langle 1 \rangle 10$. LET: $U' = (p \times \text{id}_{\mathbb{Q}})(U)$

$\langle 1 \rangle 11$. ASSUME: for a contradiction U' is open in $X^* \times \mathbb{Q}$.

Proposition 15.10.17. 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 15.10.18. 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 15.10.19. 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 15.10.20 (Cone). Let X be a topological space. The cone over X is the space $(X \times [0, 1])/(X \times \{1\})$.

Definition 15.10.21 (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 15.10.22 (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 15.10.23 (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 15.10.24. $D^n/S^{n-1} \cong S^n$

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.

□

15.11 Box Topology

Definition 15.11.1 (Box Topology). Let $\{X_i\}_{i \in I}$ be a family of topological spaces. The *box topology* on $X = \prod_{i \in I} X_i$ is the topology generated by the basis $\mathcal{B} = \{\prod_{i \in I} U_i : \{U_i\}_{i \in I} \text{ is a family with each } U_i \text{ an open set in } X_i\}$.

We prove this is a basis for a topology.

PROOF:

$\langle 1 \rangle 1$. $\bigcup \mathcal{B} = X$

PROOF: Since $\prod_{i \in I} X_i \in \mathcal{B}$.

$\langle 1 \rangle 2$. For all $B_1, B_2 \in \mathcal{B}$ and $x \in B_1 \cap B_2$, there exists $B_3 \in \mathcal{B}$ such that $x \in B_3 \subseteq B_1 \cap B_2$.

$\langle 2 \rangle 1$. LET: $B_1, B_2 \in \mathcal{B}$

$\langle 2 \rangle 2$. LET: $x \in B_1 \cap B_2$

$\langle 2 \rangle 3$. PICK a family $\{U_i\}_{i \in I}$ such that $B_1 = \prod_{i \in I} U_i$.

$\langle 2 \rangle 4$. PICK a family $\{V_i\}_{i \in I}$ such that $B_2 = \prod_{i \in I} V_i$.

$\langle 2 \rangle 5$. LET: $B_3 = \prod_{i \in I} (U_i \cap V_i)$

$\langle 2 \rangle 6$. $x \in B_3 \subseteq B_1 \cap B_2$

□

Proposition 15.11.2. *The box topology is finer than the product topology.*

PROOF: Immediate from definitions. □

Proposition 15.11.3. *On a finite family of topological spaces, the box topology and the product topology are the same.*

PROOF: Immediate from definitions. □

Proposition 15.11.4. *The box topology is strictly finer than the product topology on the Hilbert cube.*

PROOF: The set $\prod_{n=0}^{\infty} (0, 1/(n+1)^2)$ is open in the box topology but not in the product topology. □

15.11.1 Bases

Proposition 15.11.5. *Let $\{X_i\}_{i \in I}$ be a family of topological spaces. For all $i \in I$, let \mathcal{B}_i be a basis for the topology on X_i . Then $\mathcal{B} = \{\prod_{i \in I} B_i : \forall i \in I, B_i \in \mathcal{B}_i\}$ is a basis for the box topology on $\prod_{i \in I} X_i$.*

PROOF:

$\langle 1 \rangle 1$. For every family $\{B_i\}_{i \in I}$ where $\forall i \in I, B_i \in \mathcal{B}_i$, we have $\prod_{i \in I} B_i$ is open in the box topology.

PROOF: Since each B_i is open in X_i .

$\langle 1 \rangle 2$. For any open set U in the box topology and $x \in U$, there exists $B \in \mathcal{B}$ such that $x \in B \subseteq U$.

$\langle 2 \rangle 1$. LET: U be a set open in the box topology.

$\langle 2 \rangle 2$. LET: $x \in U$

$\langle 2 \rangle 3$. PICK a family $\{U_i\}_{i \in I}$ where each U_i is open in X_i such that $x \in \prod_{i \in I} U_i \subseteq U$

$\langle 2 \rangle 4$. For $i \in I$, choose $B_i \in \mathcal{B}_i$ such that $x_i \in B_i \subseteq U_i$.

$\langle 2 \rangle 5$. $\prod_{i \in I} B_i \in \mathcal{B}$

$\langle 2 \rangle 6$. $x \in \prod_{i \in I} B_i \subseteq \prod_{i \in I} U_i \subseteq U$

□

15.11.2 Subspaces

Proposition 15.11.6. *Let $\{X_i\}_{i \in I}$ be a family of topological spaces. Let Y_i be a subspace of X_i for all $i \in I$. Then the box topology on $\prod_{i \in I} Y_i$ is the same as the subspace topology that $\prod_{i \in I} Y_i$ inherits as a subspace of $\prod_{i \in I} X_i$ under the box topology.*

PROOF: A basis for the box topology is

$$\begin{aligned} & \left\{ \prod_{i \in I} V_i : V_i \text{ open in } Y_i \right\} \\ &= \left\{ \prod_{i \in I} (U_i \cap Y_i) : U_i \text{ open in } X_i \right\} \\ &= \left\{ \prod_{i \in I} U_i \cap \prod_{i \in I} Y_i : U_i \text{ open in } X_i \right\} \end{aligned}$$

which is a basis for the subspace topology by Proposition 14.7.13. □

15.11.3 Closure

Proposition 15.11.7. *Let $\{X_i\}_{i \in I}$ be a family of topological spaces. Give $\prod_{i \in I} X_i$ the box topology. Let $A_i \subseteq X_i$ for all $i \in I$. Then*

$$\prod_{i \in I} \overline{A_i} = \overline{\prod_{i \in I} A_i} .$$

PROOF:

$\langle 1 \rangle 1$. $\prod_{i \in I} \overline{A_i} \subseteq \overline{\prod_{i \in I} A_i}$

- $\langle 2 \rangle 1$. LET: $x \in \prod_{i \in I} \overline{A_i}$
 $\langle 2 \rangle 2$. For any family $\{U_i\}_{i \in I}$ where each U_i is open in X_i , if $x \in \prod_{i \in I} U_i$ then $\prod_{i \in I} U_i$ intersects $\prod_{i \in I} A_i$.
 $\langle 3 \rangle 1$. LET: $\{U_i\}_{i \in I}$ be a family where each U_i is open in X_i .
 $\langle 3 \rangle 2$. ASSUME: $x \in \prod_{i \in I} A_i$
 $\langle 3 \rangle 3$. For all $i \in I$ we have U_i intersects A_i
 PROOF: Since $\pi_i(x) \in A_i$ and U_i is a neighbourhood of $\pi_i(x)$.
 $\langle 3 \rangle 4$. $\prod_{i \in I} U_i$ intersects $\prod_{i \in I} A_i$
 $\langle 2 \rangle 3$. $x \in \overline{\prod_{i \in I} A_i}$
 PROOF: Proposition 14.13.9.
 $\langle 1 \rangle 2$. $\overline{\prod_{i \in I} A_i} \subseteq \prod_{i \in I} \overline{A_i}$
 $\langle 2 \rangle 1$. LET: $x \in \overline{\prod_{i \in I} A_i}$
 $\langle 2 \rangle 2$. LET: $i \in I$
 PROVE: $\pi_i(x) \in \overline{A_i}$
 $\langle 2 \rangle 3$. LET: U be a neighbourhood of $\pi_i(x)$ in X_i
 $\langle 2 \rangle 4$. $\pi_i^{-1}(U)$ is a neighbourhood of x in $\prod_{i \in I} X_i$
 $\langle 2 \rangle 5$. PICK $y \in \pi_i^{-1}(U) \cap \prod_{i \in I} A_i$
 $\langle 2 \rangle 6$. $\pi_i(y) \in U \cap A_i$

□

15.12 Separations

Definition 15.12.1 (Separation). Let X be a topological space. A *separation* of X is a pair (U, V) of disjoint nonempty oped subsets in X such that $U \cup V = X$.

Subspaces

Proposition 15.12.2. Let X be a topological space and Y a subspace of X . Then a separation of Y is a pair (A, B) of disjoint nonempty subsets of Y , neither of which contains a limit point of the other, such that $A \cup B = Y$.

PROOF: Since the following are equivalent:

- Neither of A and B contains a limit point of the other.
- A contains all its own limit points in Y , and B contains all its own limit points in Y .
- A and B are closed in Y .

□

15.13 Connected Spaces

Definition 15.13.1 (Connected). A topological space is *connected* iff it has no separation.

15.13.1 The Real Numbers

Example 15.13.2. The space \mathbb{R}_l is disconnected. The sets $(-\infty, 0)$ and $[0, +\infty)$ form a separation.

15.13.2 The Indiscrete Topology

Example 15.13.3. Any indiscrete space is connected.

15.13.3 The Cofinite Topology

Example 15.13.4. Any infinite set under the cofinite topology is connected.

PROOF:

$\langle 1 \rangle 1$. LET: X be an infinite set under the cofinite topology.

$\langle 1 \rangle 2$. ASSUME: for a contradiction (C, D) is a separation of X .

$\langle 1 \rangle 3$. $X = (X - C) \cup (X - D) \cup (C \cap D)$

$\langle 1 \rangle 4$. Q.E.D.

PROOF: This is a contradiction since X is infinite, $X - C$ and $X - D$ are finite, and $C \cap D = \emptyset$.

□

Example 15.13.5. The rationals are disconnected. For any irrational a , we have $(-\infty, a) \cap \mathbb{Q}$ and $(a, +\infty) \cap \mathbb{Q}$ form a separation of \mathbb{Q} .

Example 15.13.6. \mathbb{R}^ω under the box topology is not connected. The set of bounded sequences and the set of unbounded sequences form a separation.

Proposition 15.13.7. *A topological space X is connected if and only if the only sets that are both open and closed are \emptyset and X .*

PROOF: Since (U, V) is a separation of X iff U is both open and closed and $V = X - U$. □

15.13.4 Finer and Coarser

Proposition 15.13.8. *Let \mathcal{T} and \mathcal{T}' be topologies on the same set X . Assume $\mathcal{T} \subseteq \mathcal{T}'$. If \mathcal{T}' is connected then \mathcal{T} is connected.*

PROOF: If (C, D) is a separation of (X, \mathcal{T}) then it is a separation of (X, \mathcal{T}') . □

15.13.5 Boundary

Proposition 15.13.9. *Let X be a topological space. Let $A \subseteq X$. Let C be a connected subspace of X . If C intersects A and $X - A$ then C intersects ∂A .*

PROOF: Otherwise $(C \cap \overline{A}, C \cap \overline{X - A})$ would be a separation of C . □

15.13.6 Continuous Functions

Proposition 15.13.10. *The continuous image of a connected space is connected.*

PROOF:

- $\langle 1 \rangle 1.$ LET: X and Y be topological spaces.
- $\langle 1 \rangle 2.$ LET: $f : X \rightarrow Y$ be a surjective continuous function.
- $\langle 1 \rangle 3.$ LET: (C, D) be a separation of Y .
- $\langle 1 \rangle 4.$ $(f^{-1}(C), f^{-1}(D))$ is a separation of X .

□

15.13.7 Subspaces

Proposition 15.13.11. *Let X be a topological space. Let (C, D) be a separation of X . Let Y be a connected subspace of X . Then either $Y \subseteq C$ or $Y \subseteq D$.*

PROOF: Otherwise $(Y \cap C, Y \cap D)$ would be a separation of Y . □

Proposition 15.13.12. *Let X be a topological space. Let \mathcal{A} be a set of connected subspaces of X and B a connected subspace of X . Assume that, for all $A \in \mathcal{A}$, we have $A \cap B \neq \emptyset$. Then $\bigcup \mathcal{A} \cup B$ is connected.*

PROOF:

- $\langle 1 \rangle 1.$ ASSUME: for a contradiction (C, D) is a separation of $\bigcup \mathcal{A} \cup B$.
- $\langle 1 \rangle 2.$ ASSUME: w.l.o.g. $B \subseteq C$
PROOF: Proposition 15.13.11.
- $\langle 1 \rangle 3.$ For all $A \in \mathcal{A}$ we have $A \subseteq C$
PROOF: Proposition 15.13.11.
- $\langle 1 \rangle 4.$ $D = \emptyset$
- $\langle 1 \rangle 5.$ Q.E.D.

PROOF: This is a contradiction.

□

Proposition 15.13.13. *Let X be a topological space. Let A be a connected subspace of X . Let B be a subspace of X . If $A \subseteq B \subseteq \overline{A}$ then B is connected.*

PROOF:

- $\langle 1 \rangle 1.$ ASSUME: for a contradiction (C, D) is a separation of B .
- $\langle 1 \rangle 2.$ ASSUME: w.l.o.g. $A \subseteq C$
PROOF: Proposition 15.13.11.
- $\langle 1 \rangle 3.$ $\overline{A} \subseteq \overline{C}$
- $\langle 1 \rangle 4.$ $\overline{C} \cap D = \emptyset$
- $\langle 1 \rangle 5.$ $B \cap D = \emptyset$
- $\langle 1 \rangle 6.$ Q.E.D.

PROOF: This is a contradiction.

□

Corollary 15.13.13.1. *The topologist's sine curve is connected.*

PROOF: The set $\{(x, \sin 1/x) : 0 < x \leq 1\}$ is connected, since it is the continuous image of the connected set $(0, 1]$. The topologist's sine curve is its closure, hence connected by Proposition 15.13.13. \square

Proposition 15.13.14. *Let X be a topological space. Let (A_n) be a sequence of connected subspaces of X such that, for all n , we have $A_n \cap A_{n+1} \neq \emptyset$. Then $\bigcup_n A_n$ is connected.*

PROOF:

$\langle 1 \rangle 1$. ASSUME: for a contradiction (C, D) is a separation of $\bigcup_n A_n$

$\langle 1 \rangle 2$. ASSUME: w.l.o.g. $A_0 \subseteq C$

PROOF: Proposition 15.13.11.

$\langle 1 \rangle 3$. $\forall n. A_n \subseteq C$

$\langle 2 \rangle 1$. ASSUME: as induction hypothesis $A_n \subseteq C$

$\langle 2 \rangle 2$. PICK $x \in A_n \cap A_{n+1}$

$\langle 2 \rangle 3$. $x \in C$

$\langle 2 \rangle 4$. $A_{n+1} \subseteq C$

PROOF: Proposition 15.13.11.

$\langle 1 \rangle 4$. $\bigcup_n A_n \subseteq C$

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

PROOF: This is a contradiction.

\square

Proposition 15.13.15. *Let X be a connected topological space. Let $Y \subseteq X$ be connected. Let (A, B) be a separation of $X - Y$. Then $Y \cup A$ and $Y \cup B$ are connected.*

PROOF:

$\langle 1 \rangle 1$. $Y \cup A$ is connected.

$\langle 2 \rangle 1$. ASSUME: for a contradiction (C, D) is a separation of $Y \cup A$

$\langle 2 \rangle 2$. ASSUME: w.l.o.g. $Y \subseteq C$

$\langle 2 \rangle 3$. PICK C' and D' open in X such that $C = C' \cap (Y \cup A)$ and $D = D' \cap (Y \cup A)$

$\langle 2 \rangle 4$. $D = D' \cap A$

$\langle 2 \rangle 5$. $C' \cap D' \cap A = \emptyset$

$\langle 2 \rangle 6$. $A \subseteq C' \cup D'$

$\langle 2 \rangle 7$. PICK A' and B' open in X such that $A = A' - Y$ and $B = B' - Y$

$\langle 2 \rangle 8$. $A' \cap B' \subseteq Y$

$\langle 2 \rangle 9$. $X - Y \subseteq A' \cup B'$

$\langle 2 \rangle 10$. $A' \subseteq C' \cup D'$

$\langle 2 \rangle 11$. $(D' \cap A', B' \cup C')$ is a separation of X .

$\langle 1 \rangle 2$. $Y \cup B$ is connected.

PROOF: Similar.

\square

15.13.8 Order Topology

Proposition 15.13.16. *Let L be a linearly ordered set under the order topology. Then L is connected if and only if X is a linear continuum.*

PROOF:

⟨1⟩1. If L is a linear continuum then L is connected.

⟨2⟩1. LET: L be a linear continuum.

⟨2⟩2. ASSUME: for a contradiction (A, B) is a separation of L .

⟨2⟩3. PICK $a \in A$ and $b \in B$.

⟨2⟩4. ASSUME: w.l.o.g. $a < b$

⟨2⟩5. LET: $c = \sup\{x \in A : x < b\}$

⟨2⟩6. $c \notin A$

⟨3⟩1. ASSUME: for a contradiction $c \in A$.

⟨3⟩2. PICK $e > c$ such that $[c, e) \subseteq A$.

⟨3⟩3. PICK z such that $c < z < e$.

⟨3⟩4. $z \in A$

⟨3⟩5. Q.E.D.

PROOF: This contradicts ⟨2⟩5.

⟨2⟩7. $c \notin B$

⟨3⟩1. ASSUME: for a contradiction $c \in B$.

⟨3⟩2. PICK $d < c$ such that $(d, c] \subseteq B$.

⟨3⟩3. PICK z such that $d < z < c$

⟨3⟩4. z is an upper bound for $\{x \in A : x < b\}$

⟨3⟩5. Q.E.D.

PROOF: This contradicts ⟨2⟩5.

⟨2⟩8. Q.E.D.

PROOF: This is a contradiction.

⟨1⟩2. If L is connected then L is a linear continuum.

⟨2⟩1. ASSUME: L is connected.

⟨2⟩2. L is dense.

⟨3⟩1. LET: $a, b \in L$ with $a < b$.

⟨3⟩2. ASSUME: for a contradiction there is no c such that $a < c < b$.

⟨3⟩3. $((-\infty, b), (a, +\infty))$ is a separation of L .

⟨2⟩3. L has the least upper bound property.

⟨3⟩1. ASSUME: for a contradiction $S \subseteq L$ is a nonempty set bounded above with no least upper bound.

⟨3⟩2. LET: $S \uparrow$ be the set of upper bounds for S .

⟨3⟩3. LET: $S \uparrow \downarrow$ be the set of lower bounds for $S \uparrow$.

PROVE: $(S \uparrow \downarrow, S \uparrow)$ is a separation of L .

⟨3⟩4. $S \uparrow \neq \emptyset$

PROOF: Since S is bounded above.

⟨3⟩5. $S \uparrow \downarrow \neq \emptyset$

PROOF: Since $\emptyset \neq S \subseteq S \uparrow \downarrow$.

⟨3⟩6. $S \uparrow$ is open.

⟨4⟩1. LET: $u \in S \uparrow$

⟨4⟩2. PICK $v \in S \uparrow$ such that $v < u$

PROOF: Since u is not the least upper bound for S .

$\langle 4 \rangle 3$. $u \in (v, +\infty) \subseteq S \uparrow$

$\langle 3 \rangle 7$. $S \uparrow \downarrow$ is open.

$\langle 4 \rangle 1$. LET: $l \in S \uparrow \downarrow$

$\langle 4 \rangle 2$. $l \notin S \uparrow$

PROOF: Since l is not the least upper bound for S .

$\langle 4 \rangle 3$. PICK $s \in S$ such that $l < s$

$\langle 4 \rangle 4$. $l \in (-\infty, s) \subseteq S \uparrow \downarrow$

$\langle 3 \rangle 8$. $S \uparrow \cap S \uparrow \downarrow \neq \emptyset$

PROOF: An element of both would be a least upper bound for S .

$\langle 3 \rangle 9$. $S \uparrow \cup S \uparrow \downarrow = L$

$\langle 4 \rangle 1$. LET: $x \in L$

$\langle 4 \rangle 2$. ASSUME: $x \notin S \uparrow$

$\langle 4 \rangle 3$. There exists $s \in S$ such that $x < s$.

$\langle 4 \rangle 4$. $\forall u \in S \uparrow . x < u$

$\langle 4 \rangle 5$. $x \in S \uparrow \downarrow$

□

Theorem 15.13.17 (Intermediate Value Theorem). *Let X be a connected space. Let Y be a linearly ordered set under the order topology. Let $f : X \rightarrow Y$ be continuous. Let $a, b \in X$ and $r \in Y$. If $f(a) < r < f(b)$, then there exists $c \in X$ such that $f(c) = r$.*

PROOF: Otherwise $\{x \in X : f(x) < r\}$ and $\{x \in X : f(x) > r\}$ would form a separation of X . □

Corollary 15.13.17.1. *Every continuous function $[0, 1] \rightarrow [0, 1]$ has a fixed point.*

PROOF:

$\langle 1 \rangle 1$. LET: $f : [0, 1] \rightarrow [0, 1]$ be continuous.

$\langle 1 \rangle 2$. LET: $g : [0, 1] \rightarrow [-1, 1]$ be the function $g(x) = f(x) - x$.

$\langle 1 \rangle 3$. $g(0) \geq 0$

$\langle 1 \rangle 4$. $g(1) \leq 0$

$\langle 1 \rangle 5$. There exists $x \in [0, 1]$ such that $g(x) = 0$.

PROOF: Intermediate Value Theorem.

$\langle 1 \rangle 6$. There exists $x \in [0, 1]$ such that $f(x) = x$.

□

15.13.9 Product Topology

Proposition 15.13.18. *The product of a family of connected spaces is connected.*

PROOF:

$\langle 1 \rangle 1$. The product of two connected spaces is connected.

PROOF:

$\langle 2 \rangle 1$. LET: X and Y be connected topological spaces.

- <2>2. ASSUME: w.l.o.g. X and Y are nonempty.
 <2>3. PICK $(a, b) \in X \times Y$
 <2>4. $X \times \{b\}$ is connected.
 PROOF: It is homeomorphic to X .
 <2>5. For all $x \in X$ we have $\{x\} \times Y$ is connected.
 PROOF: It is homeomorphic to Y .
 <2>6. For all $x \in X$ we have $(X \times \{b\}) \cup (\{x\} \times Y)$ is connected.
 PROOF: Proposition 15.13.12.
 <2>7. $X \cup Y$ is connected.
 PROOF: Proposition 15.13.12 since $X \cup Y = \bigcup_{x \in X} ((X \times \{b\}) \cup (\{x\} \times Y))$
 and the subspaces all have the point (a, b) in common.
 <1>2. LET: $\{X_i\}_{i \in I}$ be a family of connected spaces.
 <1>3. LET: $X = \prod_{i \in I} X_i$
 <1>4. ASSUME: w.l.o.g. each X_i is nonempty.
 <1>5. PICK $a \in X$
 <1>6. For every finite $K \subseteq I$,
 LET: $X_K = \{x \in X : \forall i \notin K. \pi_i(x) = \pi_i(a)\}$
 <1>7. For every finite $K \subseteq I$, we have X_K is connected.
 PROOF: It is homeomorphic to $\prod_{i \in K} X_i$ which is connected by <1>1.
 <1>8. LET: $Y = \bigcup_{K \text{ a finite subset of } I} X_K$
 <1>9. Y is connected.
 PROOF: Proposition 15.13.12 since $a \in X_K$ for all K .
 <1>10. $X = \overline{Y}$
 <2>1. LET: $x \in X$
 <2>2. LET: U be a neighbourhood of x .
 PROVE: U intersects Y .
 <2>3. PICK a finite subset K of I and U_i open in each X_i such that $U_i = X_i$
 for all $i \notin K$, and $x \in \prod_i U_i \subseteq U$
 <2>4. LET: $y \in X$ be the point with $\pi_i(y) = \pi_i(x)$ for $i \in K$ and $\pi_i(y) = \pi_i(a)$
 for $i \notin K$
 <2>5. $y \in U \cap Y$
 <1>11. X is connected.
 PROOF: Proposition 15.13.13.
 □

Proposition 15.13.19. *Let X and Y be topological spaces. Let A be a proper subset of X and B a proper subset of Y . Then $(X \times Y) - (A \times B)$ is connected.*

PROOF:

- <1>1. PICK $x_0 \in X - A$
 <1>2. PICK $y_0 \in Y - B$
 <1>3. LET: $C = ((X - A) \times Y) \cup (X \times \{y_0\})$
 <1>4. LET: $D = (\{x_0\} \times Y) \cup (X \times (Y - B))$
 <1>5. C is connected.
 <2>1. $C = \bigcup_{x \in X - A} (\{x\} \times Y) \cup (X \times \{y_0\})$
 <2>2. For all $x \in X - A$ we have $\{x\} \times Y$ is connected.
 PROOF: It is homeomorphic to Y .

⟨2⟩3. $X \times \{y_0\}$ is connected.

PROOF: It is homeomorphic to X .

⟨2⟩4. For all $x \in X - A$ we have $(x, y_0) \in (\{x\} \times Y) \cap (X \times \{y_0\})$

⟨2⟩5. C is connected.

PROOF: Proposition 15.13.12.

⟨1⟩6. D is connected.

PROOF: Similar.

⟨1⟩7. $(X \times Y) - (A \times B) = C \cup D$

⟨1⟩8. $(X \times Y) - (A \times B)$ is connected.

PROOF: Proposition 15.13.12 since $(x_0, y_0) \in C \cap D$.

□

15.13.10 Quotient Spaces

Proposition 15.13.20. *A quotient of a connected space is connected.*

PROOF:

⟨1⟩1. LET: $p : X \twoheadrightarrow Y$ be a quotient map.

⟨1⟩2. If (C, D) is a separation of Y then $(p^{-1}(C), p^{-1}(D))$ is a separation of X .

□

Proposition 15.13.21. *Let $p : X \twoheadrightarrow Y$ be a quotient map. Assume that Y is connected, for all $y \in Y$, we have $p^{-1}(y)$ is connected. Then X is connected.*

PROOF:

⟨1⟩1. ASSUME: for a contradiction (A, B) is a separation of X .

⟨1⟩2. For all $y \in Y$, either $p^{-1}(y) \subseteq A$ or $p^{-1}(y) \subseteq B$.

⟨1⟩3. $(\{y \in Y : p^{-1}(y) \subseteq A\}, \{y \in Y : p^{-1}(y) \subseteq B\})$ form a separation of Y .

⟨1⟩4. Q.E.D.

PROOF: This is a contradiction.

□

15.14 T_1 Spaces

Definition 15.14.1 (T_1). A topological space is T_1 iff every one-point set is closed.

Proposition 15.14.2. *A topological space is T_1 iff every finite set is closed.*

PROOF: Since the union of finitely many closed sets is closed. □

Proposition 15.14.3. *Let X be a topological space. Then X is T_1 if and only if, for all $x, y \in X$, if $x \neq y$ then there exists a neighbourhood of x that does not contain y , and there exists a neighbourhood of y that does not contain x .*

PROOF:

⟨1⟩1. If X is T_1 then, for all $x, y \in X$, if $x \neq y$ then there exists a neighbourhood of x that does not contain y , and there exists a neighbourhood of y that does not contain x .

- ⟨2⟩1. ASSUME: X is T_1 .
 - ⟨2⟩2. LET: $x, y \in X$
 - ⟨2⟩3. ASSUME: $x \neq y$
 - ⟨2⟩4. $X - \{y\}$ is a neighbourhood of x that does not contain y .
 - ⟨2⟩5. $X - \{x\}$ is a neighbourhood of y that does not contain x .
 - ⟨1⟩2. If, for all $x, y \in X$, if $x \neq y$ then there exists a neighbourhood of x that does not contain y , and there exists a neighbourhood of y that does not contain x , then X is T_1 .
 - ⟨2⟩1. ASSUME: For all $x, y \in X$, if $x \neq y$ then there exists a neighbourhood of x that does not contain y , and there exists a neighbourhood of y that does not contain x .
 - ⟨2⟩2. LET: $x \in X$
PROVE: $\{x\}$ is closed.
 - ⟨2⟩3. LET: $y \in X - \{x\}$
 - ⟨2⟩4. PICK a neighbourhood U of y that does not contain x .
 - ⟨2⟩5. $y \in U \subseteq X - \{x\}$
-

15.14.1 Limit Points

Proposition 15.14.4. *Let X be a T_1 space. Let $A \subseteq X$ and $l \in X$. Then l is a limit point of A if and only if every neighbourhood of l contains infinitely many points of A .*

PROOF:

- ⟨1⟩1. If l is a limit point of A then every neighbourhood of l contains infinitely many points of A .
- ⟨2⟩1. ASSUME: l is a limit point of A .
- ⟨2⟩2. LET: U be a neighbourhood of l .
- ⟨2⟩3. ASSUME: for a contradiction $U \cap A - \{l\}$ is finite.
- ⟨2⟩4. $U \cap A - \{l\}$ is closed.
- PROOF: Since X is T_1 .
- ⟨2⟩5. $U - (A - \{l\})$ is a neighbourhood of l .
- ⟨2⟩6. $U - (A - \{l\})$ intersects A .
- ⟨2⟩7. Q.E.D.
- ⟨1⟩2. If every neighbourhood of l contains infinitely many points of A then l is a limit point of A .

PROOF: Immediate from definitions.

□

15.15 Hausdorff Spaces

Definition 15.15.1 (Hausdorff). A topological space is a *Hausdorff* space or a T_2 space iff any two distinct points have disjoint neighbourhoods.

Proposition 15.15.2. *In a Hausdorff space, a sequence has at most one limit.*

PROOF:

- ⟨1⟩1. LET: X be a Hausdorff space.
- ⟨1⟩2. LET: (a_n) be a sequence in X and $l, m \in X$
- ⟨1⟩3. ASSUME: $a_n \rightarrow l$ and $a_n \rightarrow m$
- ⟨1⟩4. ASSUME: for a contradiction $l \neq m$
- ⟨1⟩5. PICK disjoint open sets U and V with $l \in U$ and $m \in V$
- ⟨1⟩6. PICK M, N such that $\forall n \geq M. a_n \in U$ and $\forall n \geq N. a_n \in V$
- ⟨1⟩7. $a_{\max(M, N)} \in U \cap V$
- ⟨1⟩8. Q.E.D.

PROOF: This contradicts the fact that $U \cap V = \emptyset$.

□

Example 15.15.3. We cannot weaken the hypothesis from being Hausdorff to being T_1 .

In the cofinite topology on any infinite set, every sequence converges to every point.

Proposition 15.15.4. *Any linearly ordered set is Hausdorff under the order topology.*

PROOF:

- ⟨1⟩1. LET: X be a linearly ordered set under the order topology.
- ⟨1⟩2. LET: $a, b \in X$ with $a \neq b$.
- ⟨1⟩3. ASSUME: w.l.o.g. $a < b$.
- ⟨1⟩4. CASE: There exists $c \in X$ such that $a < c < b$.
 - ⟨2⟩1. LET: $U = (-\infty, c)$
 - ⟨2⟩2. LET: $V = (c, +\infty)$
 - ⟨2⟩3. U and V are disjoint open sets with $a \in U$ and $b \in V$
- ⟨1⟩5. CASE: There is no $c \in X$ such that $a < c < b$.
 - ⟨2⟩1. LET: $U = (-\infty, b)$
 - ⟨2⟩2. LET: $V = (a, +\infty)$
 - ⟨2⟩3. U and V are disjoint open sets with $a \in U$ and $b \in V$

□

Proposition 15.15.5. *A subspace of a Hausdorff space is Hausdorff.*

PROOF:

- ⟨1⟩1. LET: X be a Hausdorff space.
- ⟨1⟩2. LET: Y be a subspace of X .
- ⟨1⟩3. LET: $a, b \in Y$ with $a \neq b$.
- ⟨1⟩4. PICK disjoint open sets U and V in X with $a \in U$ and $b \in V$.
- ⟨1⟩5. $U \cap Y$ and $V \cap Y$ are disjoint open sets in Y with $a \in U \cap Y$ and $b \in V \cap Y$.

□

Proposition 15.15.6. *The disjoint union of two Hausdorff spaces is Hausdorff.*

Proposition 15.15.7. *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:

- ⟨1⟩1. ASSUME: for a contradiction $a \in A$ and $f(a) \neq g(a)$.
- ⟨1⟩2. PICK disjoint neighbourhoods U and V of $f(a)$ and $g(a)$ respectively.
- ⟨1⟩3. PICK $x \in f^{-1}(U) \cap g^{-1}(V)$
- ⟨1⟩4. $f(x) = g(x) \in U \cap V$
- ⟨1⟩5. Q.E.D.

PROOF: This is a contradiction.

□

15.15.1 Product Topology

Proposition 15.15.8. *The product of a family of Hausdorff spaces is Hausdorff.*

PROOF:

- ⟨1⟩1. LET: $\{X_i\}_{i \in I}$ be a family of Hausdorff spaces.
- ⟨1⟩2. LET: $x, y \in \prod_{i \in I} X_i$ with $x \neq y$.
- ⟨1⟩3. PICK $i \in I$ such that $\pi_i(x) \neq \pi_i(y)$
- ⟨1⟩4. PICK disjoint open sets U and V in X_i such that $\pi_i(x) \in U$ and $\pi_i(y) \in V$.
- ⟨1⟩5. $x \in \pi_i^{-1}(U)$ and $y \in \pi_i^{-1}(V)$.

□

15.15.2 Box Topology

Proposition 15.15.9. *The box product of a family of Hausdorff spaces is Hausdorff.*

PROOF:

- ⟨1⟩1. LET: $\{X_i\}_{i \in I}$ be a family of Hausdorff spaces.
- ⟨1⟩2. LET: $x, y \in \prod_{i \in I} X_i$ with $x \neq y$.
- ⟨1⟩3. PICK $i \in I$ such that $\pi_i(x) \neq \pi_i(y)$
- ⟨1⟩4. PICK disjoint open sets U and V in X_i such that $\pi_i(x) \in U$ and $\pi_i(y) \in V$.
- ⟨1⟩5. $x \in \pi_i^{-1}(U)$ and $y \in \pi_i^{-1}(V)$.

□

15.15.3 T_1 Spaces

Proposition 15.15.10. *Every Hausdorff space is T_1 .*

PROOF:

- ⟨1⟩1. LET: X be a Hausdorff space.
- ⟨1⟩2. LET: $a \in X$
 PROVE: $X - \{a\}$ is open.
- ⟨1⟩3. LET: $x \in X - \{a\}$
- ⟨1⟩4. PICK disjoint open sets U and V with $a \in U$ and $x \in V$
- ⟨1⟩5. $x \in V \subseteq X - U \subseteq X - \{a\}$

□

Example 15.15.11. The converse does not hold. If X is an infinite set under the cofinite topology, then X is T_1 but not Hausdorff.

Proposition 15.15.12. *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 $\lim_{n \rightarrow \infty} f(x_n)$. \square

Proposition 15.15.13. *Let X be a topological space. Then X is Hausdorff if and only if the diagonal $\Delta = \{(x, x) : x \in X\}$ is closed in X^2 .*

PROOF:

Δ is closed

$\Leftrightarrow X^2 - \Delta$ is open

$\Leftrightarrow \forall x, y \in X ((x, y) \notin \Delta \Rightarrow \exists V, W \text{ open in } X (x \in V \wedge y \in W \wedge V \times W \subseteq X^2 - \Delta))$

$\Leftrightarrow \forall x, y \in X (x \neq y \Rightarrow \exists V, W \text{ open in } X (x \in V \wedge y \in W \wedge V \cap W = \emptyset))$

$\Leftrightarrow X$ is Hausdorff \square

15.16 Separable Spaces

Definition 15.16.1 (Separable). A topological space is *separable* iff it has a countable dense subset.

Every second countable space is separable.

15.17 Sequential Compactness

Definition 15.17.1 (Sequentially Compact). A topological space is *sequentially compact* iff every sequence has a convergent subsequence.

15.18 Compactness

Definition 15.18.1 (Compact). A topological space is *compact* iff every open cover has a finite subcover.

Proposition 15.18.2. *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 $U_1, \dots, U_n \in P$

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

\square

Corollary 15.18.2.1. *Let f be a compact space and $f : X \rightarrow \mathbb{R}$ be locally bounded. Then f is bounded.*

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

Proposition 15.18.3. *The continuous image of a compact space is compact.*

Proposition 15.18.4. *A closed subspace of a compact space is compact.*

Proposition 15.18.5. *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 15.18.6. *A compact subspace of a Hausdorff space is closed.*

Proposition 15.18.7. *A continuous bijection from a compact space to a Hausdorff space is a homeomorphism.*

Proposition 15.18.8. *A first countable compact space is sequentially compact.*

15.19 Gluing

Definition 15.19.1 (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 $x \in X_0$.

Proposition 15.19.2. *Y is a subspace of $Y \cup_\phi X$.*

Definition 15.19.3. 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 $x \in X$.

Definition 15.19.4 (Möbius Strip). The *Möbius strip* is $([-1, 1] \times [0, 1])/\alpha$ where $\alpha(x) = -x$.

Definition 15.19.5 (Klein Bottle). The *Klein bottle* is $(S^1 \times [0, 1])/\alpha$ where $\alpha(z) = \bar{z}$.

Proposition 15.19.6. *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.

\square

15.20 Homogeneous Spaces

Definition 15.20.1 (Homogeneous). A topological space X is *homogeneous* iff, for any $x, y \in X$, there exists a homeomorphism $f : X \cong X$ such that $f(x) = y$.

15.21 Regular Spaces

Definition 15.21.1 (Regular). A topological space X is *regular* iff it is T_1 and, for every closed set A and point $x \notin A$, there exist disjoint open sets U and V with $A \subseteq U$ and $x \in V$.

15.22 Totally Disconnected Spaces

Definition 15.22.1 (Totally Disconnected). A topological space X is *totally disconnected* iff the only connected subspaces are the one-point subspaces.

Example 15.22.2. Every discrete space is totally disconnected.

Example 15.22.3. The rationals are totally disconnected.

15.23 Path Connected Spaces

Definition 15.23.1 (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 $\alpha(1) = b$.

15.23.1 The Ordered Square

Proposition 15.23.2. *The ordered square is not path connected.*

PROOF:

$\langle 1 \rangle 1$. ASSUME: for a contradiction $p : [a, b] \rightarrow I_o^2$ is a path from $(0, 0)$ to $(1, 1)$.

$\langle 1 \rangle 2$. p is surjective.

PROOF: Intermediate Value Theorem.

$\langle 1 \rangle 3$. For all $x \in [0, 1]$, the set $p^{-1}(\{x\} \times (0, 1))$ is a nonempty open set in $[0, 1]$.

$\langle 1 \rangle 4$. For all $x \in [0, 1]$ choose a rational $q_x \in p^{-1}(\{x\} \times (0, 1))$.

$\langle 1 \rangle 5$. The mapping that maps x to q_x is an injective function $[0, 1] \rightarrow \mathbb{Q}$

$\langle 1 \rangle 6$. Q.E.D.

PROOF: This contradicts the fact that $[0, 1]$ is uncountable and \mathbb{Q} is countable.

□

15.23.2 Punctured Euclidean Space

Proposition 15.23.3. *For $n > 1$, the punctured Euclidean space $\mathbb{R}^n - \{0\}$ is path connected.*

PROOF: Given points x and y , take the straight line from x to y if this does not pass through 0. Otherwise pick a point z not on this line, and take the two straight lines from x to z then from z to y . \square

15.23.3 The Topologist's Sine Curve

Proposition 15.23.4. *The topologist's sine curve is not path connected.*

PROOF:

$\langle 1 \rangle 1$. LET: $S = \{(x, \sin 1/x) : 0 < x \leq 1\}$

$\langle 1 \rangle 2$. ASSUME: for a contradiction $p : [0, 1] \rightarrow \overline{S}$ is a path from $(0, 0)$ to $(1, \sin 1)$.

$\langle 1 \rangle 3$. LET: b be the largest element of $p^{-1}(\{0\} \times [-1, 1])$

$\langle 1 \rangle 4$. For n a positive integer, choose t_n such that $b < t_n < ((n-1)b + 1)/n$ and $\pi_2(p(t_n)) = (-1)^n$

$\langle 1 \rangle 5$. $t_n \rightarrow b$ as $n \rightarrow \infty$

$\langle 1 \rangle 6$. $(p(t_n))$ does not converge.

$\langle 1 \rangle 7$. Q.E.D.

PROOF: This is a contradiction.

\square

15.23.4 The Long Line

Proposition 15.23.5. *The long line is path connected.*

PROOF:

$\langle 1 \rangle 1$. LET: $L = S_\Omega \times [0, 1)$ be the long line.

$\langle 1 \rangle 2$. LET: $(a, b), (c, d) \in L$

$\langle 1 \rangle 3$. PICK e such that $a < e$ and $c < e$

$\langle 1 \rangle 4$. $(a, b), (c, d) \in [(0, 0), (e, 0)) \cong [0, 1)$

PROOF: Using Proposition 6.5.2.

$\langle 1 \rangle 5$. There is a path from (a, b) to (c, d) .

\square

15.23.5 Continuous Functions

Proposition 15.23.6. *The continuous image of a path connected space is path connected.*

PROOF:

$\langle 1 \rangle 1$. LET: X be a path connected space and Y a topological space.

$\langle 1 \rangle 2$. LET: $f : X \rightarrow Y$ be a surjective continuous function.

PROVE: Y is path connected.

$\langle 1 \rangle 3$. LET: $a, b \in Y$

$\langle 1 \rangle 4$. PICK $x, y \in X$ with $f(x) = a$ and $f(y) = b$.

$\langle 1 \rangle 5$. PICK a path $p : [0, 1] \rightarrow X$ from x to y .

$\langle 1 \rangle 6$. $f \circ p$ is a path from a to b .

\square

15.23.6 Subspaces

Proposition 15.23.7. *Let $\{X\}$ be a topological space. Let \mathcal{A} be a set of connected subspaces of X . If $\bigcap \mathcal{A} \neq \emptyset$ then $\bigcup \mathcal{A}$ is connected.*

PROOF:

- $\langle 1 \rangle 1$. PICK $a \in \bigcap \mathcal{A}$
- $\langle 1 \rangle 2$. PICK $x, y \in \bigcup \mathcal{A}$
- $\langle 1 \rangle 3$. PICK $A, B \in \mathcal{A}$ with $x \in A$ and $y \in B$.
- $\langle 1 \rangle 4$. PICK a path p from x to a in A , and a path q from a to y in B .
- $\langle 1 \rangle 5$. The concatenation of p and q is a path from x to y in $\bigcup \mathcal{A}$.

□

Proposition 15.23.8. *A quotient of a path connected space is path connected.*

15.23.7 Product Topology

Proposition 15.23.9. *The product of a family of path connected spaces is path connected.*

PROOF:

- $\langle 1 \rangle 1$. LET: $\{X_i\}_{i \in I}$ be a family of path connected spaces.
- $\langle 1 \rangle 2$. LET: $x, y \in \prod_{i \in I} X_i$
- $\langle 1 \rangle 3$. For $i \in I$, PICK a path $p_i : [0, 1] \rightarrow X_i$ from $\pi_i(x)$ to $\pi_i(y)$
- $\langle 1 \rangle 4$. $\lambda t \in [0, 1]. \lambda i \in I. p_i(t)$ is a path from x to y in $\prod_{i \in I} X_i$.

□

Proposition 15.23.10. *Let $A \subseteq \mathbb{R}^2$. If A is countable then $\mathbb{R}^2 - A$ is path connected.*

PROOF:

- $\langle 1 \rangle 1$. LET: $x, y \in \mathbb{R}^2 - A$
- $\langle 1 \rangle 2$. PICK two non-parallel lines L through x and L' through y that do not pass through any points in A .

PROOF: These exist since uncountably many lines pass through any point.

- $\langle 1 \rangle 3$. There exists a path from x to y that follows L from x to the point of intersection of L and L' , and then follows L' to y .

□

15.23.8 Connected Spaces

Proposition 15.23.11. *Every path connected space is connected.*

PROOF:

- $\langle 1 \rangle 1$. LET: X be a path connected space.
- $\langle 1 \rangle 2$. ASSUME: for a contradiction (A, B) is a separation of X .
- $\langle 1 \rangle 3$. PICK $a \in A$ and $b \in B$
- $\langle 1 \rangle 4$. PICK a path $p : [0, 1] \rightarrow X$ from a to b .

⟨1⟩5. $(p^{-1}(A), p^{-1}(B))$ is a separation of $[0, 1]$.

⟨1⟩6. Q.E.D.

PROOF: This contradicts Proposition 15.13.16.

□

Corollary 15.23.11.1. *For $n > 1$, we have \mathbb{R}^n and \mathbb{R} are not homeomorphic.*

PROOF: Removing a point from \mathbb{R} gives a disconnected space. □

Proposition 15.23.12. *Every open connected subspace of \mathbb{R}^2 is path connected.*

PROOF:

⟨1⟩1. LET: U be an open connected subspace of \mathbb{R}^2 .

⟨1⟩2. ASSUME: w.l.o.g. $U \neq \emptyset$

⟨1⟩3. PICK $x_0 \in U$

⟨1⟩4. LET: $V = \{x \in U : \text{there exists a path from } x_0 \text{ to } x\}$

⟨1⟩5. V is open in U .

⟨2⟩1. LET: $x \in V$

⟨2⟩2. PICK $\epsilon > 0$ such that $B(x, \epsilon) \subseteq U$

⟨2⟩3. $B(x, \epsilon) \subseteq V$

PROOF: For all $y \in B(x, \epsilon)$, take a path from x_0 to x and then a straight line from x to y .

⟨1⟩6. V is closed in U .

⟨2⟩1. LET: $x \in U - V$

⟨2⟩2. PICK $\epsilon > 0$ such that $B(x, \epsilon) \subseteq U$

⟨2⟩3. $B(x, \epsilon) \subseteq U - V$

⟨3⟩1. LET: $y \in B(x, \epsilon)$

⟨3⟩2. There is a path from y to x .

⟨3⟩3. There is no path from x_0 to y .

⟨1⟩7. $V = U$

PROOF: U is connected.

□

15.24 Locally Homeomorphic

Definition 15.24.1. Let X and Y be topological spaces. Then X is *locally homeomorphic* to Y if and only if every point in X has a neighbourhood that is homeomorphic to an open set in Y .

15.24.1 The Long Line

Proposition 15.24.2. *The long line is locally homeomorphic to $[0, 1)$.*

PROOF: By Proposition 6.5.2. □

15.25 Components

Definition 15.25.1 ((Connected) Component). Let X be a topological space. Define the equivalence relation \sim on X by: $x \sim y$ iff there exists a connected $C \subseteq X$ such that $x \in C$ and $y \in C$. The *components* of X are the equivalence classes with respect to \sim .

We prove this is an equivalence relation.

PROOF:

$\langle 1 \rangle 1.$ \sim is reflexive.

PROOF: For any $x \in X$, we have $\{x\}$ is connected and $x \in \{x\}$, hence $x \sim x$.

$\langle 1 \rangle 2.$ \sim is symmetric.

PROOF: Immediate from definition.

$\langle 1 \rangle 3.$ \sim is transitive.

$\langle 2 \rangle 1.$ ASSUME: $x \sim y$ and $y \sim z$

$\langle 2 \rangle 2.$ PICK connected subspaces C and D of X with $x \in C$, $y \in C$, $y \in D$ and $z \in D$.

$\langle 2 \rangle 3.$ $C \cup D$ is connected.

PROOF: Proposition 15.13.12.

$\langle 2 \rangle 4.$ $x \in C \cup D$ and $z \in C \cup D$.

$\langle 2 \rangle 5.$ $x \sim z$

□

Example 15.25.2. The components of \mathbb{Q} are the singleton subsets.

Example 15.25.3. The components of \mathbb{R}_l are the singleton subsets.

Proposition 15.25.4. *Every component of a topological space is connected.*

PROOF:

$\langle 1 \rangle 1.$ LET: C be a component of the topological space X .

$\langle 1 \rangle 2.$ ASSUME: for a contradiction (A, B) is a separation of C .

$\langle 1 \rangle 3.$ PICK $a \in A$ and $b \in B$.

$\langle 1 \rangle 4.$ $a \sim b$

$\langle 1 \rangle 5.$ PICK a connected subspace D of X such that $a \in D$ and $b \in D$.

$\langle 1 \rangle 6.$ $D \subseteq C$

$\langle 1 \rangle 7.$ $(A \cap D, B \cap D)$ is a separation of D .

$\langle 1 \rangle 8.$ Q.E.D.

PROOF: This is a contradiction.

□

Proposition 15.25.5. *Let X be a topological space. Let A be a nonempty connected subspace of X . Then there exists a unique component C of X such that $A \subseteq C$.*

PROOF:

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

$\langle 1 \rangle 2.$ LET: C be the \sim -equivalence class of a .

$\langle 1 \rangle 3.$ $A \subseteq C$

PROOF: For all $x \in A$ we have $a \sim x$ hence $x \in C$.

$\langle 1 \rangle 4$. For any component C' , if $A \subseteq C'$ then $C' = C$.

PROOF: Since the components are pairwise disjoint.

□

Proposition 15.25.6. *Every component of a topological space is closed.*

PROOF:

$\langle 1 \rangle 1$. LET: X be a topological space.

$\langle 1 \rangle 2$. LET: C be a component of X .

$\langle 1 \rangle 3$. \overline{C} is connected.

PROOF: Proposition 15.13.13.

$\langle 1 \rangle 4$. $\overline{C} \subseteq C$

PROOF: Proposition 15.25.5.

$\langle 1 \rangle 5$. $C = \overline{C}$

□

Corollary 15.25.6.1. *If a topological space has only finitely many components, then its components are open.*

15.26 Path Components

Definition 15.26.1 (Path Component). Let X be a topological space. Define the equivalence relation \sim on X by: $x \sim y$ iff there exists a path from x to y . The *path components* of X are the equivalence classes with respect to \sim .

We prove \sim is an equivalence relation.

PROOF:

$\langle 1 \rangle 1$. \sim is reflexive.

PROOF: For any $a \in X$ the constant path at a is a path from a to a .

$\langle 1 \rangle 2$. \sim is symmetric.

PROOF: If p is a path from a to b then the reverse of p is a path from b to a .

$\langle 1 \rangle 3$. \sim is transitive.

PROOF: If p is a path from a to b and q is a path from b to c then the concatenation of p and q is a path from a to c .

□

Example 15.26.2. The topologist's sine curve has two path components, namely $\{0\} \times [0, 1]$ (which is closed and not open) and $\{(x, \sin 1/x) : 0 < x \leq 1\}$ (which is open and not closed).

Proposition 15.26.3. *Every path component is path connected.*

PROOF: If x and y are in the same path component then $x \sim y$ so there is a path from x to y . □

Corollary 15.26.3.1. *Every path component is a subset of a component.*

Proposition 15.26.4. *Let X be a topological space. Let A be a nonempty path connected subspace of X . Then there exists a unique path component C of X such that $A \subseteq C$.*

PROOF:

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

$\langle 1 \rangle 2$. LET: C be the path component of a .

$\langle 1 \rangle 3$. $A \subseteq C$

PROOF: For all $x \in A$ we have $a \sim x$ (because A is path connected) hence $x \in C$.

$\langle 1 \rangle 4$. For any path component C' , if $A \subseteq C'$ then $C = C'$.

PROOF: This holds because the path components are pairwise disjoint.

□

Example 15.26.5. In \mathbb{R}^ω under the box topology, \vec{x} and \vec{y} are in the same component if and only if $\vec{x} - \vec{y}$ is eventually zero.

PROOF:

$\langle 1 \rangle 1$. LET: B be the set of sequences that are eventually zero.

$\langle 1 \rangle 2$. B is connected.

PROOF: For $\vec{x} \in B$, the straight line path from 0 to \vec{x} is continuous.

$\langle 1 \rangle 3$. B is maximally connected.

PROOF: Since $(B, \mathbb{R}^\omega - B)$ form a separation of \mathbb{R}^ω .

$\langle 1 \rangle 4$. For all $\vec{y} \in \mathbb{R}^\omega$, the component that contains \vec{y} is $\{\vec{x} \in \mathbb{R}^\omega : \vec{x} - \vec{y} \text{ is eventually zero}\}$.

PROOF: Since the function that maps \vec{x} to $\vec{x} + \vec{y}$ is a homeomorphism of \mathbb{R}^ω with itself.

□

Example 15.26.6. The path components of I_o^2 are $\{\{x\} \times [0, 1] : 0 \leq x \leq 1\}$.

PROOF:

$\langle 1 \rangle 1$. For all $x \in [0, 1]$ we have $\{x\} \times [0, 1]$ is path connected.

PROOF: It is homeomorphic to $[0, 1]$.

$\langle 1 \rangle 2$. Given $x, y, s, t \in [0, 1]$ with $x \neq y$, there is no path from (x, s) to (y, t) .

$\langle 2 \rangle 1$. ASSUME: for a contradiction $p : [0, 1] \rightarrow I_o^2$ is a path from (x, s) to (y, t) .

$\langle 2 \rangle 2$. For z between x and y , PICK a rational $q_z \in [0, 1]$ such that $p(q_z) \in \{z\} \times [0, 1]$.

$\langle 2 \rangle 3$. $\{q_z : z \text{ is between } x \text{ and } y\}$ is an uncountable set of rationals.

$\langle 2 \rangle 4$. Q.E.D.

PROOF: This is a contradiction.

□

15.27 Weak Local Connectedness

Definition 15.27.1 (Weakly Locally Connected). Let X be a topological space and $x \in X$. Then X is *weakly locally connected* at x iff, for every neighbourhood

U of x , there exists a connected $Y \subseteq X$ and a neighbourhood V of x such that $V \subseteq Y \subseteq U$.

15.28 Local Connectedness

Definition 15.28.1 (Locally Connected). Let X be a topological space and $x \in X$. Then X is *locally connected* at x iff, for every neighbourhood U of x , there exists a connected neighbourhood V of x such that $V \subseteq U$.

The space X is *locally connected* iff it is locally connected at every point.

Example 15.28.2. Every interval and ray in the real line is connected and locally connected.

Example 15.28.3. The space $[-1, 0) \cup (0, 1]$ is locally connected but not connected.

Example 15.28.4. The topologist's sine curve is connected but not locally connected.

Example 15.28.5. The rationals \mathbb{Q} are neither connected nor locally connected.

Example 15.28.6. For n a positive integer, let $a_n = (1/n, 0)$. Let $p = (0, 0)$. Let the infinite broom X be the union of all the line segments joining (a_{n+1}, q) to $(a_n, 0)$ for n any positive integer and q any rational in $[0, 1/n]$. Then X is weakly locally connected at p but not locally connected at p .

PROOF:

- ⟨1⟩1. X is weakly locally connected at p .
- ⟨2⟩1. LET: U be any neighbourhood of p .
- ⟨2⟩2. PICK N such that, for all $n \geq N$ and every rational $q \in [0, 1/n]$, the line segment joining (a_{n+1}, q) to $(a_n, 0)$ is included in U .
- ⟨2⟩3. LET: Y be the union of all these line segments.
- ⟨2⟩4. Y is connected.
- ⟨2⟩5. LET: $V = B(p, 1/n) \cap X$
- ⟨2⟩6. $V \subseteq Y \subseteq U$
- ⟨1⟩2. X is not locally connected at p .
- ⟨2⟩1. LET: $U = B(p, 1/2) \cap X$
- ⟨2⟩2. LET: V be a neighbourhood of p with $V \subseteq U$
PROVE: V is disconnected.
- ⟨2⟩3. LET: n be least such that $(a_n, 0) \in V$
- ⟨2⟩4. $(a_{n-1}, 0) \notin V$
- ⟨2⟩5. Some part of a line segment joining some (a_n, q) to $(a_{n-1}, 0)$ is in V
- ⟨2⟩6. V is disconnected.

□

Theorem 15.28.7. Let X be a topological space. Then X is locally connected if and only if, for every open set U in X , every component of U is open in X .

PROOF:

- ⟨1⟩1. If X is locally connected then, for every open set U in X , every component of U is open in X .
 - ⟨2⟩1. ASSUME: X is locally connected.
 - ⟨2⟩2. LET: U be an open set in X .
 - ⟨2⟩3. LET: C be a component of U .
 - ⟨2⟩4. LET: $x \in C$
 - ⟨2⟩5. PICK a connected neighbourhood V of x in X such that $V \subseteq U$
 - ⟨2⟩6. $x \in V \subseteq C$
- ⟨1⟩2. If, for every open set U in X , every component of U is open in X , then X is locally connected.
 - ⟨2⟩1. ASSUME: For every open set U in X , every component of U is open in X .
 - ⟨2⟩2. LET: $x \in X$
 - ⟨2⟩3. LET: U be a neighbourhood of x .
 - ⟨2⟩4. LET: V be the component of U that contains x .
 - ⟨2⟩5. V is a connected neighbourhood of x and $V \subseteq U$.

□

Proposition 15.28.8. *The ordered square is locally connected.*

PROOF: Since every basic open set is connected because it is a linear continuum.

□

Example 15.28.9. Let T be the union of all line segments connecting a point $(q, 0)$ to $(0, 1)$ where $q \in [0, 1]$ is rational, and all line segments connecting a point $(q, 1)$ to $(1, 0)$ where $q \in [0, 1]$ is rational. Then T is path connected but is locally connected at no point.

Proposition 15.28.10. *If a topological space is weakly locally connected at every point then it is locally connected.*

PROOF:

- ⟨1⟩1. LET: X be a topological space that is weakly locally connected at every point.
- ⟨1⟩2. For every open set U in X , every component of U is open in X .
 - ⟨2⟩1. LET: U be an open set in X .
 - ⟨2⟩2. LET: C be a component of U .
 - ⟨2⟩3. For all $x \in C$, there exists a neighbourhood V of x such that $V \subseteq C$.
 - ⟨3⟩1. LET: $x \in C$
 - ⟨3⟩2. PICK a connected $Y \subseteq X$ and a neighbourhood V of x such that $V \subseteq Y \subseteq U$
 - PROOF: ⟨1⟩1
 - ⟨3⟩3. $Y \subseteq C$
 - PROOF: Proposition 15.25.5.
 - ⟨3⟩4. $V \subseteq C$
- ⟨2⟩4. C is open.
- PROOF: Proposition 14.1.7.

⟨1⟩3. X is locally connected.

PROOF: Theorem 15.28.7.

□

Proposition 15.28.11. *A quotient of a locally connected space is locally connected.*

PROOF:

⟨1⟩1. LET: X be a locally connected space.

⟨1⟩2. LET: $p : X \rightarrow Y$ be a quotient map.

⟨1⟩3. For every open set V in Y , every component of V is open in Y .

⟨2⟩1. LET: V be an open set in Y .

⟨2⟩2. LET: C be a component of V .

⟨2⟩3. $p^{-1}(C)$ is a union of components of $p^{-1}(V)$

⟨3⟩1. LET: $x \in p^{-1}(C)$

⟨3⟩2. LET: D be the component of $p^{-1}(V)$ that contains x .

PROVE: $D \subseteq p^{-1}(C)$

⟨3⟩3. $p(D)$ is connected.

PROOF: Proposition 15.13.10.

⟨3⟩4. $p(D) \subseteq C$

⟨3⟩5. $D \subseteq p^{-1}(C)$

⟨2⟩4. Every component of $p^{-1}(V)$ is open in X .

PROOF: Theorem 15.28.7.

⟨2⟩5. $p^{-1}(C)$ is open in X .

⟨2⟩6. C is open in Y .

⟨1⟩4. Y is locally connected.

PROOF: Theorem 15.28.7.

□

15.29 Local Path Connectedness

Definition 15.29.1 (Locally Path Connected). Let X be a topological space and $x \in X$. Then X is *locally path connected* at x iff, for every neighbourhood U of x , there exists a path connected neighbourhood V of x such that $V \subseteq U$.

The space X is *locally path connected* iff it is locally connected at every point.

Theorem 15.29.2. *Let X be a topological space. Then X is locally path connected if and only if, for every open set U in X , every path component of U is open in X .*

PROOF:

⟨1⟩1. If X is locally path connected then, for every open set U in X , every path component of U is open in X .

⟨2⟩1. ASSUME: X is locally path connected.

⟨2⟩2. LET: U be an open set in X .

⟨2⟩3. LET: C be a path component of U .

- ⟨2⟩4. LET: $x \in C$
- ⟨2⟩5. PICK a path connected neighbourhood V of x in X such that $V \subseteq U$
- ⟨2⟩6. $x \in V \subseteq C$
- ⟨1⟩2. If, for every open set U in X , every path component of U is open in X , then X is locally path connected.
- ⟨2⟩1. ASSUME: For every open set U in X , every path component of U is open in X .
- ⟨2⟩2. LET: $x \in X$
- ⟨2⟩3. LET: U be a neighbourhood of x .
- ⟨2⟩4. LET: V be the path component of U that contains x .
- ⟨2⟩5. V is a path connected neighbourhood of x and $V \subseteq U$.

□

Theorem 15.29.3. *In a locally path connected space, the components are the same as the path components.*

PROOF:

- ⟨1⟩1. LET: X be a locally path connected space.
- ⟨1⟩2. LET: P be a path component of X .
- ⟨1⟩3. LET: C be the component that includes P .
- PROVE: $P = C$
- ⟨1⟩4. LET: Q be the union of all the path components of C other than P .
- ⟨1⟩5. P and Q are open in C .
- PROOF: Theorem 15.29.2.
- ⟨1⟩6. $P \cup Q = C$ and $P \cap Q = \emptyset$
- ⟨1⟩7. $Q = \emptyset$
- PROOF: Otherwise (P, Q) would be a separation of C .
- ⟨1⟩8. $P = C$

□

Example 15.29.4. The converse does not hold. In \mathbb{Q} , the components are the same as the path components, namely the one-point sets, but \mathbb{Q} is not locally path connected.

Example 15.29.5. The ordered square is not locally path connected.

PROOF:

- ⟨1⟩1. ASSUME: for a contradiction I_o^2 is locally path connected at $(0, 1)$.
- ⟨1⟩2. PICK a path connected neighbourhood U of $(0, 1)$.
- ⟨1⟩3. PICK $a > 0$ such that $[(0, 1), (a, 0)] \subseteq U$
- ⟨1⟩4. PICK a path $p : [0, 1] \rightarrow I_o^2$ from $(0, 1)$ to $(a, 0)$.
- ⟨1⟩5. For every $x \in (0, a)$, PICK a rational $q_x \in [0, 1]$ such that $q_x \in ((x, 0), (x, 1))$
- ⟨1⟩6. $\{q_x : x \in (0, a)\}$ is an uncountable set of rationals.
- ⟨1⟩7. Q.E.D.

PROOF: This is a contradiction.

□

Proposition 15.29.6. *Every connected open subspace of a locally path connected space is path connected.*

PROOF:

$\langle 1 \rangle 1$. LET: X be a locally path connected space.

$\langle 1 \rangle 2$. LET: U be a connected open subspace.

$\langle 1 \rangle 3$. LET: P be a path component of U .

PROVE: $P = U$

$\langle 1 \rangle 4$. LET: Q be the union of the path components of U that are not P .

$\langle 1 \rangle 5$. P and Q are open.

PROOF: Theorem 15.29.2.

$\langle 1 \rangle 6$. $Q = \emptyset$

PROOF: Otherwise (P, Q) would be a separation of U .

$\langle 1 \rangle 7$. $P = U$

□

15.30 Quasicomponents

Definition 15.30.1 (Quasicomponent). Let X be a topological space. Define the equivalence relation \sim on X by: $x \sim y$ iff there is no separation (U, V) of X with $x \in U$ and $y \in V$. The *quasicomponents* of X are the equivalence classes with respect to \sim .

We prove this is an equivalence relation.

PROOF:

$\langle 1 \rangle 1$. \sim is reflexive.

PROOF: For any $x \in X$, there cannot exist a separation (U, V) of X with $x \in U$ and $x \in V$.

$\langle 1 \rangle 2$. \sim is symmetric.

PROOF: Immediate from definition.

$\langle 1 \rangle 3$. \sim is transitive.

$\langle 2 \rangle 1$. ASSUME: $x \sim y$ and $y \sim z$

$\langle 2 \rangle 2$. ASSUME: for a contradiction (U, V) is a separation of X with $x \in U$ and $z \in V$.

$\langle 2 \rangle 3$. $y \in U$ or $y \in V$

$\langle 2 \rangle 4$. $y \notin U$

PROOF: $y \in U$ would contradict the fact that $y \sim z$.

$\langle 2 \rangle 5$. $y \notin V$

PROOF: $y \in V$ would contradict the fact that $x \sim y$.

$\langle 2 \rangle 6$. Q.E.D.

PROOF: This is a contradiction.

□

Proposition 15.30.2. *Every component of a topological space is a subset of a quasicomponent.*

PROOF:

$\langle 1 \rangle 1$. LET: X be a topological space.

$\langle 1 \rangle 2$. LET: C be a component of X .

PROVE: $\forall x, y \in C. x \sim y$
 $\langle 1 \rangle 3$. LET: $x, y \in C$
 $\langle 1 \rangle 4$. ASSUME: for a contradiction (U, V) is a separation of X with $x \in U$ and $y \in V$
 $\langle 1 \rangle 5$. $(U \cap C, V \cap C)$ is a separation of C .
 $\langle 1 \rangle 6$. Q.E.D.
 PROOF: This contradicts the fact that C is connected (Proposition 15.25.4).
 \square

Proposition 15.30.3. *In a locally connected topological space, the components are the same as the quasicomponents.*

PROOF:
 $\langle 1 \rangle 1$. LET: X be a locally connected topological space.
 $\langle 1 \rangle 2$. LET: C be a component of X .
 $\langle 1 \rangle 3$. LET: Q be the quasicomponent that includes C .
 PROVE: $Q = C$
 $\langle 1 \rangle 4$. ASSUME: for a contradiction $C \neq Q$
 $\langle 1 \rangle 5$. PICK $c \in C$ and $d \in Q - C$
 $\langle 1 \rangle 6$. $(C, X - C)$ is a separation of X with $c \in C$ and $d \in X - C$.
 PROOF: Since the components of X are open (Theorem 15.28.7).
 $\langle 1 \rangle 7$. Q.E.D.
 PROOF: This contradicts the fact that $c \sim d$.
 \square

15.31 Compact Spaces

Definition 15.31.1 (Open Cover). Let X be a topological space. An *open cover* of X is a cover of X whose elements are open sets.

Definition 15.31.2 (Compact). A topological space is *compact* iff every open cover includes a finite subcover.

Example 15.31.3. The space \mathbb{R} is not compact, because the open cover $\{(n, n+2) : n \in \mathbb{Z}\}$ has no finite subcover.

Example 15.31.4. Every finite topological space is compact.

Example 15.31.5. Any set under the cofinite topology is compact.

Lemma 15.31.6. *Let X be a topological space and Y a subspace of X . Then Y is compact if and only if every covering of Y by sets open in X contains a finite subcollection that covers Y .*

PROOF:
 $\langle 1 \rangle 1$. If Y is compact then every covering of Y by sets open in X contains a finite subcollection that covers Y .
 $\langle 2 \rangle 1$. ASSUME: Y is compact.

- ⟨2⟩2. LET: \mathcal{A} be a covering of Y by sets open in X .
 - ⟨2⟩3. $\{U \cap Y : U \in \mathcal{A}\}$ is an open covering of Y .
 - ⟨2⟩4. PICK a finite subcovering $\{U_1 \cap Y, \dots, U_n \cap Y\}$.
 - ⟨2⟩5. $\{U_1, \dots, U_n\}$ is a finite subcollection of \mathcal{A} that covers Y .
 - ⟨1⟩2. If every covering of Y by sets open in X contains a finite subcollection that covers Y then Y is compact.
 - ⟨2⟩1. ASSUME: Every covering of Y by sets open in X contains a finite subcollection that covers Y .
 - ⟨2⟩2. LET: \mathcal{A} be an open cover of Y .
 - ⟨2⟩3. $\{U \text{ open in } X : U \cap Y \in \mathcal{A}\}$ covers Y .
 - ⟨2⟩4. PICK a finite subcollection $\{U_1, \dots, U_n\}$ that covers Y .
 - ⟨2⟩5. $\{U_1 \cap Y, \dots, U_n \cap Y\}$ is a finite subcollection of \mathcal{A} that covers Y .
-

Theorem 15.31.7. *Every closed subspace of a compact space is compact.*

PROOF:

- ⟨1⟩1. LET: X be a compact space.
- ⟨1⟩2. LET: C be a closed subspace of X .
- ⟨1⟩3. Every covering of C by sets open in X contains a finite subcollection that covers C .
- ⟨2⟩1. LET: \mathcal{A} be a covering of C by sets open in X .
- ⟨2⟩2. $\mathcal{A} \cup \{X - C\}$ is an open covering of X .
- ⟨2⟩3. PICK a finite subcover \mathcal{B}
- ⟨2⟩4. $\mathcal{B} - \{X - C\}$ is a finite subcollection of \mathcal{A} that covers C .
- ⟨1⟩4. C is compact.

PROOF: Lemma 15.31.6.

□

Lemma 15.31.8. *Let X be a Hausdorff space. Let Y be a compact subspace. Let $x \in X - Y$. Then there exist disjoint open sets U and V such that $x \in U$ and $Y \subseteq V$.*

PROOF:

- ⟨1⟩1. For all $y \in Y$, there exist disjoint open sets U' and V' with $x \in U'$ and $y \in V'$.
 - ⟨1⟩2. $\{V' \text{ open in } X : \exists U' \text{ open in } X. U' \cap V' = \emptyset \wedge x \in U'\}$ is an cover of Y by sets open in X .
 - ⟨1⟩3. PICK a finite subcollection $\{V_1, \dots, V_n\}$ that covers Y .
 - ⟨1⟩4. For $i = 1, \dots, n$, PICK an open set U_i with $U_i \cap V_i = \emptyset$ and $x \in U_i$.
 - ⟨1⟩5. LET: $U = U_1 \cap \dots \cap U_n$ and $V = V_1 \cup \dots \cup V_n$
 - ⟨1⟩6. U and V are disjoint open sets with $x \in U$ and $Y \subseteq V$.
-

Proposition 15.31.9. *Let X be a Hausdorff space. Let A and B be disjoint compact subspaces of X . Then there exist disjoint open sets U and V with $A \subseteq U$ and $B \subseteq V$.*

PROOF:

$\langle 1 \rangle 1$. For all $x \in A$, there exist disjoint open sets U' and V' with $x \in U'$ and $B \subseteq V'$.

PROOF: Lemma 15.31.8.

$\langle 1 \rangle 2$. $\{U' \text{ open in } X : \exists V' \text{ open in } X. U' \cap V' = \emptyset \wedge B \subseteq V'\}$ is a set of open sets that covers A .

$\langle 1 \rangle 3$. PICK a finite subset $\{U_1, \dots, U_n\}$ that covers A .

PROOF: Lemma 15.31.6.

$\langle 1 \rangle 4$. For $i = 1, \dots, n$, PICK V_i open in X such that $U_i \cap V_i = \emptyset$ and $B \subseteq V_i$.

$\langle 1 \rangle 5$. LET: $U = U_1 \cup \dots \cup U_n$

$\langle 1 \rangle 6$. LET: $V = V_1 \cap \dots \cap V_n$

$\langle 1 \rangle 7$. U and V are disjoint and open.

$\langle 1 \rangle 8$. $A \subseteq U$

$\langle 1 \rangle 9$. $B \subseteq V$

□

Theorem 15.31.10. *Every compact subspace of a Hausdorff space is closed.*

PROOF:

$\langle 1 \rangle 1$. LET: X be a Hausdorff space.

$\langle 1 \rangle 2$. LET: Y be a compact subspace of X .

$\langle 1 \rangle 3$. For any $x \in X - Y$ there exists an open set U such that $x \in U \subseteq X - Y$.

PROOF: Lemma 15.31.8.

$\langle 1 \rangle 4$. $X - Y$ is open.

PROOF: Proposition 14.1.7.

$\langle 1 \rangle 5$. Y is closed.

□

Example 15.31.11. We cannot weaken the hypothesis from the space being Hausdorff to the space being T_1 .

Let X be any infinite set under the cofinite topology. Then X is T_1 . The closed sets are the finite sets and X , but every subspace is compact.

Theorem 15.31.12. *The continuous image of a compact space is compact.*

PROOF:

$\langle 1 \rangle 1$. LET: X be a compact space and $f : X \rightarrow Y$ be a surjective continuous function.

$\langle 1 \rangle 2$. LET: \mathcal{V} be an open cover of Y .

$\langle 1 \rangle 3$. $\{f^{-1}(V) : V \in \mathcal{V}\}$ is an open cover of X .

$\langle 1 \rangle 4$. PICK a finite subcover $\{f^{-1}(V_1), \dots, f^{-1}(V_n)\}$.

$\langle 1 \rangle 5$. $\{V_1, \dots, V_n\}$ covers Y .

□

Proposition 15.31.13. *Let X be a compact space and Y a Hausdorff space. Every continuous function from X to Y is a closed map.*

PROOF:

$\langle 1 \rangle 1$. LET: $f : X \rightarrow Y$ be continuous.

⟨1⟩2. LET: C be a closed set in X .

⟨1⟩3. C is compact.

PROOF: Theorem 15.31.7.

⟨1⟩4. $f(C)$ is compact.

PROOF: Theorem 15.31.12.

⟨1⟩5. $f(C)$ is closed in Y .

PROOF: Theorem 15.31.10.

□

Corollary 15.31.13.1. *Let X be a compact space and Y a Hausdorff space. Let $f : X \rightarrow Y$ be a continuous bijection. Then f is a homeomorphism.*

Corollary 15.31.13.2. *Let \mathcal{T} and \mathcal{T}' be two compact Hausdorff topologies on the same set X . Then either $\mathcal{T} = \mathcal{T}'$ or they are incompatible.*

Theorem 15.31.14. *Let X and Y be topological spaces. Let A be a compact subspace of X and B a compact subspace of Y . Let N be an open set that includes $A \times B$. Then there exists open sets U in X and V in Y such that*

$$A \times B \subseteq U \times V \subseteq N.$$

PROOF:

⟨1⟩1. For all $x \in A$, there exist open sets U in X and V in Y such that $x \in U$, $B \subseteq V$, and $U \times V \subseteq N$.

⟨2⟩1. LET: $x \in A$

⟨2⟩2. For all $y \in B$, there exist neighbourhoods U of x and V of y such that $U \times V \subseteq N$

⟨2⟩3. PICK open sets V_1, \dots, V_n that cover B such that, for $i = 1, \dots, n$, there exists a neighbourhood U_i of x such that $U_i \times V_i \subseteq N$

⟨2⟩4. LET: $U = U_1 \cap \dots \cap U_n$

⟨2⟩5. LET: $V = V_1 \cup \dots \cup V_n$

⟨2⟩6. U is open in X .

⟨2⟩7. V is open in Y .

⟨2⟩8. $x \in U$

⟨2⟩9. $B \subseteq V$

⟨2⟩10. $U \times V \subseteq N$

⟨1⟩2. PICK open sets U_1, \dots, U_n in X that cover A such that, for $i = 1, \dots, n$, there exists V_i open in Y such that $B \subseteq V_i$ and $U_i \times V_i \subseteq N$.

⟨1⟩3. LET: $U = U_1 \cup \dots \cup U_n$

⟨1⟩4. LET: $V = V_1 \cap \dots \cap V_n$

⟨1⟩5. U is open in X .

⟨1⟩6. V is open in Y .

⟨1⟩7. $A \times B \subseteq U \times V \subseteq N$

□

Corollary 15.31.14.1 (Tube Lemma). *Let X be a topological space and Y a compact space. Let $x_0 \in X$. Let N be an open set in $X \times Y$ that includes $\{x_0\} \times Y$. Then there exists a neighbourhood W of x_0 such that $W \times Y \subseteq N$.*

Theorem 15.31.15. *The product of two compact spaces is compact.*

PROOF:

- <1>1. LET: X and Y be compact spaces.
 <1>2. LET: \mathcal{A} be an open covering of $X \times Y$.
 <1>3. For all $x \in X$, there exists a neighbourhood W of x such that $W \times Y$ can be covered by finitely many elements of \mathcal{A} .
 <2>1. LET: $x \in X$
 <2>2. $\{x\} \times Y$ is compact.
 PROOF: It is homeomorphic to Y .
 <2>3. PICK a finite subcollection $\{A_1, \dots, A_n\}$ of \mathcal{A} that covers $\{x\} \times Y$.
 <2>4. There exists a neighbourhood W of x such that $W \times Y \subseteq A_1 \cup \dots \cup A_n$.
 PROOF: Tube Lemma
 <1>4. PICK finitely many open sets W_1, \dots, W_n that cover X such that each $W_i \times Y$ can be covered by finitely many elements of \mathcal{A} .
 <1>5. For $i = 1, \dots, n$, PICK a finite subset \mathcal{A}_i of \mathcal{A} that covers $W_i \times Y$.
 <1>6. $\mathcal{A}_1 \cup \dots \cup \mathcal{A}_n$ covers $X \times Y$.
 □

Theorem 15.31.16. *Let X be a topological space. Then X is compact if and only if, for every set \mathcal{C} of compact sets, if \mathcal{C} has the finite intersection property then $\bigcap \mathcal{C} \neq \emptyset$.*

PROOF: The following are equivalent:

- X is compact.
- For every set \mathcal{A} of open sets, if $\bigcup \mathcal{A} = X$ then there is a finite subset of \mathcal{A} that covers X .
- For every set \mathcal{C} of closed sets, if $\bigcup_{C \in \mathcal{C}} (X - C) = X$ then there is a finite subset $\mathcal{C}_0 \subseteq \mathcal{C}$ such that $\bigcup_{C \in \mathcal{C}_0} (X - C) = X$.
- For every set \mathcal{C} of closed sets, if $\bigcap \mathcal{C} = \emptyset$ then there is a finite subset $\mathcal{C}_0 \subseteq \mathcal{C}$ such that $\bigcap \mathcal{C}_0 = \emptyset$.
- For every set \mathcal{C} of closed sets, if \mathcal{C} has the finite intersection property then $\bigcap \mathcal{C} \neq \emptyset$.

□

Corollary 15.31.16.1. *Let X be a compact set. Let (C_n) be a sequence of nonempty closed sets such that $C_0 \supseteq C_1 \supseteq C_2 \supseteq \dots$. Then $\bigcap_{n=0}^{\infty} C_n \neq \emptyset$.*

Proposition 15.31.17. *Let X be a topological space. Let Y and Z be compact subspaces of X . The $Y \cup Z$ is compact.*

PROOF:

- <1>1. LET: \mathcal{U} be a set of open sets that covers $Y \cup Z$.
 <1>2. PICK finite subsets \mathcal{U}_1 that covers Y and \mathcal{U}_2 that covers Z .

⟨1⟩3. $\mathcal{U}_1 \cup \mathcal{U}_2$ is a finite subset of \mathcal{U} that covers $Y \cup Z$.

□

Proposition 15.31.18. *Let X be a topological space and Y a compact space. Then the projection $\pi_1 : X \times Y \rightarrow X$ is a closed map.*

PROOF:

⟨1⟩1. LET: C be closed in $X \times Y$.

⟨1⟩2. LET: $x \in X - \pi_1(C)$

⟨1⟩3. $\{x\} \times Y \subseteq (X \times Y) - C$

⟨1⟩4. PICK a neighbourhood U of x such that $U \times Y \subseteq (X \times Y) - C$

PROOF: Tube Lemma.

⟨1⟩5. $x \in U \subseteq X - \pi_1(C)$

□

Theorem 15.31.19. *Let X be a topological space and Y a compact Hausdorff space. Let $f : X \rightarrow Y$. Then f is continuous if and only if the graph of f ,*

$$G_f = \{(x, f(x)) : x \in X\} ,$$

is closed in $X \times Y$.

PROOF:

⟨1⟩1. If f is continuous then G_f is closed in $X \times Y$.

⟨2⟩1. ASSUME: f is continuous.

⟨2⟩2. LET: $(x, y) \in (X \times Y) - G_f$

⟨2⟩3. PICK disjoint open neighbourhoods U of y and V of $f(x)$.

⟨2⟩4. $(x, y) \in (f^{-1}(V) \times U) \subseteq (X \times Y) - G_f$

⟨1⟩2. If G_f is closed in $X \times Y$ then f is continuous.

⟨2⟩1. ASSUME: G_f is closed in $X \times Y$.

⟨2⟩2. LET: $x_0 \in X$

⟨2⟩3. LET: V be a neighbourhood of $f(x_0)$.

⟨2⟩4. $G_f \cap (X \times (Y - V))$ is closed.

⟨2⟩5. $\pi_1(G_f \cap (X \times (Y - V)))$ is closed.

PROOF: Proposition 15.31.18.

⟨2⟩6. LET: $U = X - \pi_1(G_f \cap (X \times (Y - V)))$

⟨2⟩7. $x_0 \in U$

⟨2⟩8. $f(U) \subseteq V$

□

Theorem 15.31.20. *Let X be a compact Hausdorff space. Let \mathcal{A} be a set of closed connected subspaces of X that is linearly ordered under inclusion. Then $\bigcap \mathcal{A}$ is connected.*

PROOF:

⟨1⟩1. ASSUME: for a contradiction (C, D) is a separation of $\bigcap \mathcal{A}$.

⟨1⟩2. PICK disjoint open sets U and V such that $C \subseteq U$ and $D \subseteq V$.

⟨2⟩1. C and D are closed in X .

PROOF: Proposition 15.3.6.

⟨2⟩2. C and D are compact.

PROOF: Theorem 15.31.7.

⟨2⟩3. Q.E.D.

PROOF: Proposition 15.31.9.

⟨1⟩3. $\bigcap_{A \in \mathcal{A}} (A - (U \cup V))$ is nonempty.

⟨2⟩1. $\{A - (U \cap V) : A \in \mathcal{A}\}$ has the finite intersection property.

⟨3⟩1. LET: $A_1, \dots, A_n \in \mathcal{A}$

⟨3⟩2. ASSUME: w.l.o.g. $A_1 \supseteq \dots \supseteq A_n$

PROOF: \mathcal{A} is linearly ordered by inclusion.

⟨3⟩3. $\bigcap_{i=1}^n (A_i - (U \cup V)) = A_n - (U \cup V)$

⟨3⟩4. $A_n - (U \cup V) \neq \emptyset$

PROOF: Otherwise $(A_n \cap U, A_n \cap V)$ would be a separation of A_n .

⟨2⟩2. Q.E.D.

PROOF: Theorem 15.31.16.

⟨1⟩4. Q.E.D.

PROOF: This is a contradiction.

□

Theorem 15.31.21. *Let X be a linearly ordered set with the least upper bound property under the order topology. Every closed interval in X is compact.*

PROOF:

⟨1⟩1. LET: $a, b \in X$ with $a < b$.

⟨1⟩2. LET: \mathcal{A} be an open covering of $[a, b]$

⟨1⟩3. For any $x \in [a, b)$, there exists $y \in (x, b]$ such that $[x, y]$ can be covered by at most two elements of \mathcal{A} .

⟨2⟩1. LET: $x \in [a, b)$

⟨2⟩2. PICK $U \in \mathcal{A}$ with $x \in U$.

⟨2⟩3. PICK $y > x$ such that $[x, y] \subseteq U$.

⟨2⟩4. PICK $V \in \mathcal{A}$ such that $y \in V$.

⟨2⟩5. $[x, y]$ can be covered by U and V .

⟨1⟩4. LET: $C = \{y \in (a, b] : [a, y] \text{ can be covered by finitely many elements of } \mathcal{A}\}$

⟨1⟩5. $C \neq \emptyset$

PROOF: By ⟨1⟩3, there exists $y \in (a, b]$ such that $[a, y]$ can be covered by at most two elements of \mathcal{A} .

⟨1⟩6. LET: $c = \sup C$

⟨1⟩7. $c \in C$

⟨2⟩1. PICK $U \in \mathcal{A}$ such that $c \in U$.

⟨2⟩2. PICK $y < c$ such that $(y, c] \subseteq U$.

⟨2⟩3. PICK $z \in C$ such that $y < z$

⟨2⟩4. PICK a finite $\mathcal{A}_0 \subseteq \mathcal{A}$ that covers $[a, z]$.

⟨2⟩5. $\mathcal{A}_0 \cup \{U\}$ covers $[a, c]$.

⟨2⟩6. $c \in C$

⟨1⟩8. $c = b$

⟨2⟩1. ASSUME: for a contradiction $c < b$.

$\langle 2 \rangle 2$. PICK $y > c$ such that $[c, y]$ can be covered by at most two elements of \mathcal{A} .

$\langle 2 \rangle 3$. $[a, c]$ can be covered by finitely many elements of \mathcal{A} .

PROOF: $\langle 1 \rangle 7$

$\langle 2 \rangle 4$. $[a, y]$ can be covered by finitely many elements of \mathcal{A} .

$\langle 2 \rangle 5$. $y \in C$

$\langle 2 \rangle 6$. Q.E.D.

PROOF: This is a contradiction.

$\langle 1 \rangle 9$. $[a, b]$ can be covered by finitely many elements of \mathcal{A} .

□

Corollary 15.31.21.1. *Every closed interval in \mathbb{R} is compact.*

Proposition 15.31.22. *A linearly ordered set that is compact under the order topology has a greatest and a least element.*

PROOF:

$\langle 1 \rangle 1$. LET: X be a linearly ordered set that is compact under the order topology.

$\langle 1 \rangle 2$. X has a greatest element.

$\langle 2 \rangle 1$. ASSUME: for a contradiction X has no greatest element.

$\langle 2 \rangle 2$. The open rays $(-\infty, a)$ form an open cover of X .

$\langle 2 \rangle 3$. PICK a finite subcover $\{(-\infty, a_1), \dots, (-\infty, a_n)\}$ where $a_1 \leq \dots \leq a_n$

$\langle 2 \rangle 4$. $a_n < a_n$

$\langle 2 \rangle 5$. Q.E.D.

PROOF: This is a contradiction.

$\langle 1 \rangle 3$. X has a least element.

PROOF: Similar.

□

Corollary 15.31.22.1 (Extreme Value Theorem). *Let X be a compact space and Y a linearly ordered set in the order topology. Let $f : X \rightarrow Y$ be continuous. Then there exist $c, d \in X$ such that, for all $x \in X$, we have $f(c) \leq f(x) \leq f(d)$.*

PROOF: Since $f(X)$ is compact, and so has a greatest and least element. □

15.32 Perfect Maps

Definition 15.32.1 (Perfect Map). Let X and Y be topological spaces. A *perfect map* from X to Y is a closed continuous surjective map $p : X \rightarrow Y$ such that, for all $y \in Y$, we have $p^{-1}(y)$ is compact.

Proposition 15.32.2. *Let X be a topological space and Y a compact space. If there exists a perfect map $X \rightarrow Y$, then X is compact.*

PROOF:

$\langle 1 \rangle 1$. LET: $p : X \rightarrow Y$ be a perfect map.

$\langle 1 \rangle 2$. For all $y \in Y$ and every open set U such that $p^{-1}(y) \subseteq U$, there exists a neighbourhood W of y such that $p^{-1}(W) \subseteq U$.

- ⟨2⟩1. LET: $y \in Y$
- ⟨2⟩2. LET: U be an open set such that $p^{-1}(y) \subseteq U$.
- ⟨2⟩3. LET: $W = Y - p(X - U)$
- ⟨2⟩4. W is open.
 - ⟨3⟩1. $X - U$ is closed.
 - PROOF: Proposition 14.2.2, ⟨2⟩2.
 - ⟨3⟩2. $p(X - U)$ is closed.
 - PROOF: Since p is a closed map (⟨1⟩1).
 - ⟨3⟩3. $Y - p(X - U)$ is open.
- ⟨2⟩5. $y \in W$
 - ⟨3⟩1. ASSUME: for a contradiction $y \in p(X - U)$
 - ⟨3⟩2. PICK $x \in X - U$ such that $p(x) = y$
 - ⟨3⟩3. $x \in p^{-1}(y)$
 - ⟨3⟩4. $x \in U$
 - PROOF: ⟨2⟩2
 - ⟨3⟩5. Q.E.D.
 - PROOF: This contradicts ⟨3⟩2.
- ⟨2⟩6. $p^{-1}(W) \subseteq U$
 - ⟨3⟩1. LET: $x \in p^{-1}(W)$
 - ⟨3⟩2. $p(x) \in W$
 - ⟨3⟩3. $p(x) \notin p(X - U)$
 - PROOF: ⟨2⟩3
 - ⟨3⟩4. $x \notin X - U$
 - ⟨3⟩5. $x \in U$
- ⟨1⟩3. LET: \mathcal{U} be an open cover of X .
- ⟨1⟩4. For every $y \in Y$, there exists a neighbourhood W of y such that $p^{-1}(W)$ can be covered by finitely many elements of \mathcal{U} .
 - ⟨2⟩1. LET: $y \in Y$
 - ⟨2⟩2. PICK finitely many sets $U_1, \dots, U_n \in \mathcal{U}$ that cover $p^{-1}(y)$
 - PROOF: Since $p^{-1}(y)$ is compact.
 - ⟨2⟩3. There exists a neighbourhood W of y such that $p^{-1}(W) \subseteq U_1 \cup \dots \cup U_n$.
 - PROOF: ⟨1⟩2
- ⟨1⟩5. PICK finitely many open sets W_1, \dots, W_n in Y such that each $p^{-1}(W_i)$ can be covered by finitely many elements of \mathcal{U} .
 - PROOF: Since Y is compact.
- ⟨1⟩6. For $i = 1, \dots, n$, PICK a finite subset \mathcal{U}_i of \mathcal{U} such that $p^{-1}(W_i) \subseteq \bigcup \mathcal{U}_i$.
- ⟨1⟩7. $\mathcal{U}_1 \cup \dots \cup \mathcal{U}_n$ covers X .

□

Chapter 16

Metric Spaces

16.1 Metric Spaces

Definition 16.1.1 (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 16.1.2 (Discrete Metric). On any set X , define the *discrete* metric by $d(x, y) = 0$ if $x = y$, 1 if $x \neq y$.

Definition 16.1.3 (Standard Metric). The *standard metric* on \mathbb{R} is defined by $d(x, y) = |x - y|$.

Definition 16.1.4 (Distance to a Set). Let X be a metric space. Let $A \subseteq X$ be nonempty and $x \in X$. The *distance from x to A* is

$$d(x, A) = \inf_{a \in A} d(x, a) \ .$$

16.1.1 Balls

Definition 16.1.5 ((Open) Ball). Let X be a metric space. Let $x \in X$ and $r > 0$. The *(open) ball* with *centre x* and *radius r* is

$$B(x, r) = \{y \in X \mid d(x, y) < r\} \ .$$

Definition 16.1.6 (Closed Ball). Let X be a metric space. Let $x \in X$ and $r > 0$. The *closed ball* with centre x and radius r is

$$\overline{B(x, r)} = \{y \in X \mid d(x, y) < r\} .$$

Definition 16.1.7 (Metric Topology). Let (X, d) be a metric space. The *metric topology* on X is the topology generated by the basis consisting of the balls.

We prove this is a basis for a topology.

PROOF:

$\langle 1 \rangle 1$. Every point is a member of some ball.

PROOF: Since $x \in B(x, 1)$.

$\langle 1 \rangle 2$. If B_1 and B_2 are balls and $x \in B_1 \cap B_2$, then there exists a ball B_3 such that $x \in B_3 \subseteq B_1 \cap B_2$.

$\langle 2 \rangle 1$. LET: $x \in B(a, \epsilon_1) \cap B(b, \epsilon_2)$

$\langle 2 \rangle 2$. LET: $\epsilon = \min(\epsilon_1 - d(x, a), \epsilon_2 - d(x, b))$

PROVE: $x \in B(x, \epsilon) \subseteq B(a, \epsilon_1) \cap B(b, \epsilon_2)$

$\langle 2 \rangle 3$. $B(x, \epsilon) \subseteq B(a, \epsilon_1)$

$\langle 3 \rangle 1$. LET: $y \in B(x, \epsilon)$

$\langle 3 \rangle 2$. $d(y, a) < \epsilon_1$

PROOF:

$$d(y, a) \leq d(y, x) + d(x, a) \quad (\text{Triangle Inequality})$$

$$< \epsilon + d(x, a) \quad (\langle 3 \rangle 1)$$

$$\leq \epsilon_1 \quad (\langle 2 \rangle 2)$$

$\langle 2 \rangle 4$. $B(x, \epsilon) \subseteq B(b, \epsilon_2)$

PROOF: Similar.

□

Proposition 16.1.8. *The discrete metric on a set X induces the discrete topology.*

PROOF: Since $B(x, 1/2) = \{x\}$ for all $x \in X$. □

Proposition 16.1.9. *The standard metric on \mathbb{R} induces the standard topology.*

PROOF:

$\langle 1 \rangle 1$. Every ball is open in the standard topology.

PROOF: Since $B(a, \epsilon) = (a - \epsilon, a + \epsilon)$.

$\langle 1 \rangle 2$. Every open ray is open in the metric topology.

PROOF: If $x \in (a, +\infty)$ then $x \in B(x, x - a) \subseteq (a, +\infty)$. Similarly for $(-\infty, a)$.

□

Proposition 16.1.10. *Multiplication is a continuous function $\mathbb{R}^2 \rightarrow \mathbb{R}$.*

PROOF:

$\langle 1 \rangle 1$. LET: $(x, y) \in \mathbb{R}^2$ and $\epsilon > 0$

$\langle 1 \rangle 2$. LET: $\delta = \min(\epsilon/(|x| + |y| + 1), 1)$

$\langle 1 \rangle 3$. LET: $(x', y') \in \mathbb{R}^2$ with $\rho((x, y), (x', y')) < \delta$

$$\langle 1 \rangle 4. |x - x'|, |y - y'| < \delta$$

$$\langle 1 \rangle 5. |xy - x'y'| < \epsilon$$

PROOF:

$$\begin{aligned} |xy - x'y'| &= |xy - xy' + xy - x'y - xy + x'y + xy' - x'y'| \\ &\leq |xy - xy'| + |xy - x'y| + |xy - x'y - xy' + x'y'| = |x||y - y'| + |x - x'||y| + |x - x'||y - y'| \\ &< |x|\delta + |y|\delta + \delta^2 \end{aligned} \quad (\langle 1 \rangle 4)$$

$$\leq |x|\delta + |y|\delta + \delta \quad (\langle 1 \rangle 2)$$

$$= (|x| + |y| + 1)\delta$$

$$\leq \epsilon \quad (\langle 1 \rangle 2)$$

□

Corollary 16.1.10.1. *The unit circle S^1 is a closed subset of \mathbb{R}^2 .*

PROOF: The function f that maps (x, y) to $x^2 + y^2$ is continuous, and $S^1 = f^{-1}(\{1\})$. □

Corollary 16.1.10.2. *The unit ball B^2 is a closed subset of \mathbb{R}^2 .*

PROOF: The function f that maps (x, y) to $x^2 + y^2$ is continuous, and $B^2 = f^{-1}([0, 1])$. □

Proposition 16.1.11. *Let (a_n) and (b_n) be sequences of real numbers. Let $c, s, t \in \mathbb{R}$. Assume*

$$\sum_{n=0}^{\infty} a_n = s \text{ and } \sum_{n=0}^{\infty} b_n = t .$$

Then

$$\sum_{n=0}^{\infty} (ca_n + b_n) = cs + t .$$

PROOF:

$$\sum_{n=0}^N (ca_n + b_n) = c \sum_{n=0}^N a_n + \sum_{n=0}^N b_n \rightarrow cs + t \text{ as } n \rightarrow \infty \quad \square$$

Proposition 16.1.12 (Comparison Test). *Let (a_n) and (b_n) be sequences of real numbers. Assume $|a_n| \leq b_n$ for all n . Assume $\sum_{n=0}^{\infty} b_n$ converges. Then $\sum_{n=0}^{\infty} a_n$ converges.*

PROOF:

$\langle 1 \rangle 1$. For all n ,

$$\text{LET: } c_n = |a_n| + a_n$$

$\langle 1 \rangle 2$. $\sum_{n=0}^{\infty} |a_n|$ converges.

PROOF: Since $(\sum_{n=0}^N |a_n|)_N$ is an increasing sequence of real numbers bounded above by $\sum_{n=0}^{\infty} b_n$.

$\langle 1 \rangle 3$. $\sum_{n=0}^{\infty} c_n$ converges.

PROOF: Since $(\sum_{n=0}^N c_n)_N$ is an increasing sequence of real numbers bounded above by $2 \sum_{n=0}^{\infty} a_n$.

⟨1⟩4. $\sum_{n=0}^{\infty} a_n$ converges.

PROOF: Since $a_n = c_n - |a_n|$.

□

Proposition 16.1.13. *Let X be a metric space. Let $U \subseteq X$. Then U is open if and only if, for all $x \in U$, there exists $\epsilon > 0$ such that $B(x, \epsilon) \subseteq U$.*

PROOF:

⟨1⟩1. If U is open then, for all $x \in U$, there exists $\epsilon > 0$ such that $B(x, \epsilon) \subseteq U$.

⟨2⟩1. ASSUME: U is open.

⟨2⟩2. LET: $x \in U$

⟨2⟩3. PICK a ball $B(a, \delta)$ such that $x \in B(a, \delta) \subseteq U$

⟨2⟩4. LET: $\epsilon = \delta - d(a, x)$

PROVE: $B(x, \epsilon) \subseteq U$

⟨2⟩5. LET: $y \in B(x, \epsilon)$

⟨2⟩6. $y \in B(a, \delta)$

PROOF:

$$\begin{aligned} d(a, y) &\leq d(a, x) + d(x, y) && \text{(Triangle Inequality)} \\ &< d(a, x) + \epsilon && (\langle 2 \rangle 5) \\ &= \delta \end{aligned}$$

⟨2⟩7. $y \in U$

PROOF: ⟨2⟩3

⟨1⟩2. If, for all $x \in U$, there exists $\epsilon > 0$ such that $B(x, \epsilon) \subseteq U$, then U is open.

PROOF: Immediate from definition of the metric topology.

□

Proposition 16.1.14. *Let X be a metric space. Let $a, b, c \in X$. Then*

$$|d(a, b) - d(a, c)| \leq d(b, c) .$$

PROOF:

⟨1⟩1. $d(a, b) - d(a, c) \leq d(b, c)$

PROOF: Triangle Inequality.

⟨1⟩2. $d(a, c) - d(a, b) \leq d(b, c)$

PROOF: Triangle Inequality.

□

Proposition 16.1.15. *Let (X, d) be a metric space. Then the metric topology on X is the coarsest topology such that $d : X^2 \rightarrow \mathbb{R}$ is continuous.*

PROOF:

⟨1⟩1. d is continuous with respect to the metric topology.

⟨2⟩1. LET: $(a, b) \in X^2$

⟨2⟩2. LET: V be a neighbourhood of $d(a, b)$.

⟨2⟩3. PICK $\epsilon > 0$ such that $(d(a, b) - \epsilon, d(a, b) + \epsilon) \subseteq V$.

⟨2⟩4. LET: $U = B(a, \epsilon/2) \times B(b, \epsilon/2)$

⟨2⟩5. LET: $(x, y) \in U$

⟨2⟩6. $|d(x, y) - d(a, b)| < \epsilon$

PROOF:

$$\begin{aligned} |d(x, y) - d(a, b)| &\leq |d(x, y) - d(a, y)| + |d(a, y) - d(a, b)| \\ &\leq d(a, x) + d(b, y) && \text{(Proposition 16.1.14)} \\ &< \epsilon \end{aligned}$$

$\langle 2 \rangle 7. d(x, y) \in V$

$\langle 1 \rangle 2.$ If \mathcal{T} is a topology on X with respect to which d is continuous then \mathcal{T} is finer than the metric topology.

$\langle 2 \rangle 1.$ LET: \mathcal{T} be a topology on X with respect to which d is continuous.

$\langle 2 \rangle 2.$ LET: $a \in X$ and $\epsilon > 0$.

PROVE: $B(a, \epsilon) \in \mathcal{T}$

$\langle 2 \rangle 3.$ LET: $x \in B(a, \epsilon)$

$\langle 2 \rangle 4.$ $(a, x) \in d^{-1}((0, \epsilon))$

$\langle 2 \rangle 5.$ PICK $U, V \in \mathcal{T}$ such that $(a, x) \in U \times V \subseteq d^{-1}((0, \epsilon))$

$\langle 2 \rangle 6.$ $x \in V \subseteq B(a, \epsilon)$

□

Proposition 16.1.16. Let d and d' be two metrics on the same set X . Let \mathcal{T} and \mathcal{T}' be the topologies they induce. Then $\mathcal{T} \subseteq \mathcal{T}'$ if and only if, for all $x \in X$ and $\epsilon > 0$, there exists $\delta > 0$ such that

$$B_{d'}(x, \delta) \subseteq B_d(x, \epsilon) .$$

PROOF:

$\langle 1 \rangle 1.$ If $\mathcal{T} \subseteq \mathcal{T}'$ then, for all $x \in X$ and $\epsilon > 0$, there exists $\delta > 0$ such that

$$B_{d'}(x, \delta) \subseteq B_d(x, \epsilon).$$

$\langle 2 \rangle 1.$ ASSUME: $\mathcal{T} \subseteq \mathcal{T}'$

$\langle 2 \rangle 2.$ LET: $x \in X$ and $\epsilon > 0$

$\langle 2 \rangle 3.$ $x \in B_d(x, \epsilon) \in \mathcal{T}'$

$\langle 2 \rangle 4.$ There exists $\delta > 0$ such that $B_{d'}(x, \delta) \subseteq B_d(x, \epsilon)$

PROOF: Proposition 16.1.13.

$\langle 1 \rangle 2.$ If, for all $x \in X$ and $\epsilon > 0$, there exists $\delta > 0$ such that $B_{d'}(x, \delta) \subseteq B_d(x, \epsilon)$, then $\mathcal{T} \subseteq \mathcal{T}'$.

$\langle 2 \rangle 1.$ ASSUME: For all $x \in X$ and $\epsilon > 0$, there exists $\delta > 0$ such that $B_{d'}(x, \delta) \subseteq B_d(x, \epsilon)$.

$\langle 2 \rangle 2.$ LET: $U \in \mathcal{T}$

$\langle 2 \rangle 3.$ For all $x \in U$, there exists $\delta > 0$ such that $B_{d'}(x, \delta) \subseteq U$

$\langle 3 \rangle 1.$ LET: $x \in U$

$\langle 3 \rangle 2.$ PICK $\epsilon > 0$ such that $B_d(x, \epsilon) \subseteq U$

PROOF: Proposition 16.1.13.

$\langle 3 \rangle 3.$ PICK $\delta > 0$ such that $B_{d'}(x, \delta) \subseteq B_d(x, \epsilon)$.

PROOF: $\langle 2 \rangle 1$

$\langle 3 \rangle 4.$ $B_{d'}(x, \delta) \subseteq U$

$\langle 2 \rangle 4.$ $U \in \mathcal{T}'$

PROOF: Proposition 16.1.13.

□

Definition 16.1.17 (Metrisable). A topological space is *metrisable* iff there exists a metric that induces its topology.

Proposition 16.1.18. \mathbb{R}^2 under the dictionary order is metrizable.

PROOF:

$\langle 1 \rangle 1$. LET: $d : (\mathbb{R}^2)^2 \rightarrow \mathbb{R}$ be defined by

$$d((x_1, y_1), (x_2, y_2)) = \begin{cases} \min(|y_2 - y_1|, 1) & \text{if } x_1 = x_2 \\ 1 & \text{if } x_1 \neq x_2 \end{cases}$$

$\langle 1 \rangle 2$. d is a metric.

$\langle 2 \rangle 1$. For all $x, y \in \mathbb{R}^2$ we have $d(x, y) \geq 0$.

PROOF: Immediate from definition.

$\langle 2 \rangle 2$. For all $x, y \in \mathbb{R}^2$ we have $d(x, y) = 0$ iff $x = y$.

PROOF: Immediate from definition.

$\langle 2 \rangle 3$. For all $x, y \in \mathbb{R}^2$ we have $d(x, y) = d(y, x)$.

PROOF: Immediate from definition.

$\langle 2 \rangle 4$. For all $x, y, z \in \mathbb{R}^2$ we have $d(x, z) \leq d(x, y) + d(y, z)$.

PROOF: Easy.

$\langle 1 \rangle 3$. The metric topology induced by d is finer than the order topology.

$\langle 2 \rangle 1$. LET: $a, b \in \mathbb{R}^2$

$\langle 2 \rangle 2$. LET: $x \in (a, b)$

$\langle 2 \rangle 3$. CASE: $\pi_1(x) = \pi_1(a) = \pi_1(b)$

$\langle 3 \rangle 1$. LET: $\epsilon = \min(\pi_2(x) - \pi_2(a), \pi_2(b) - \pi_2(x))$

$\langle 3 \rangle 2$. $B(x, \epsilon) \subseteq (a, b)$

$\langle 2 \rangle 4$. CASE: $\pi_1(a) = \pi_1(x) < \pi_1(b)$

$\langle 3 \rangle 1$. LET: $\epsilon = \pi_2(x) - \pi_2(a)$

$\langle 3 \rangle 2$. $B(x, \epsilon) \subseteq (a, b)$

$\langle 2 \rangle 5$. CASE: $\pi_1(a) < \pi_1(x) = \pi_1(b)$

PROOF: Similar.

$\langle 2 \rangle 6$. CASE: $\pi_1(a) < \pi_1(x) < \pi_1(b)$

PROOF: Then $B(x, \epsilon) \subseteq (a, b)$.

$\langle 1 \rangle 4$. The order topology is finer than the metric topology.

PROOF: Since $B((a, b), \epsilon) = ((a, b - \epsilon), (a, b + \epsilon))$ if $\epsilon \leq 1$, and \mathbb{R}^2 if $\epsilon > 1$.

□

Proposition 16.1.19. Every metrizable space is first countable.

PROOF: For any point a , the set $\{B(a, 1/n) : n \in \mathbb{Z}_+\}$ is a local basis at a . □

A metric space is compact if and only if it is sequentially compact.

A metric space is separable if and only if it is second countable.

Proposition 16.1.20. Every compact metric space is bounded.

PROOF:

$\langle 1 \rangle 1$. LET: X be a compact metric space.

$\langle 1 \rangle 2$. ASSUME: w.l.o.g. X is nonempty.

$\langle 1 \rangle 3$. PICK $a \in X$

$\langle 1 \rangle 4$. $\{B(a, n) : n \in \mathbb{Z}_+\}$ is an open cover of X .

$\langle 1 \rangle 5$. PICK a finite subcover $\{B(a, n_1), \dots, B(a, n_k)\}$.

$\langle 1 \rangle 6$. LET: $N = \max(n_1, \dots, n_k)$

⟨1⟩7. $X = B(a, N)$

□

Example 16.1.21. The converse does not hold. An infinite discrete space is bounded but not compact.

16.1.2 Subspaces

Proposition 16.1.22. *Let (X, d) be a metric space and $Y \subseteq X$. Then $d|Y^2$ is a metric on Y that induces the subspace topology.*

PROOF:

⟨1⟩1. LET: $d' = d|Y^2 : Y^2 \rightarrow \mathbb{R}$

⟨1⟩2. d' is a metric.

PROOF: Each of the axioms follows from the axiom in X .

⟨1⟩3. The metric topology induced by d' is finer than the subspace topology.

⟨2⟩1. LET: U be open in X

PROVE: $U \cap Y$ is open in the d' -topology.

⟨2⟩2. LET: $y \in U \cap Y$

⟨2⟩3. PICK $\epsilon > 0$ such that $B_d(y, \epsilon) \subseteq U$

⟨2⟩4. $B_{d'}(y, \epsilon) \subseteq U \cap Y$

⟨1⟩4. The subspace topology is finer than the metric topology induced by d' .

⟨2⟩1. LET: $y \in Y$ and $\epsilon > 0$

PROVE: $B_{d'}(y, \epsilon)$ is open in the subspace topology.

⟨2⟩2. $B_{d'}(y, \epsilon) = B_d(y, \epsilon) \cap Y$

□

16.1.3 Convergence

Proposition 16.1.23 (Sequence Lemma). *Let X be a metric space. Let $A \subseteq X$. Let $l \in \overline{A}$. Then there exists a sequence in A that converges to l .*

PROOF:

⟨1⟩1. For $n \in \mathbb{N}$, PICK $a_n \in B(l, 1/(n+1)) \cap A$.

⟨1⟩2. $a_n \rightarrow l$ as $n \rightarrow \infty$.

□

Corollary 16.1.23.1. \mathbb{R}^ω under the box topology is not first countable.

PROOF:

⟨1⟩1. LET: A be the set of all sequences of positive reals.

⟨1⟩2. $0 \in \overline{A}$

⟨1⟩3. LET: (a_n) be a sequence in A

PROVE: (a_n) does not converge to 0.

⟨1⟩4. For all $n \in \mathbb{N}$,

LET: $a_n = (x_{nm})$

⟨1⟩5. LET: $B' = \prod_{n=0}^{\infty} (-x_{nn}, x_{nn})$

⟨1⟩6. B' is open in the box topology.

- $\langle 1 \rangle 7. 0 \in B'$
 $\langle 1 \rangle 8. \text{ For all } n \text{ we have } a_n \notin B'$
 \square

Corollary 16.1.23.2. *If J is an uncountable set then \mathbb{R}^J under the product topology is not first countable.*

PROOF:

- $\langle 1 \rangle 1. \text{ LET: } A = \{x \in \mathbb{R}^J : \pi_j(x) = 1 \text{ for all but finitely many } j \in J\}$
 $\langle 1 \rangle 2. 0 \in \overline{A}$
 $\langle 1 \rangle 3. \text{ LET: } (a_n) \text{ be a sequence in } A.$
 $\text{PROVE: } (a_n) \text{ does not converge to } 0.$
 $\langle 1 \rangle 4. \text{ For } n \in \mathbb{N},$
 $\text{LET: } J_n = \{j \in J : \pi_j(a_n) \neq 1\}$
 $\langle 1 \rangle 5. \bigcup_{n \in \mathbb{N}} J_n \text{ is countable.}$
 $\langle 1 \rangle 6. \text{ PICK } \beta \in J - \bigcup_{n \in \mathbb{N}} J_n$
 $\langle 1 \rangle 7. \forall n \in \mathbb{N}. \pi_\beta(a_n) = 1$
 $\langle 1 \rangle 8. \text{ LET: } U = \pi_\beta^{-1}((-1, 1))$
 $\langle 1 \rangle 9. 0 \in U$
 $\langle 1 \rangle 10. \forall n \in \mathbb{N}. a_n \notin U$
 $\langle 1 \rangle 11. (a_n) \text{ does not converge to } 0.$
 \square

16.1.4 Continuous Functions

Proposition 16.1.24. *Let X and Y be metric spaces. Let $f : X \rightarrow Y$. Then f is continuous if and only if, for all $x \in X$ and $\epsilon > 0$, there exists $\delta > 0$ such that, for all $y \in X$, if $d(x, y) < \delta$ then $d(f(x), f(y)) < \epsilon$.*

PROOF:

- $\langle 1 \rangle 1. \text{ If } f \text{ is continuous then, for all } x \in X \text{ and } \epsilon > 0, \text{ there exists } \delta > 0 \text{ such}$
 $\text{that, for all } y \in X, \text{ if } d(x, y) < \delta \text{ then } d(f(x), f(y)) < \epsilon.$
 $\langle 2 \rangle 1. \text{ ASSUME: } f \text{ is continuous.}$
 $\langle 2 \rangle 2. \text{ LET: } x \in X$
 $\langle 2 \rangle 3. \text{ LET: } \epsilon > 0$
 $\langle 2 \rangle 4. x \in f^{-1}(B(f(x), \epsilon))$
 $\langle 2 \rangle 5. \text{ There exists } \delta > 0 \text{ such that } B(x, \delta) \subseteq f^{-1}(B(f(x), \epsilon)).$
 $\langle 1 \rangle 2. \text{ If, for all } x \in X \text{ and } \epsilon > 0, \text{ there exists } \delta > 0 \text{ such that, for all } y \in X, \text{ if}$
 $d(x, y) < \delta \text{ then } d(f(x), f(y)) < \epsilon, \text{ then } f \text{ is continuous.}$
 $\langle 2 \rangle 1. \text{ ASSUME: For all } x \in X \text{ and } \epsilon > 0, \text{ there exists } \delta > 0 \text{ such that, for all}$
 $y \in X, \text{ if } d(x, y) < \delta \text{ then } d(f(x), f(y)) < \epsilon.$
 $\langle 2 \rangle 2. \text{ LET: } V \text{ be open in } Y$
 $\langle 2 \rangle 3. \text{ LET: } x \in f^{-1}(V)$
 $\langle 2 \rangle 4. \text{ PICK } \epsilon > 0 \text{ such that } B(f(x), \epsilon) \subseteq V$
 $\langle 2 \rangle 5. \text{ PICK } \delta > 0 \text{ such that, for all } y \in X, \text{ if } d(x, y) < \delta \text{ then } d(f(x), f(y)) < \epsilon.$
 $\langle 2 \rangle 6. B(x, \delta) \subseteq f^{-1}(V)$
 \square

Proposition 16.1.25. *Let X be a metrizable space and Y a topological space. Let $f : X \rightarrow Y$. Assume that, for every sequence (x_n) in X and $l \in X$, if $x_n \rightarrow l$ as $n \rightarrow \infty$ then $f(x_n) \rightarrow f(l)$ as $n \rightarrow \infty$. Then f is continuous.*

PROOF:

$\langle 1 \rangle 1$. LET: $A \subseteq X$

PROVE: $f(\overline{A}) \subseteq \overline{f(A)}$

$\langle 1 \rangle 2$. LET: $l \in \overline{A}$

PROVE: $f(l) \in \overline{f(A)}$

$\langle 1 \rangle 3$. PICK a sequence (x_n) in A such that $x_n \rightarrow l$ as $n \rightarrow \infty$.

$\langle 1 \rangle 4$. $f(x_n) \rightarrow f(l)$ as $n \rightarrow \infty$.

$\langle 1 \rangle 5$. $f(l) \in \overline{f(A)}$

□

Proposition 16.1.26. *The function $i : \mathbb{R} - \{0\} \rightarrow \mathbb{R}$ that maps x to x^{-1} is continuous.*

PROOF:

$\langle 1 \rangle 1$. LET: $a, b \in \mathbb{R}$ with $a < b$

PROVE: $i^{-1}((a, b))$ is open.

$\langle 1 \rangle 2$. CASE: $0 < a$

PROOF: $i^{-1}((a, b)) = (b^{-1}, a^{-1})$

$\langle 1 \rangle 3$. CASE: $a = 0$

PROOF: $i^{-1}((a, b)) = (b^{-1}, +\infty)$

$\langle 1 \rangle 4$. CASE: $a < 0 < b$

PROOF: $i^{-1}((a, b)) = (-\infty, a^{-1}) \cup (b^{-1}, +\infty)$

$\langle 1 \rangle 5$. CASE: $b = 0$

PROOF: $i^{-1}((a, b)) = (-\infty, a^{-1})$

$\langle 1 \rangle 6$. CASE: $b < 0$

PROOF: $i^{-1}((a, b)) = (b^{-1}, a^{-1})$

□

Proposition 16.1.27. *Subtraction is a continuous function $\mathbb{R}^2 \rightarrow \mathbb{R}$.*

PROOF: Since $a - b = a + (-1)b$ and both addition and multiplication are continuous. □

Proposition 16.1.28. *Division is a continuous function $\mathbb{R} \times (\mathbb{R} - \{0\}) \rightarrow \mathbb{R}$.*

PROOF: Since both multiplication and the function that maps x to x^{-1} are continuous. □

Proposition 16.1.29. *Let X be a metric space. Let $A \subseteq X$ be nonempty. The function $d(-, A) : X \rightarrow \mathbb{R}$ is continuous.*

PROOF:

$\langle 1 \rangle 1$. LET: $x \in X$ and $\epsilon > 0$.

$\langle 1 \rangle 2$. LET: $\delta = \epsilon/2$

$\langle 1 \rangle 3$. LET: $y \in X$ with $d(x, y) < \delta$.

$\langle 1 \rangle 4.$ $d(x, A) < d(y, A) + \epsilon$

$\langle 2 \rangle 1.$ $\forall a \in A. d(x, a) < d(y, a) + \delta$

PROOF:

$$\begin{aligned} d(x, a) &\leq d(y, a) + d(x, y) && \text{(Triangle Inequality)} \\ &< d(y, a) + \delta && (\langle 1 \rangle 3) \end{aligned}$$

$\langle 2 \rangle 2.$ $\forall a \in A. d(x, A) < d(y, a) + \delta$

$\langle 2 \rangle 3.$ $\forall a \in A. d(x, A) - \delta < d(y, a)$

$\langle 2 \rangle 4.$ $d(x, A) - \delta \leq d(y, A)$

$\langle 2 \rangle 5.$ $d(x, A) \leq d(y, A) + \delta$

$\langle 2 \rangle 6.$ $d(x, A) < d(y, A) + \epsilon$

$\langle 1 \rangle 5.$ $d(y, A) < d(x, A) + \epsilon$

PROOF: Similar.

$\langle 1 \rangle 6.$ $|d(x, A) - d(y, A)| < \epsilon$

□

Proposition 16.1.30. *Addition is a continuous function $\mathbb{R}^2 \rightarrow \mathbb{R}$.*

PROOF:

$\langle 1 \rangle 1.$ LET: $(x, y) \in \mathbb{R}^2$ and $\epsilon > 0$

$\langle 1 \rangle 2.$ LET: $\delta = \epsilon/2$

$\langle 1 \rangle 3.$ LET: $(x', y') \in (x - \delta, x + \delta) \times (y - \delta, y + \delta)$

$\langle 1 \rangle 4.$ $|x - x'|, |y - y'| < \delta$

$\langle 1 \rangle 5.$ $|(x + y) - (x' + y')| < \epsilon$

PROOF:

$$\begin{aligned} |(x + y) - (x' + y')| &\leq |x - x'| + |y - y'| \\ &< \delta + \delta && (\langle 1 \rangle 4) \\ &= \epsilon && (\langle 1 \rangle 2) \end{aligned}$$

□

16.1.5 First Countable Spaces

Proposition 16.1.31. *Every metrizable space is first countable.*

PROOF: For any point x , the set $\{B(x, 1/n) : n \in \mathbb{Z}_+\}$ is a countable basis at x .

□

Corollary 16.1.31.1. \mathbb{R}^ω under the box topology is not metrizable.

Corollary 16.1.31.2. If J is an uncountable set then \mathbb{R}^J under the product topology is not metrizable.

16.1.6 Hausdorff Spaces

Proposition 16.1.32. *Every metric space is Hausdorff.*

PROOF:

$\langle 1 \rangle 1.$ LET: X be a metric space.

- <1>2. LET: $x, y \in X$ with $x \neq y$.
 <1>3. LET: $\epsilon = d(x, y)$
 <1>4. $B(x, \epsilon/2)$ and $B(y, \epsilon/2)$ are disjoint neighbourhoods of x and y .
 \square

16.1.7 Bounded Sets

Definition 16.1.33 (Bounded). Let X be a metric space. Let $A \subseteq X$. Then A is *bounded* iff there exists M such that $\forall x, y \in A. d(x, y) \leq M$. Its *diameter* is then defined to be

$$\text{diam } A := \sup\{d(x, y) : x, y \in A\} .$$

16.1.8 Uniform Convergence

Definition 16.1.34 (Uniform Convergence). Let X be a set and Y a metric space. Let (f_n) be a sequence of functions $X \rightarrow Y$, and $f : X \rightarrow Y$. Then (f_n) *converges uniformly* to f iff, for all $\epsilon > 0$, there exists N such that

$$\forall n \geq N. \forall x \in X. d(f_n(x), f(x)) < \epsilon .$$

Example 16.1.35. For $n \in \mathbb{N}$ define $f_n : [0, 1] \rightarrow \mathbb{R}$ by $f_n(x) = x^n$. Define $f : [0, 1] \rightarrow \mathbb{R}$ by $f(x) = 0$ for $x < 1$, $f(1) = 1$. Then f_n converges pointwise to f , but does not converge uniformly to f .

We prove that, for all N , there exists $n \geq N$ and $x \in [0, 1]$ such that $|x^n - f(x)| \geq 1/2$. Take $n = N$ and x to be the N th root of $3/4$.

Example 16.1.36. For $n \in \mathbb{N}$, define $f_n : \mathbb{R} \rightarrow \mathbb{R}$ by

$$f_n(x) = \frac{1}{n^3[x - (1/n)]^2 + 1} .$$

Then for all $x \in \mathbb{R}$ we have $f_n(x) \rightarrow 0$ as $n \rightarrow \infty$, but (f_n) does not converge uniformly to 0.

We prove that, for all N , there exists $n \geq N$ and $x \in \mathbb{R}$ such that $|f_n(x)| \geq 1/2$. Take $n = N$ and $x = 1/N$. We have $f_N(1/N) = 1$.

Theorem 16.1.37 (Uniform Limit Theorem). *Let X be a topological space and Y a metric space. Let (f_n) be a sequence of functions $X \rightarrow Y$, and $f : X \rightarrow Y$. If every f_n is continuous and (f_n) converges uniformly to f , then f is continuous.*

PROOF:

<1>1. LET: V be open in Y .

<1>2. LET: $x_0 \in f^{-1}(V)$

PROVE: There exists a neighbourhood U of x_0 such that $f(U) \subseteq V$.

<1>3. LET: $y_0 = f(x_0)$

<1>4. PICK $\epsilon > 0$ such that $B(y_0, \epsilon) \subseteq V$.

- $\langle 1 \rangle 5$. PICK N such that $\forall n \geq N. \forall x \in X. d(f_n(x), f(x)) < \epsilon/3$.
 $\langle 1 \rangle 6$. PICK a neighbourhood U of x_0 such that $f_N(U) \subseteq B(f_N(x_0), \epsilon/3)$.
 PROVE: $f(U) \subseteq V$
 $\langle 1 \rangle 7$. LET: $y \in U$
 $\langle 1 \rangle 8$. $d(f(y), y_0) < \epsilon$
 PROOF:

$$\begin{aligned} d(f(y), y_0) &\leq d(f(y), f_N(y)) + d(f_N(y), f_N(x_0)) + d(f_N(x_0), y_0) \\ &< \epsilon/3 + \epsilon/3 + \epsilon/3 & (\langle 1 \rangle 5, \langle 1 \rangle 6)l \\ &= \epsilon \end{aligned}$$

 $\langle 1 \rangle 9$. $f(y) \in V$
 PROOF: $\langle 1 \rangle 4$
 \square

Proposition 16.1.38. *Let X be a topological space. Let Y be a metric space. Let f_n be a sequence of functions $X \rightarrow Y$ and $f : X \rightarrow Y$. Let x_n be a sequence of points in X and $l \in X$. If f_n converges uniformly to f , x_n converges to l , and f is continuous, then $f_n(x_n)$ converges to $f(l)$.*

- PROOF:
 $\langle 1 \rangle 1$. f is continuous.
 $\langle 1 \rangle 2$. LET: $\epsilon > 0$
 $\langle 1 \rangle 3$. PICK $\delta > 0$ such that $\forall y \in X. d(y, l) < \delta \Rightarrow d(f(y), f(l)) < \epsilon/2$
 $\langle 1 \rangle 4$. PICK N such that $\forall n \geq N. \forall x \in X. d(f_n(x), f(x)) < \epsilon/2$ and $\forall n \geq N. d(x_n, l) < \delta$
 $\langle 1 \rangle 5$. For all $n \geq N$ we have $d(f_n(x_n), f(l)) < \epsilon$
 PROOF:

$$\begin{aligned} d(f_n(x_n), f(l)) &\leq d(f_n(x_n), f(x_n)) + d(f(x_n), f(l)) \\ &< \epsilon/2 + \epsilon/2 \\ &= \epsilon \end{aligned}$$

 \square

Theorem 16.1.39 (Weierstrass M -Test). *Let X be a set. Let (f_n) be a sequence of functions $X \rightarrow \mathbb{R}$. Let (M_n) be a sequence of real numbers. For $n \in \mathbb{N}$, let*

$$s_n(x) = \sum_{i=0}^n f_i(x) \quad .$$

Assume that $\forall n \in \mathbb{N}. \forall x \in X. |f_n(x)| \leq M_n$. Assume that $\sum_{n=0}^{\infty} M_n$ converges. Then (s_n) uniformly converges to s where $s(x) = \sum_{n=0}^{\infty} f_n(x)$.

- PROOF:
 $\langle 1 \rangle 1$. For all $x \in X$ we have $\sum_{n=0}^{\infty} f_n(x)$ converges.
 PROOF: By the Comparison Test.
 $\langle 1 \rangle 2$. For $n \in \mathbb{N}$,
 LET: $r_n = \sum_{i=n+1}^{\infty} M_i$.
 $\langle 1 \rangle 3$. For all $k, n \in \mathbb{N}$ and $x \in X$, if $k > n$ then $|s_k(x) - s_n(x)| \leq r_n$.

PROOF:

$$\begin{aligned}
 |s_k(x) - s_n(x)| &= \left| \sum_{i=n+1}^k f_i(x) \right| \\
 &\leq \sum_{i=n+1}^k |f_i(x)| \\
 &\leq \sum_{i=n+1}^k M_i \\
 &\leq \sum_{i=n+1}^{\infty} M_i \\
 &= r_n
 \end{aligned}$$

$\langle 1 \rangle 4$. For all $n \in \mathbb{N}$ we have $|s(x) - s_n(x)| \leq r_n$.

PROOF: Taking the limit $k \rightarrow \infty$ in $\langle 1 \rangle 3$.

$\langle 1 \rangle 5$. (s_n) converges uniformly to s .

PROOF: We have $\bar{\rho}(s_n, s) \leq r_n$ and so $\bar{\rho}(s_n, s) \rightarrow 0$ as $n \rightarrow \infty$ by the Sandwich Theorem.

□

Theorem 16.1.40. *Let X be a compact space. Let $f_n : X \rightarrow \mathbb{R}$ be a monotone increasing sequence of continuous functions, and $f : X \rightarrow \mathbb{R}$ be continuous. If f_n converges to f pointwise, then f_n converges to f uniformly.*

PROOF:

$\langle 1 \rangle 1$. LET: $\epsilon > 0$

$\langle 1 \rangle 2$. For all $x \in X$, there exists a neighbourhood U of x and an integer N such that, for all $y \in U$, we have $|f_N(y) - f(y)| < \epsilon$

$\langle 2 \rangle 1$. LET: $x \in X$

$\langle 2 \rangle 2$. PICK N such that $\forall n \geq N, |f_n(x) - f(x)| < \epsilon/3$.

$\langle 2 \rangle 3$. PICK neighbourhoods U_1, U_2 of x such that $\forall y \in U_1, |f_N(y) - f_N(x)| < \epsilon/3$ and $\forall y \in U, |f(y) - f(x)| < \epsilon/3$.

$\langle 2 \rangle 4$. LET: $U = U_1 \cap U_2$

$\langle 2 \rangle 5$. LET: $y \in U$

$\langle 2 \rangle 6$. $|f_N(y) - f(y)| < \epsilon$

PROOF:

$$\begin{aligned}
 |f_N(y) - f(y)| &\leq |f_N(y) - f_N(x)| + |f_N(x) - f(x)| + |f(x) - f(y)| \quad (\text{Triangle Inequality}) \\
 &< \epsilon/3 + \epsilon/3 + \epsilon/3 \quad (\langle 2 \rangle 2, \langle 2 \rangle 3) \\
 &= \epsilon
 \end{aligned}$$

$\langle 1 \rangle 3$. PICK open sets U_1, \dots, U_k that cover X such that, for all i , there exists N_i such that $\forall y \in U_i, |f_{N_i}(y) - f(y)| < \epsilon$

$\langle 1 \rangle 4$. LET: $N = \max(N_1, \dots, N_k)$

$\langle 1 \rangle 5$. For all $x \in X$ we have $|f_N(x) - f(x)| < \epsilon$

$\langle 1 \rangle 6$. For all $n \geq N$ and $x \in X$ we have $|f_n(x) - f(x)| < \epsilon$

□

Example 16.1.41. We cannot remove the requirement that (f_n) is monotone increasing.

For all $n \in \mathbb{Z}_+$, define $f_n : [0, 1] \rightarrow \mathbb{R}$ by

$$f_n(x) = \frac{1}{n^3[x - (1/n)]^2 + 1} .$$

Then $f_n(x) \rightarrow 0$ as $n \rightarrow \infty$ for all x , but the convergence is not uniform.

Example 16.1.42. We cannot remove the requirement that X is compact.

For all $n \in \mathbb{Z}_+$, define $f_n : [0, 1] \rightarrow \mathbb{R}$ by $f_n(x) = -x^n$. Then (f_n) is monotone increasing and $f_n(x) \rightarrow 0$ as $n \rightarrow \infty$ for all x , but the convergence is not uniform.

16.1.9 Standard Bounded Metric

Definition 16.1.43 (Standard Bounded Metric). Let (X, d) be a metric space. The *standard bounded metric* corresponding to d is

$$\bar{d}(x, y) := \min(d(x, y), 1) .$$

Proposition 16.1.44. *The standard bounded metric associated with d induces the same topology as d .*

PROOF:

- $\langle 1 \rangle 1$. LET: (X, d) be a metric space.
- $\langle 1 \rangle 2$. Every d -ball is open under the topology induced by \bar{d} .
 - $\langle 2 \rangle 1$. LET: $a \in X$ and $\epsilon > 0$
 - $\langle 2 \rangle 2$. LET: $x \in B_d(a, \epsilon)$
 - $\langle 2 \rangle 3$. LET: $\delta = \min(\epsilon - d(a, x), 1/2)$
 - $\langle 2 \rangle 4$. $B_{\bar{d}}(x, \delta) \subseteq B_d(a, \epsilon)$
- $\langle 1 \rangle 3$. Every \bar{d} -ball is open under the topology induced by d .

PROOF: Since $B_{\bar{d}}(a, \epsilon) = B_d(a, \epsilon)$ if $\epsilon \leq 1$, and X if $\epsilon > 1$.

□

16.1.10 Product Spaces

Proposition 16.1.45. *The product of a countable family of metrizable spaces is metrizable.*

PROOF:

- $\langle 1 \rangle 1$. LET: (X_n, d_n) be a sequence of metric spaces.
- $\langle 1 \rangle 2$. For $n \in \mathbb{N}$,
 - LET: \bar{d}_n be the standard bounded metric associated with d_n .
- $\langle 1 \rangle 3$. LET: $X = \prod_{n \in \mathbb{N}} X_n$
- $\langle 1 \rangle 4$. Define $D : X^2 \rightarrow \mathbb{R}$ by $D(x, y) = \sup_{n \in \mathbb{N}} \bar{d}_n(\pi_n(x), \pi_n(y)) / (n + 1)$.
- $\langle 1 \rangle 5$. D is a metric on X .
 - $\langle 2 \rangle 1$. For all $x, y \in X$ we have $D(x, y) \geq 0$.

- ⟨2⟩2. For all $x, y \in X$ we have $D(x, y) = 0$ iff $x = y$.
- ⟨2⟩3. For all $x, y \in X$ we have $D(x, y) = D(y, x)$.
- ⟨2⟩4. For all $x, y, z \in X$ we have $D(x, z) \leq D(x, y) + D(y, z)$.
- ⟨1⟩6. The product topology is finer than the metric topology induced by D .
 - ⟨2⟩1. LET: $a \in X$ and $\epsilon > 0$.
 - ⟨2⟩2. LET: $x \in B(a, \epsilon)$
 - ⟨2⟩3. LET: $\delta = \epsilon - D(a, x)$
 - ⟨2⟩4. PICK $N \in \mathbb{N}$ such that $1/(N+1) < \delta$
 - ⟨2⟩5. $x \in \prod_{n=0}^N B_{d_n}(\pi_n(a), n\delta) \times \prod_{n=N+1}^{\infty} B(a, \epsilon)$
- ⟨1⟩7. The metric topology induced by D is finer than the product topology.
 - ⟨2⟩1. LET: $n \in \mathbb{N}$ and U be an open set in X_n .
PROVE: $\pi_n^{-1}(U)$ is open in the metric topology.
 - ⟨2⟩2. LET: $x \in \pi_n^{-1}(U)$
 - ⟨2⟩3. PICK $\epsilon > 0$ such that $B_{d_n}(\pi_n(x), \epsilon) \subseteq U$
 - ⟨2⟩4. $B(x, \epsilon/(n+1)) \subseteq \pi_n^{-1}(U)$

□

Definition 16.1.46. For $n \geq 1$, the *unit ball* B^n is the closed ball $\overline{B(0, 1)}$ in \mathbb{R}^n under the Euclidean metric.

Theorem 16.1.47. Let n be a positive integer. Let A be a subspace of \mathbb{R}^n . Then A is compact if and only if it is closed and bounded.

PROOF:

- ⟨1⟩1. If A is compact then A is closed.
PROOF: Theorem 15.31.10.
- ⟨1⟩2. If A is compact then A is bounded.
PROOF: Proposition 16.1.20.
- ⟨1⟩3. If A is closed and bounded then A is compact.
 - ⟨2⟩1. ASSUME: A is closed and bounded.
 - ⟨2⟩2. PICK M such that $\forall \vec{x}, \vec{y} \in A. \rho(\vec{x}, \vec{y}) < M$.
 - ⟨2⟩3. ASSUME: w.l.o.g. $A \neq \emptyset$
 - ⟨2⟩4. PICK $\vec{a} \in A$
 - ⟨2⟩5. $A \subseteq \prod_{i=1}^n [a_i - M, a_i + M]$
 - ⟨2⟩6. A is compact.
PROOF: Theorem 15.31.7.

Corollary 16.1.47.1. For $n \geq 1$, the unit sphere S^{n-1} and the unit ball B^n are compact.

16.2 Uniform Metric

Definition 16.2.1 (Uniform Metric). Let J be a nonempty set. The *uniform metric* $\bar{\rho}$ on \mathbb{R}^J is defined by

$$\bar{\rho}(x, y) = \sup_{j \in J} \bar{d}(x_j, y_j)$$

where \bar{d} is the standard bounded metric associated with the standard metric on \mathbb{R} .

On \mathbb{R}^n we call the uniform metric the *square metric* and denote it by ρ .

The topology it induces is called the *uniform topology*.

We prove this is a metric.

PROOF:

$\langle 1 \rangle 1$. For all $x, y \in \mathbb{R}^\omega$ we have $\bar{\rho}(x, y) \geq 0$.

PROOF: Pick $j_0 \in J$. Then

$$\begin{aligned}\bar{\rho}(x, y) &= \sup_j \bar{d}(x_j, y_j) \\ &\geq \bar{d}(x_{j_0}, y_{j_0}) \\ &\geq 0\end{aligned}$$

$\langle 1 \rangle 2$. For all $x, y \in \mathbb{R}^\omega$ we have $\bar{\rho}(x, y) = 0$ iff $x = y$.

PROOF:

$$\begin{aligned}\bar{\rho}(x, y) = 0 &\Leftrightarrow \sup_j \bar{d}(x_j, y_j) = 0 \\ &\Leftrightarrow \forall j. \bar{d}(x_j, y_j) = 0 \\ &\Leftrightarrow \forall j. x_j = y_j \\ &\Leftrightarrow x = y\end{aligned}$$

$\langle 1 \rangle 3$. For all $x, y \in \mathbb{R}^\omega$ we have $\bar{\rho}(x, y) = \bar{\rho}(y, x)$.

PROOF:

$$\begin{aligned}\bar{\rho}(x, y) &= \sup_j \bar{d}(x_j, y_j) \\ &= \sup_j \bar{d}(y_j, x_j) \\ &= \bar{\rho}(y, x)\end{aligned}$$

$\langle 1 \rangle 4$. For all $x, y, z \in \mathbb{R}^\omega$ we have $\bar{\rho}(x, z) \leq \bar{\rho}(x, y) + \bar{\rho}(y, z)$.

PROOF:

$$\begin{aligned}\bar{\rho}(x, z) &= \sup_j \bar{d}(x_j, z_j) \\ &\leq \sup_j (\bar{d}(x_j, y_j) + \bar{d}(y_j, z_j)) \\ &\leq \sup_j \bar{d}(x_j, y_j) + \sup_j \bar{d}(y_j, z_j) \\ &= \bar{\rho}(x, y) + \bar{\rho}(y, z)\end{aligned}$$

□

Proposition 16.2.2. *The uniform topology is finer than the product topology. It is strictly finer iff J is infinite.*

PROOF:

$\langle 1 \rangle 1$. The uniform topology is finer than the product topology.

$\langle 2 \rangle 1$. LET: U be open in \mathbb{R} and $j \in J$

PROVE: $\pi_j^{-1}(U)$ is open in the uniform topology.

$\langle 2 \rangle 2$. LET: $x \in \pi_j^{-1}(U)$

- ⟨2⟩3. $\pi_j(x) \in U$
- ⟨2⟩4. PICK $\epsilon > 0$ such that $B_{\bar{d}}(\pi_j(x), \epsilon) \subseteq U$
- ⟨2⟩5. $B_{\bar{p}}(x, \epsilon) \subseteq \pi_j^{-1}(U)$
- ⟨1⟩2. If J is finite then the uniform topology is equal to the product topology.
PROOF: In \mathbb{R}^n , the uniform topology is the square topology.
- ⟨1⟩3. If J is infinite then the uniform topology is not equal to the product topology.
PROOF: If J is infinite then $B(0, 1)$ is not open in the product topology.

□

Proposition 16.2.3. *The uniform topology is coarser than the box topology. It is strictly coarser iff J is infinite.*

PROOF:

- ⟨1⟩1. The uniform topology is coarser than the box topology.
- ⟨2⟩1. LET: U be open in the uniform topology.
PROVE: U is open in the box topology.
- ⟨2⟩2. LET: $x \in U$
- ⟨2⟩3. PICK $\epsilon > 0$ such that $B(x, \epsilon) \subseteq U$
- ⟨2⟩4. $\prod_{j \in J} (x_j - \epsilon, x_j + \epsilon) \subseteq U$
- ⟨1⟩2. If J is finite then the uniform topology is equal to the box topology.
PROOF: On \mathbb{R}^n , the uniform metric is the square metric.
- ⟨1⟩3. If J is infinite then the uniform topology is not equal to the box topology.
- ⟨2⟩1. ASSUME: J is infinite.
- ⟨2⟩2. PICK a sequence (j_n) of distinct elements in J .
- ⟨2⟩3. LET: $U = \prod_j U_j$ where $J_{j_n} = (-1/(n+1), 1/(n+1))$ for $n \in \mathbb{N}$ and $J_j = (-1, 1)$ for all other j .
- ⟨2⟩4. U is not open in the uniform topology.

□

Proposition 16.2.4. *The uniform topology on \mathbb{R}^∞ is strictly finer than the product topology.*

PROOF: The set of all sequences $(x_n) \in \mathbb{R}^\infty$ such that $\forall n. |x_n| < 1$ is open in the uniform topology but not in the product topology. □

Proposition 16.2.5. *The uniform topology on \mathbb{R}^∞ is strictly coarser than the box topology.*

PROOF: The set of sequences $(x_n) \in \mathbb{R}^\infty$ such that $\forall n. |x_n| < 1/n$ is open in the box topology but not in the uniform topology. □

Proposition 16.2.6. *The uniform topology on the Hilbert cube is the same as the product topology.*

PROOF:

- ⟨1⟩1. LET: (x_n) be in the Hilbert cube H and $\epsilon > 0$.
PROVE: $B((x_n), \epsilon) \cap H$ is open in the product topology.
- ⟨1⟩2. PICK N such that $1/N < \epsilon$

$\langle 1 \rangle 3.$ $B((x_n), \epsilon) = (\prod_{n=0}^N (x_n - \epsilon, x_n + \epsilon) \times \prod_{n=N+1}^{\infty} [0, 1/(n+1)]) \cap H$
 \square

Corollary 16.2.6.1. *The uniform topology on the Hilbert cube is strictly finer than the box topology.*

Proposition 16.2.7. *Let X be a set and Y a metric space. Let (f_n) be a sequence of functions $X \rightarrow Y$, and $f : X \rightarrow Y$. Then (f_n) converges uniformly to f iff (f_n) converges to f in Y^X under the uniform topology.*

PROOF:

$\langle 1 \rangle 1.$ If (f_n) converges uniformly to f then (f_n) converges to f in Y^X under the uniform topology.

$\langle 2 \rangle 1.$ ASSUME: (f_n) converges uniformly to f .

$\langle 2 \rangle 2.$ LET: $\epsilon > 0$

$\langle 2 \rangle 3.$ PICK N such that $\forall n \geq N. \forall x \in X. d(f_n(x), f(x)) < \epsilon/2$

$\langle 2 \rangle 4.$ $\forall n \geq N. \bar{\rho}(f_n, f) \leq \epsilon/2$

$\langle 2 \rangle 5.$ $\forall n \geq N. \bar{\rho}(f_n, f) < \epsilon$

$\langle 1 \rangle 2.$ If (f_n) converges to f in Y^X under the uniform topology then (f_n) converges uniformly to f .

$\langle 2 \rangle 1.$ ASSUME: (f_n) converges to f in Y^X under the uniform topology.

$\langle 2 \rangle 2.$ LET: $\epsilon > 0$

$\langle 2 \rangle 3.$ PICK N such that $\forall n \geq N. \bar{\rho}(f_n, f) < \epsilon$

$\langle 2 \rangle 4.$ $\forall n \geq N. \forall x \in X. d(f_n(x), f(x)) < \epsilon$

\square

Proposition 16.2.8. *In \mathbb{R}^ω under the uniform topology, \vec{x} and \vec{y} lie in the same component if and only if $\vec{x} - \vec{y}$ is bounded.*

PROOF:

$\langle 1 \rangle 1.$ The set of bounded sequences form a component of \mathbb{R}^ω .

$\langle 2 \rangle 1.$ LET: B be the set of bounded sequences.

$\langle 2 \rangle 2.$ B is connected.

$\langle 3 \rangle 1.$ LET: $\vec{x} \in B$

PROVE: The straight line path $p : [0, 1] \rightarrow \mathbb{R}^\omega$ from 0 to \vec{x} is continuous.

$\langle 3 \rangle 2.$ LET: $t \in [0, 1]$ and $\epsilon > 0$

$\langle 3 \rangle 3.$ PICK $B > 0$ such that $\forall n. |x_n| < B$

$\langle 3 \rangle 4.$ LET: $\delta = \epsilon/B$

$\langle 3 \rangle 5.$ LET: $s \in [0, 1]$ with $|s - t| < \delta$

$\langle 3 \rangle 6.$ For all n we have $|p(s)_n - p(t)_n| < \epsilon/2$

PROOF:

$$\begin{aligned} |p(s)_n - p(t)_n| &= |s - t| |x_n| \\ &< \delta B \\ &= \epsilon \end{aligned}$$

$\langle 3 \rangle 7.$ $\bar{\rho}(p(s), p(t)) \leq \epsilon/2$

$\langle 3 \rangle 8.$ $\bar{\rho}(p(s), p(t)) < \epsilon$

⟨2⟩3. B is maximally connected.

PROOF: Since $(B, \mathbb{R}^\omega - B)$ form a separation of \mathbb{R}^ω .

⟨1⟩2. For any $\vec{y} \in \mathbb{R}^\omega$, the component containing \vec{y} is $\{\vec{x} \in \mathbb{R}^\omega : \vec{x} - \vec{y} \text{ is bounded}\}$.

PROOF: Since the function that maps \vec{x} to $\vec{x} + \vec{y}$ is a homeomorphism between \mathbb{R}^ω and itself.

□

16.2.1 Products

Definition 16.2.9 (Euclidean Metric). Let X and Y be metric spaces. The *Euclidean metric* on $X \times Y$ is

$$d((x_1, y_1), (x_2, y_2)) = \sqrt{d(x_1, x_2)^2 + d(y_1, y_2)^2}.$$

We write $X \times Y$ for the set $X \times Y$ under this metric.

We prove this is a metric.

PROOF:

⟨1⟩1. $d((x_1, y_1), (x_2, y_2)) \geq 0$

PROOF: Immediate from definition.

⟨1⟩2. $d((x_1, y_1), (x_2, y_2)) = 0$ iff $(x_1, y_1) = (x_2, y_2)$

PROOF: $\sqrt{d(x_1, x_2)^2 + d(y_1, y_2)^2} = 0$ iff $d(x_1, x_2) = d(y_1, y_2) = 0$ iff $x_1 = x_2$ and $y_1 = y_2$.

⟨1⟩3. $d((x_1, y_1), (x_2, y_2)) = d((x_2, y_2), (x_1, y_1))$

PROOF: Since $\sqrt{d(x_1, x_2)^2 + d(y_1, y_2)^2} = \sqrt{d(x_2, x_1)^2 + d(y_2, y_1)^2}$.

⟨1⟩4. The triangle inequality holds.

PROOF:

$$\begin{aligned} & (d((x_1, y_1), (x_2, y_2)) + d((x_2, y_2), (x_3, y_3)))^2 \\ &= d((x_1, y_1), (x_2, y_2))^2 + 2d((x_1, y_1), (x_2, y_2))d((x_2, y_2), (x_3, y_3)) + d((x_2, y_2), (x_3, y_3))^2 \\ &= d(x_1, x_2)^2 + d(y_1, y_2)^2 + 2\sqrt{(d(x_1, x_2)^2 + d(y_1, y_2)^2)(d(x_2, x_3)^2 + d(y_2, y_3)^2)} + d(x_2, x_3)^2 + d(y_2, y_3)^2 \\ &\geq d(x_1, x_2)^2 + d(x_2, x_3)^2 + d(y_1, y_2)^2 + d(y_2, y_3)^2 + 2(d(x_1, x_2)d(x_2, x_3) + d(y_1, y_2)d(y_2, y_3)) \\ &\quad (\text{Cauchy-Schwarz}) \\ &= (d(x_1, x_2) + d(x_2, x_3))^2 + (d(y_1, y_2) + d(y_2, y_3))^2 \\ &\geq d(x_1, x_3)^2 + d(y_1, y_3)^2 \\ &= d((x_1, y_1), (x_3, y_3))^2 \end{aligned}$$

□

Proposition 16.2.10. Let X and Y be metric spaces. The Euclidean metric on $X \times Y$ induces the product topology on $X \times Y$.

PROOF:

⟨1⟩1. Every open ball is open in the product topology.

⟨2⟩1. LET: $(x, y) \in B((a, b), \epsilon)$

PROVE: $B(x, \sqrt{\epsilon}) \times B(y, \sqrt{\epsilon}) \subseteq B((a, b), \epsilon)$

⟨2⟩2. LET: $x' \in B(x, \sqrt{(\epsilon - d((x, y), (a, b)))^2/2})$ and $y' \in B(y, \sqrt{(\epsilon - d((x, y), (a, b)))^2/2})$

PROVE: $d((x', y'), (a, b)) < \epsilon$
 $\langle 2 \rangle 3. d((x', y'), (x, y)) < \epsilon - d((x, y), (a, b))$

PROOF:

$$\begin{aligned} d((x', y'), (x, y)) &= \sqrt{d(x', x)^2 + d(y', y)^2} \\ &< \sqrt{(\epsilon - d((x, y), (a, b)))^2/2 + (\epsilon - d((x, y), (a, b)))^2/2} \\ &= \epsilon - d((x, y), (a, b)) \end{aligned}$$

$\langle 2 \rangle 4. d((x', y'), (a, b)) < \epsilon$

PROOF:

$$\begin{aligned} d((x', y'), (a, b)) &\leq d((x', y'), (x, y)) + d((x, y), (a, b)) \quad (\text{Triangle Inequality}) \\ &< \epsilon \end{aligned} \quad (\langle 2 \rangle 3)$$

$\langle 1 \rangle 2.$ If U is open in X and V is open in Y then $U \times V$ is open under the Euclidean metric.

$\langle 2 \rangle 1.$ LET: $(x, y) \in U \times V$

$\langle 2 \rangle 2.$ PICK $\delta, \epsilon > 0$ such that $B(x, \delta) \subseteq U$ and $B(y, \epsilon) \subseteq V$

PROVE: $(B((x, y), \min(\delta, \epsilon))) \subseteq U \times V$

$\langle 2 \rangle 3.$ LET: $(x', y') \in B((x, y), \min(\delta, \epsilon))$

$\langle 2 \rangle 4. d(x', x) < \delta$

$\langle 3 \rangle 1. d((x', y'), (x, y)) < \min(\delta, \epsilon)$

$\langle 3 \rangle 2. d(x', x)^2 + d(y', y)^2 < \delta^2$

$\langle 3 \rangle 3. d(x', x)^2 < \delta^2$

$\langle 2 \rangle 5. d(y', y) < \epsilon$

PROOF: Similar.

$\langle 2 \rangle 6. (x', y') \in U \times V$

□

Proposition 16.2.11. *The square metric on \mathbb{R}^n induces the product topology.*

PROOF:

$\langle 1 \rangle 1.$ LET: d be the Euclidean metric on \mathbb{R}^n and ρ the square metric.

$\langle 1 \rangle 2.$ For all $x \in X$ and $\epsilon > 0$, there exists $\delta > 0$ such that $B_d(x, \delta) \subseteq B_\rho(x, \epsilon)$

PROOF: If $d(x, y) < \epsilon$ then $\rho(x, y) < \epsilon$.

$\langle 1 \rangle 3.$ For all $x \in X$ and $\epsilon > 0$, there exists $\delta > 0$ such that $B_\rho(x, \delta) \subseteq B_d(x, \epsilon)$

PROOF: If $\rho(x, y) < \epsilon/\sqrt{n}$ then $d(x, y) < \epsilon$.

$\langle 1 \rangle 4.$ d and ρ induce the same topology.

PROOF: Proposition 16.1.16.

□

16.2.2 Connected Spaces

Example 16.2.12. The space \mathbb{R}^ω under the uniform topology is disconnected. The set of bounded sequences and the set of unbounded sequences form a separation.

16.3 Isometric Embeddings

Definition 16.3.1 (Isometric Embedding). Let X and Y be metric spaces. Let $f : X \rightarrow Y$. Then f is an *isometric embedding* of X in Y iff, for all $x, y \in X$, we have $d(f(x), f(y)) = d(x, y)$.

Proposition 16.3.2. *Every isometric embedding is an embedding.*

PROOF:

$\langle 1 \rangle 1$. LET: X and Y be metric spaces.

$\langle 1 \rangle 2$. LET: $f : X \rightarrow Y$ be an isometric embedding.

$\langle 1 \rangle 3$. f is injective.

$\langle 1 \rangle 4$. The subspace topology induced by f is finer than the metric topology.

$\langle 2 \rangle 1$. LET: $x \in X$ and $\epsilon > 0$

PROVE: $B(x, \epsilon)$ is open in the subspace topology.

$\langle 2 \rangle 2$. $B(x, \epsilon) = f^{-1}(B(f(x), \epsilon))$

$\langle 1 \rangle 5$. The metric topology is finer than the subspace topology induced by f .

$\langle 2 \rangle 1$. LET: V be open in Y

PROVE: $f^{-1}(V)$ is open in X

$\langle 2 \rangle 2$. LET: $x \in f^{-1}(V)$

$\langle 2 \rangle 3$. PICK $\epsilon > 0$ such that $B(f(x), \epsilon) \subseteq V$

$\langle 2 \rangle 4$. $B(x, \epsilon) \subseteq f^{-1}(V)$

□

16.4 Lebesgue Numbers

Definition 16.4.1 (Lebesgue Number). Let X be a metric space. Let \mathcal{A} be an open covering of X . A *Lebesgue number* for \mathcal{A} is a real number $\delta > 0$ such that every bounded set with diameter $< \delta$ is included in some member of \mathcal{A} .

Lemma 16.4.2 (Lebesgue Number Lemma). *In a compact metric space, every open cover has a Lebesgue number.*

PROOF:

$\langle 1 \rangle 1$. LET: X be a compact metric space.

$\langle 1 \rangle 2$. LET: \mathcal{A} be an open cover of X .

$\langle 1 \rangle 3$. ASSUME: w.l.o.g. $X \notin \mathcal{A}$

$\langle 1 \rangle 4$. PICK $A_1, \dots, A_n \in \mathcal{A}$ that cover X .

$\langle 1 \rangle 5$. For $i = 1, \dots, n$,

LET: $C_i = X - A_i$.

$\langle 1 \rangle 6$. LET: $f : X \rightarrow \mathbb{R}$ be the function

$$f(x) = \frac{1}{n} \sum_{i=1}^n d(x, C_i) .$$

PROOF: Each C_i is nonempty by $\langle 1 \rangle 3$.

$\langle 1 \rangle 7$. $\forall x \in X. f(x) > 0$

$\langle 2 \rangle 1$. LET: $x \in X$

- $\langle 2 \rangle 2$. PICK i such that $x \in A_i$
 $\langle 2 \rangle 3$. PICK $\epsilon > 0$ such that $B(x, \epsilon) \subseteq A_i$
 $\langle 2 \rangle 4$. $d(x, C_i) \geq \epsilon$
 $\langle 2 \rangle 5$. $f(x) \geq \epsilon/n$
 $\langle 1 \rangle 8$. LET: δ be the minimum value of $f(X)$.
 PROVE: δ is a Lebesgue number for \mathcal{A} .
 PROOF: $f(X)$ has a least element by the Extreme Value Theorem.
 $\langle 1 \rangle 9$. LET: $B \subseteq X$ have diameter $< \delta$
 $\langle 1 \rangle 10$. PICK $x_0 \in B$
 $\langle 1 \rangle 11$. $B \subseteq B(x_0, \delta)$
 $\langle 1 \rangle 12$. LET: m be such that $d(x_0, C_m) = \max(d(x_0, C_1), \dots, d(x_0, C_n))$
 $\langle 1 \rangle 13$. $d(x_0, C_m) \geq \delta$
 PROOF:

$$\delta \leq f(x_0) \quad (\langle 1 \rangle 8)$$

$$= \frac{1}{n} \sum_{i=1}^n d(x_0, C_i) \quad (\langle 1 \rangle 6)$$

$$\leq \frac{1}{n} \sum_{i=1}^n d(x_0, C_m) \quad (\langle 1 \rangle 12)$$

$$= d(x_0, C_m)$$

- $\langle 1 \rangle 14$. $B \subseteq A_m$
 PROOF: $\langle 1 \rangle 11, \langle 1 \rangle 13$
 \square

16.5 Uniform Continuity

Definition 16.5.1 (Uniformly Continuous). Let X and Y be metric spaces. Let $f : X \rightarrow Y$. Then f is *uniformly continuous* iff, for all $\epsilon > 0$, there exists $\delta > 0$ such that, for all $x, y \in X$, if $d(x, y) < \delta$ then $d(f(x), f(y)) < \epsilon$.

Theorem 16.5.2 (Uniform Continuity Theorem). *Every continuous function from a compact metric space to a metric space is uniformly continuous.*

PROOF:

- $\langle 1 \rangle 1$. LET: X be a compact metric space.
 $\langle 1 \rangle 2$. LET: Y be a metric space.
 $\langle 1 \rangle 3$. LET: $f : X \rightarrow Y$ be continuous.
 $\langle 1 \rangle 4$. LET: $\epsilon > 0$
 $\langle 1 \rangle 5$. PICK a Lebesgue number δ for $\{f^{-1}(B(y, \epsilon/2)) : y \in Y\}$.
 $\langle 1 \rangle 6$. LET: $x, x' \in X$
 $\langle 1 \rangle 7$. ASSUME: $d(x, x') < \delta$
 $\langle 1 \rangle 8$. PICK $y \in Y$ such that $\{x, x'\} \subseteq f^{-1}(B(y, \epsilon/2))$
 $\langle 1 \rangle 9$. $d(f(x), f(x')) < \epsilon$

PROOF:

$$\begin{aligned}
 d(f(x), f(x')) &\leq d(f(x), y) + d(y, f(x')) && \text{(Triangle Inequality)} \\
 &< \epsilon/2 + \epsilon/2 && (\langle 1 \rangle 8) \\
 &= \epsilon
 \end{aligned}$$

□

16.6 Complete Metric Spaces

Definition 16.6.1 (Complete). A metric space is *complete* iff every Cauchy sequence converges.

Example 16.6.2. \mathbb{R} is complete.

Proposition 16.6.3. *The product of two complete metric spaces is complete.*

Proposition 16.6.4. *Every compact metric space is complete.*

Proposition 16.6.5. *Let X be a complete metric space and $A \subseteq X$. Then A is complete if and only if A is closed.*

Definition 16.6.6 (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 16.6.7. *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 $\phi(\lim_{n \rightarrow \infty} i_1(x_n)) = \lim_{n \rightarrow \infty} i_2(x_n)$. □

Theorem 16.6.8. *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 $d(x_n, y_n) \rightarrow 0$. □

16.7 Manifolds

Definition 16.7.1 (Manifold). An *n -dimensional manifold* is a second countable Hausdorff space locally homeomorphic to \mathbb{R}^n .

Chapter 17

Homotopy Theory

17.1 Homotopies

Definition 17.1.1 (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

- $\forall x \in X. h(x, 0) = f(x)$
- $\forall x \in X. h(x, 1) = g(x)$

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

Definition 17.1.3. Let **HTop** be the category whose objects are the small topological spaces and whose morphisms are the homotopy classes of continuous functions.

A *homotopy functor* is a functor $\mathbf{Top} \rightarrow \mathcal{C}$ that factors through the canonical functor $\mathbf{Top} \rightarrow \mathbf{HTop}$.

Definition 17.1.4. A functor $F : \mathbf{Top} \rightarrow \mathcal{C}$ is *homotopy invariant* iff, for any topological spaces X, Y and continuous functions $f, g : X \rightarrow Y$, if $f \simeq g$ then $Hf = Hg$.

Basepoint-preserving homotopy.

17.2 Homotopy Equivalence

Definition 17.2.1 (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 17.2.2 (Contractible). A topological space X is *contractible* iff $X \simeq 1$.

Example 17.2.3. \mathbb{R}^n is contractible.

Example 17.2.4. D^n is contractible.

Definition 17.2.5 (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 17.2.6 (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 $a \in X$ and $t \in [0, 1]$, we have $h(a, t) = a$.

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

Example 17.2.7. $\{0\}$ is a strong deformation retract of \mathbb{R}^n and of D^n .

Example 17.2.8. S^1 is a strong deformation retract of the torus $S^1 \times D^2$.

Example 17.2.9. S^{n-1} is a strong deformation retract of $D^n - \{0\}$.

Example 17.2.10. For any topological space X , the singleton consisting of the vertex is a strong deformation retract of the cone over X .

Chapter 18

Simplicial Complexes

Definition 18.0.1 (Simplex). A k -dimensional simplex or k -simplex in \mathbb{R}^n is the convex hull $s(x_0, \dots, x_k)$ of $k + 1$ points in general position.

Definition 18.0.2 (Face). A *sub-simplex* or *face* of $s(x_0, \dots, x_k)$ is the convex hull of a subset of $\{x_0, \dots, x_k\}$.

Definition 18.0.3 (Simplicial Complex). A *simplicial complex* in \mathbb{R}^n is a set K of simplices such that:

- for every simplex s in K , every face of s is in K .
- The intersection of two simplices $s_1, s_2 \in K$ is either empty or is a face of both s_1 and s_2 .
- K is locally finite, i.e. every point of \mathbb{R}^n has a neighbourhood that only intersects finitely many elements of K .

The topological space *underlying* K is $|K| = \bigcup K$ as a subspace of \mathbb{R}^n .

18.1 Cell Decompositions

Definition 18.1.1 (n -cell). An n -cell is a topological space homeomorphic to \mathbb{R}^n .

Definition 18.1.2 (Cell Decomposition). Let X be a topological space. A *cell decomposition* of X is a partition of X into subspaces that are n -cells.

Definition 18.1.3 (n -skeleton). Given a cell decomposition of X , the n -skeleton X^n is the union of all the cells of dimension $\leq n$.

18.2 CW-complexes

Definition 18.2.1 (CW-Complex). A *CW-complex* consists of a topological space X and a cell decomposition \mathcal{E} of X such that:

1. *Characteristic Maps* For every n -cell $e \in \mathcal{E}$, there exists a continuous map $\Phi_e : D^n \rightarrow X$ such that $\Phi_e((D^n)^\circ) = e$, the corestriction $\Phi_e : (D^n)^\circ \approx e$ is a homeomorphism, and $\Phi_e(S^n)$ is the union of all the cells in \mathcal{E} of dimension $< n$.
2. *Closure Finiteness* For all $e \in \mathcal{E}$, we have \bar{e} intersects only finitely many other cells in \mathcal{E} .
3. *Weak Topology* Given $A \subseteq X$, we have A is closed iff for all $e \in \mathcal{E}$, $A \cap \bar{e}$ is closed.

Proposition 18.2.2. *If a cell decomposition \mathcal{E} satisfies the Characteristic Maps axiom, then for every n -cell $e \in \mathcal{E}$ we have $\bar{e} = \Phi_e(D^n)$. Therefore \bar{e} is compact and $\bar{e} - e = \Phi_e(S^{n-1}) \subseteq X^{n-1}$.*

PROOF:

$\langle 1 \rangle 1.$ $e \subseteq \Phi_e(D^n) \subseteq \bar{e}$

PROOF:

$$\begin{aligned}
 e &= \Phi_e((D^n)^\circ) \\
 &\subseteq \Phi_e(D^n) \\
 &= \Phi_e(\overline{(D^n)^\circ}) \\
 &\subseteq \overline{\Phi_e((D^n)^\circ)} \\
 &= \bar{e}
 \end{aligned}$$

$\langle 1 \rangle 2.$ $\Phi_e(D^n)$ is compact.

PROOF: Because D^n is compact.

$\langle 1 \rangle 3.$ $\Phi_e(D^n)$ is closed.

$\langle 1 \rangle 4.$ $\Phi_e(D^n) = \bar{e}$

□

Chapter 19

Topological Groups

19.1 Topological Groups

Definition 19.1.1 (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 19.1.2. \mathbb{Z} is a topological group under addition.

PROOF: The function that sends (x, y) to xy^{-1} is continuous because the topology on \mathbb{Z} is discrete. \square

Example 19.1.3. \mathbb{R} is a topological group under addition.

PROOF: From Propositions 16.1.30 and 16.1.10. \square

Example 19.1.4. \mathbb{R}_+ is a topological group under multiplication.

PROOF: From Propositions 16.1.10 and 16.1.26. \square

Example 19.1.5. S^1 as a subspace of \mathbb{C} is a topological group under multiplication.

PROOF:

$\langle 1 \rangle 1$. LET: $f : S^1 \rightarrow S^1$ be the function $f(x, y) = xy^{-1}$

$\langle 1 \rangle 2$. LET: U be an open set in S^1

PROVE: $f^{-1}(U)$ is open in $(S^1)^2$

$\langle 1 \rangle 3$. LET: $(x, y) \in f^{-1}(U)$

$\langle 1 \rangle 4$. $xy^{-1} \in U$

$\langle 1 \rangle 5$. LET: $x = e^{i\phi}$ and $y = e^{i\psi}$

$\langle 1 \rangle 6$. $xy^{-1} = e^{i(\phi-\psi)} \in U$

$\langle 1 \rangle 7$. PICK $\epsilon > 0$ such that, for all t , if $|\phi - \psi - t| < \epsilon$ then $e^{it} \in U$

$\langle 1 \rangle 8$. $(x, y) \in \{e^{it} : |\phi - t| < \epsilon/2\} \times \{e^{it} : |\psi - t| < \epsilon/2\} \subseteq f^{-1}(U)$

\square

Example 19.1.6. $GL(n, \mathbb{R})$ is a topological group considered as a subspace of \mathbb{R}^{n^2} .

PROOF: Since the calculations for matrix multiplication and inverse are compositions of continuous functions. \square

Example 19.1.7. $GL(n, \mathbb{C})$ is a topological group.

PROOF: Similar. \square

Proposition 19.1.8. *Let G be a group with a topology. Then G is a topological group if and only if the functions $m : G^2 \rightarrow G$ that sends (x, y) to xy and the function $i : G \rightarrow G$ that sends x to x^{-1} are continuous.*

PROOF:

$\langle 1 \rangle 1$. If G is a topological group then i is continuous.

PROOF: Since $x^{-1} = ex^{-1}$.

$\langle 1 \rangle 2$. If G is a topological group then m is continuous.

PROOF: Since $xy = x(y^{-1})^{-1}$.

$\langle 1 \rangle 3$. If m and i are continuous then G is a topological group.

PROOF: Since $xy^{-1} = m(x, i(y))$.

\square

Proposition 19.1.9. *Let G be a topological group. Let $\alpha \in G$. The function that maps x to αx is a homeomorphism between G and itself.*

PROOF:

$\langle 1 \rangle 1$. For any $\alpha \in G$, the function that maps x to αx is continuous.

PROOF: From the definition of topological group.

$\langle 1 \rangle 2$. For any $\alpha \in G$, the function that maps x to αx is a homeomorphism between G and itself.

PROOF: Its inverse is the function that maps x to $\alpha^{-1}x$.

\square

Corollary 19.1.9.1. *Every topological group is homogeneous.*

Proposition 19.1.10. *Let G be a topological group. Let $\alpha \in G$. The function that maps x to $x\alpha$ is a homeomorphism between G and itself.*

PROOF: Similar. \square

19.1.1 Subgroups

Proposition 19.1.11. *Any subgroup of a topological group is a topological group under the subspace topology.*

PROOF: Since the restriction of continuous functions is continuous. \square

Proposition 19.1.12. *Let G be a topological group and H a subgroup of G . Then \overline{H} is a topological group under the subspace topology.*

PROOF:

$\langle 1 \rangle 1$. LET: $x, y \in \overline{H}$

PROVE: $xy^{-1} \in \overline{H}$

$\langle 1 \rangle 2$. LET: U be a neighbourhood of xy^{-1} .

PROVE: U intersects H .

$\langle 1 \rangle 3$. LET: $f : G^2 \rightarrow G$ be the function that maps (x, y) to xy^{-1} .

$\langle 1 \rangle 4$. $f^{-1}(U)$ is a neighbourhood of (x, y)

$\langle 1 \rangle 5$. PICK neighbourhoods V of x and W of y such that $V \times W \subseteq f^{-1}(U)$.

$\langle 1 \rangle 6$. PICK elements $x' \in V \cap H$ and $y' \in W \cap H$

$\langle 1 \rangle 7$. $x'y'^{-1} \in U \cap H$

□

Proposition 19.1.13. *Let G be a topological group. The component of G that contains e is a normal subgroup of G .*

PROOF:

$\langle 1 \rangle 1$. LET: C be the component that contains e .

$\langle 1 \rangle 2$. For all $x \in G$, we have Cx is the component of G that contains x .

PROOF: Since right multiplication by x is a homeomorphism between G and itself.

$\langle 1 \rangle 3$. C is a subgroup of G .

$\langle 2 \rangle 1$. LET: $g, h \in C$

$\langle 2 \rangle 2$. $C = Ch$

PROOF: $\langle 1 \rangle 2$

$\langle 2 \rangle 3$. PICK $x \in C$ such that $xh = g$

$\langle 2 \rangle 4$. $x = gh^{-1}$

$\langle 2 \rangle 5$. $gh^{-1} \in C$

$\langle 1 \rangle 4$. C is a normal subgroup of G .

$\langle 2 \rangle 1$. LET: $g \in G$ and $h \in C$.

PROVE: $ghg^{-1} \in C$

$\langle 2 \rangle 2$. $C = Ch^{-1}$

$\langle 2 \rangle 3$. $Cg = Ch^{-1}g$

$\langle 2 \rangle 4$. $g \in Ch^{-1}g$

$\langle 2 \rangle 5$. PICK $x \in C$ such that $g = xh^{-1}g$

$\langle 2 \rangle 6$. $x = ghg^{-1}$

$\langle 2 \rangle 7$. $ghg^{-1} \in C$

□

19.1.2 Left Cosets

Proposition 19.1.14. *Let G be a topological group and H a subgroup of G . Give G/H the quotient topology. Let $\alpha \in G$. Define $f_\alpha : G/H \rightarrow G/H$ by*

$$f_\alpha(xH) = \alpha xH .$$

Then f_α is a homeomorphism.

PROOF:

$\langle 1 \rangle 1$. For all $\alpha \in G$ we have f_α is well defined.

- 1

Proposition 19.1.15. *Let G be a T_1 topological group and H a closed subgroup of G . Then G/H is T_1 .*

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$\langle 1 \rangle 1$. LET: U be open in G .
 $\langle 1 \rangle 2$. $\forall h \in H. Uh$ is open in G .
 PROOF: Since the function that maps g to gh is an automorphism of G .
 $\langle 1 \rangle 3$. UH is open in G
 PROOF: It is $\bigcup_{h \in H} Uh$.

⟨1⟩4. $UH = \pi^{-1}(\pi(U))$

PROOF:

$$\begin{aligned}\pi^{-1}(\pi(U)) &= \{x \in G : \exists y \in U. xH = yH\} \\ &= \{x \in G : \exists y \in U. x^{-1}y \in H\} \\ &= \{x \in G : \exists y \in U. \exists h \in H. y^{-1}x = h\} \\ &= \{x \in G : \exists y \in U. \exists h \in H. x = yh\} \\ &= UH\end{aligned}$$

⟨1⟩5. $\pi^{-1}(\pi(U))$ is open in G .

⟨1⟩6. $\pi(U)$ is open in G/H .

□

Proposition 19.1.17. *Let G be a topological group. Let H be a normal subgroup of G . Then G/H is a topological group.*

PROOF:

⟨1⟩1. LET: $f : G^2 \rightarrow G$ be the map $f(x, y) = xy^{-1}$

⟨1⟩2. LET: $g : (G/H)^2 \rightarrow G/H$ be the map $g(xH, yH) = xy^{-1}H$

⟨1⟩3. $g \circ (\pi \times \pi) = \pi \circ f : G^2 \rightarrow G/H$

⟨1⟩4. $g \circ (\pi \times \pi)$ is continuous.

PROOF: Since π and f are continuous.

⟨1⟩5. π is an open quotient map.

PROOF: Proposition 19.1.16.

⟨1⟩6. $\pi \times \pi$ is an open quotient map.

PROOF: Corollary 15.10.7.1.

⟨1⟩7. g is continuous.

PROOF: Theorem 15.10.3.

□

19.1.3 Homogeneous Spaces

Definition 19.1.18 (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 19.1.19. *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 □

19.2 Symmetric Neighbourhoods

Definition 19.2.1 (Symmetric Neighbourhood). Let G be a topological group. Let V be a neighbourhood of e . Then V is *symmetric* iff $V = V^{-1}$.

Proposition 19.2.2. *Let G be a topological group. Let U be a neighbourhood of e . Then there exists a symmetric neighbourhood V of e such that $VV \subseteq U$.*

PROOF:

- ⟨1⟩1. PICK a neighbourhood V' of e such that $V'V' \subseteq U$.
- ⟨2⟩1. LET: $m : G^2 \rightarrow G$ be the function $m(x, y) = xy$
- ⟨2⟩2. $m^{-1}(U)$ is open in G^2
- ⟨2⟩3. $(e, e) \in m^{-1}(U)$
- ⟨2⟩4. PICK neighbourhoods V_1, V_2 of e such that $V_1 \times V_2 \subseteq m^{-1}(U)$
- ⟨2⟩5. LET: $V' = V_1 \cap V_2$
- ⟨1⟩2. PICK a neighbourhood W of e such that $WW^{-1} \subseteq V'$
- ⟨2⟩1. LET: $f : G^2 \rightarrow G$ be the function $m(x, y) = xy^{-1}$
- ⟨2⟩2. $f^{-1}(V')$ is open in G^2
- ⟨2⟩3. $(e, e) \in m^{-1}(V')$
- ⟨2⟩4. PICK neighbourhoods W_1, W_2 of e such that $W_1 \times W_2 \subseteq f^{-1}(V')$
- ⟨2⟩5. LET: $W = W_1 \cap W_2$
- ⟨1⟩3. LET: $V = WW^{-1}$
- ⟨1⟩4. V is a neighbourhood of e .
- ⟨1⟩5. V is symmetric.
- ⟨1⟩6. $VV \subseteq U$

□

Proposition 19.2.3. *Every T_1 topological group is regular.*

PROOF:

- ⟨1⟩1. LET: G be a T_1 topological group.
- ⟨1⟩2. LET: A be a closed set in G and $x \in G - A$.
- ⟨1⟩3. $G - Ax^{-1}$ is a neighbourhood of e .
- ⟨1⟩4. PICK a symmetric neighbourhood V of e such that $VV \subseteq G - Ax^{-1}$.
- ⟨1⟩5. LET: $U = VA$ and $U' = Vx$
- ⟨1⟩6. U and U' are disjoint open sets with $A \subseteq U$ and $x \in U'$.

□

Proposition 19.2.4. *Let G be a T_1 topological group. Let H be a closed subgroup of G . Then G/H is regular.*

PROOF:

- ⟨1⟩1. LET: A be a closed set in G/H and $xH \in G/H - A$.
- ⟨1⟩2. $G - \pi^{-1}(A)x^{-1}$ is a neighbourhood of e .
- ⟨1⟩3. PICK a symmetric neighbourhood V of e such that $VV \subseteq G - \pi^{-1}(A)x^{-1}$.
- ⟨1⟩4. LET: $U = \pi(V)A$ and $U' = \pi(V)(xH)$.
- ⟨1⟩5. U and U' are disjoint open sets with $A \subseteq U$ and $xH \in U'$
- ⟨2⟩1. ASSUME: for a contradiction $U \cap U' \neq \emptyset$.
- ⟨2⟩2. PICK $v_1, v_2 \in V$ and $a \in G$ such that $aH \in A$ and $v_1aH = v_2xH$.
- ⟨2⟩3. $a^{-1}v_1^{-1}v_2x \in H$
- ⟨2⟩4. $v_1^{-1}v_2 \in \pi^{-1}(A)x^{-1}$
- ⟨2⟩5. Q.E.D.

PROOF: This contradicts ⟨1⟩3.

□

Proposition 19.2.5. *Let G be a topological group. Let A and B be subspaces of G . If A is closed and B is compact, then AB is closed.*

PROOF:

$\langle 1 \rangle 1$. For all $c \in G - AB$, there exists a neighbourhood W of c such that $WB^{-1} \cap A = \emptyset$.

$\langle 2 \rangle 1$. LET: $c \in G - AB$

$\langle 2 \rangle 2$. LET: $\phi : G^2 \rightarrow G$ be the function $\phi(x, y) = xy^{-1}$

$\langle 2 \rangle 3$. $\{c\} \times B \subseteq \phi^{-1}(G - A)$

$\langle 2 \rangle 4$. PICK a neighbourhood W of c such that $W \times B \subseteq \phi^{-1}(G - A)$

PROOF: Tube Lemma.

$\langle 2 \rangle 5$. $WB^{-1} \cap A = \emptyset$

$\langle 1 \rangle 2$. For all $c \in G - AB$, there exists a neighbourhood W of c such that $W \subseteq G - AB$.

□

Corollary 19.2.5.1. *Let G be a topological group. Let H be a compact subgroup of G . Let $p : G \rightarrow G/H$ be the quotient map. Then p is a perfect map.*

PROOF: The only thing remaining to prove is that, for all $gH \in G/H$, we have $p^{-1}(gH)$ is compact. This holds because $p^{-1}(gH) = gH$ is homeomorphic to H . □

Corollary 19.2.5.2. *Let G be a topological group. Let H be a compact subgroup of G . If G/H is compact then G is compact.*

19.3 Continuous Actions

Definition 19.3.1 (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:

- $\forall x \in X. ex = x$
- $\forall g, h \in G. \forall x \in X. g(hx) = (gh)x$

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

Definition 19.3.2 (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 19.3.3. *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 19.3.4 (Stabilizer). Let X be a G -space and $x \in X$. The *stabilizer* of x is $G_x := \{g \in G : gx = x\}$.

Proposition 19.3.5. *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: Theorem 15.10.3.

□

Chapter 20

Topological Vector Spaces

Definition 20.0.1 (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 20.0.2. *Every topological vector space is a topological group under addition.*

PROOF: Immediate from the definition. \square

Theorem 20.0.3. *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 20.0.4. *Let E be a topological vector space and E_0 a subspace of E . Then $\overline{E_0}$ is a subspace of E .*

Definition 20.0.5. Let E be a topological vector space. The topological space associated with E is $E/\overline{\{0\}}$.

20.1 Cauchy Sequences

Definition 20.1.1 (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 20.1.2 (Complete Topological Vector Space). A topological vector space is *complete* iff every Cauchy sequence converges.

20.2 Seminorms

Definition 20.2.1 (Seminorm). Let E be a vector space over K . A *seminorm* on E is a function $\| \cdot \| : E \rightarrow \mathbb{R}$ such that:

1. $\forall x \in E, \|x\| \geq 0$
2. $\forall \alpha \in K, \forall x \in E, \|\alpha x\| = |\alpha| \|x\|$
3. *Triangle Inequality* $\forall x, y \in E, \|x + y\| \leq \|x\| + \|y\|$

Example 20.2.2. The function that maps (x_1, \dots, x_n) to $|x_i|$ is a seminorm on \mathbb{R}^n .

Definition 20.2.3. 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 $x \in E$.

Proposition 20.2.4. E is a topological vector space under this topology. It is Hausdorff iff, for all $x \in E$, if $\forall \lambda \in \Lambda, \lambda(x) = 0$ then $x = 0$.

20.3 Fréchet Spaces

Definition 20.3.1 (Pre-Fréchet Space). A *pre-Fréchet space* is a Hausdorff topological vector space whose topology is generated by a countable set of seminorms.

Proposition 20.3.2. 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 20.3.3 (Fréchet Space). A *Fréchet space* is a complete pre-Fréchet space.

20.4 Normed Spaces

Definition 20.4.1 (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 20.4.2. 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 .

Definition 20.4.3 (p -norm). For any $p \geq 1$, the p -norm on \mathbb{R}^n is defined by

$$\|\vec{x}\|_p := \left(\sum_{i=1}^n |x_i|^p \right)^{\frac{1}{p}}.$$

We prove this is a norm.

PROOF:

$\langle 1 \rangle 1$. For all $\vec{x} \in \mathbb{R}^n$ we have $\|\vec{x}\|_p \geq 0$

PROOF: Immediate from definition.

$\langle 1 \rangle 2$. For all $\alpha \in \mathbb{R}$ and $\vec{x} \in \mathbb{R}^n$ we have $\|\alpha \vec{x}\|_p = |\alpha| \|\vec{x}\|_p$

PROOF:

$$\begin{aligned} \|\alpha(x_1, \dots, x_n)\| &= \|(\alpha x_1, \dots, \alpha x_n)\| \\ &= \left(\sum_{i=1}^n (\alpha x_i)^p \right)^{\frac{1}{p}} \\ &= \left(|\alpha|^p \sum_{i=1}^n x_i^p \right)^{\frac{1}{p}} \\ &= |\alpha| \left(\sum_{i=1}^n x_i^p \right)^{\frac{1}{p}} \\ &= |\alpha| \|\vec{x}\|_p \end{aligned}$$

$\langle 1 \rangle 3$. The triangle inequality holds.

PROOF:

$$\begin{aligned} \|\vec{x} + \vec{y}\|_p^p &= \sum_{i=1}^n |x_i + y_i|^p \\ &= \sum_{i=1}^n |x_i + y_i| |x_i + y_i|^{p-1} \\ &\leq \sum_{i=1}^n (|x_i| + |y_i|) |x_i + y_i|^{p-1} \\ &= \sum_{i=1}^n |x_i| |x_i + y_i|^{p-1} + \sum_{i=1}^n |y_i| |x_i + y_i|^{p-1} \\ &\leq \left(\sum_{i=1}^n |x_i|^p \right)^{\frac{1}{p}} \left(\sum_{i=1}^n |x_i + y_i|^p \right)^{\frac{p-1}{p}} + \left(\sum_{i=1}^n |y_i|^p \right)^{\frac{1}{p}} \left(\sum_{i=1}^n |x_i + y_i|^p \right)^{\frac{p-1}{p}} \quad (\text{Hölder's Inequality}) \\ &= (\|\vec{x}\|_p + \|\vec{y}\|_p) \|\vec{x} + \vec{y}\|_p^{p-1} \end{aligned}$$

Assuming w.l.o.g. $\|\vec{x} + \vec{y}\|_p^{p-1} \neq 0$ (using ??) we have $\|\vec{x} + \vec{y}\|_p \leq \|\vec{x}\|_p + \|\vec{y}\|_p$.

$\langle 1 \rangle 4$. For any $\vec{x} \in \mathbb{R}^n$, we have $\|\vec{x}\| = 0$ iff $\vec{x} = \vec{0}$.

PROOF: $\sum_{i=1}^n x_i^p = 0$ iff $x_1 = \dots = x_n = 0$.

□

Proposition 20.4.4. The p -norm on \mathbb{R}^n induces the product topology.

PROOF:

⟨1⟩1. LET: d be the metric induced by the p -norm and ρ the square metric on \mathbb{R}^n .

⟨1⟩2. The metric topology is finer than the product topology.

⟨2⟩1. LET: $\vec{x} \in \mathbb{R}^n$ and $\epsilon > 0$

⟨2⟩2. LET: $\delta = \epsilon/n^{\frac{1}{p}}$

PROVE: $B_\rho(\vec{x}, \delta) \subseteq B_d(\vec{x}, \epsilon)$

⟨2⟩3. LET: $\vec{y} \in B_\rho(\vec{x}, \delta)$

⟨2⟩4. $\forall i. |x_i - y_i| < \delta$

⟨2⟩5. $d(\vec{x}, \vec{y}) < \epsilon$

PROOF:

$$\begin{aligned} d(\vec{x}, \vec{y}) &= \left(\sum_{i=1}^n |x_i - y_i|^p \right)^{\frac{1}{p}} \\ &< \left(\sum_{i=1}^n \delta^p \right)^{\frac{1}{p}} && (\langle 2 \rangle 4) \\ &= n^{\frac{1}{p}} \delta \\ &= \epsilon && (\langle 2 \rangle 2) \end{aligned}$$

⟨1⟩3. The product topology is finer than the metric topology.

⟨2⟩1. LET: $\vec{x} \in \mathbb{R}^n$ and $\epsilon > 0$

⟨2⟩2. LET: $\vec{y} \in B_d(\vec{x}, \epsilon)$

⟨2⟩3. $d(\vec{x}, \vec{y}) < \epsilon$

⟨2⟩4. $\sum_{i=1}^n |x_i - y_i|^p < \epsilon^p$

⟨2⟩5. $\forall i. |x_i - y_i|^p < \epsilon^p$

⟨2⟩6. $\forall i. |x_i - y_i| < \epsilon$

⟨2⟩7. $\rho(\vec{x}, \vec{y}) < \epsilon$

□

Definition 20.4.5 (Sup-norm). The *sup-norm* on \mathbb{R}^n is defined by

$$\|(x_1, \dots, x_n)\|_\infty := \max(|x_1|, \dots, |x_n|) .$$

Proposition 20.4.6. The 2-norm on \mathbb{R}^n induces the standard metric.

PROOF: Immediate from definitions. □

Definition 20.4.7. For $p \geq 1$, the normed space l_p is the set of all sequences (x_n) in \mathbb{R} such that $\sum_{n=1}^\infty x_n^p$ converges, under

$$\|(x_n)\|_p := \left(\sum_{i=1}^\infty |x_i|^p \right)^{\frac{1}{p}} .$$

Proposition 20.4.8. The spaces l_p for $p \geq 1$ are all homeomorphic.

PROOF: See Kadets, Mikhail Iosifovich. 1967. Proof of the topological equivalence of all separable infinite-dimensional banach spaces. Functional Analysis and Its Applications 1 (1): 53–62. <http://dx.doi.org/10.1007/BF01075865>.

Proposition 20.4.9. *The metric topology on l_2 is strictly finer than the uniform topology.*

PROOF:

⟨1⟩1. LET: d be the metric induced by the l^2 -norm and $\bar{\rho}$ the uniform topology.

⟨1⟩2. The metric topology is finer than the uniform topology.

⟨2⟩1. LET: $x \in l_2$

⟨2⟩2. LET: $\epsilon > 0$

⟨2⟩3. LET: $\delta = \epsilon/2$

⟨2⟩4. LET: $y \in B_d(x, \delta)$

⟨2⟩5. $\sum_{n=0}^{\infty} (x_n - y_n)^2 < \delta^2$

⟨2⟩6. $\forall n. (x_n - y_n)^2 < \delta^2$

⟨2⟩7. $\forall n. |x_n - y_n| < \delta$

⟨2⟩8. $\forall n. \bar{d}(x_n, y_n) < \delta$

⟨2⟩9. $\bar{\rho}(x, y) \leq \delta$

⟨2⟩10. $\bar{\rho}(x, y) < \epsilon$

⟨2⟩11. $y \in B_{\bar{\rho}}(x, \epsilon)$

⟨1⟩3. The metric topology is not the same as the uniform topology.

⟨2⟩1. ASSUME: for a contradiction $B_d(0, 1)$ is open in the uniform topology.

⟨2⟩2. PICK $\epsilon > 0$ such that $B_{\bar{\rho}}(0, \epsilon) \subseteq B_d(0, 1)$

⟨2⟩3. PICK an integer N such that $1/N < \epsilon^2/4$

⟨2⟩4. LET: (x_n) be the sequence with $x_n = \epsilon/2$ for $n < N$ and $x_n = 0$ for $n \geq N$

⟨2⟩5. $(x_n) \in l_2$

⟨2⟩6. $(x_n) \in B_{\bar{\rho}}(0, \epsilon)$

PROOF: Since $\bar{\rho}((x_n), 0) = \epsilon/2$.

⟨2⟩7. $d((x_n), 0) > 1$

PROOF:

$$\begin{aligned} d((x_n), 0)^2 &= \sum_{n=0}^{\infty} x_n^2 \\ &= N\epsilon^2/4 \\ &> 1 \end{aligned}$$

□

Proposition 20.4.10. *The metric topology on l_2 is strictly coarser than the box topology.*

PROOF:

⟨1⟩1. The box topology is finer than the metric topology.

⟨2⟩1. LET: $(x_n) \in l_2$ and $\epsilon > 0$.

⟨2⟩2. LET: $(y_n) \in B((x_n), \epsilon)$

⟨2⟩3. PICK a sequence of real numbers (δ_n) such that $\sum_{n=0}^{\infty} \delta_n^2 < (\epsilon - d((x_n), (y_n)))^2$

⟨2⟩4. LET: $U = \prod_n (y_n - \delta_n, y_n + \delta_n)$

PROVE: $U \subseteq B((x_n), \epsilon)$

⟨2⟩5. LET: $(z_n) \in U$

⟨2⟩6. $d((z_n), (y_n)) < \epsilon - d((x_n), (y_n))$

PROOF:

$$\begin{aligned} d((z_n), (y_n))^2 &= \sum_{n=0}^{\infty} (z_n - y_n)^2 \\ &< \sum_{n=0}^{\infty} \delta_n^2 \\ &< (\epsilon - d((x_n), (y_n)))^2 \end{aligned}$$

$$\langle 2 \rangle 7. d((z_n), (x_n)) < \epsilon$$

$\langle 1 \rangle 2.$ The box topology is not equal to the metric topology.

$$\langle 2 \rangle 1. \text{ LET: } U = \prod_n (-1/n, 1/n)$$

$\langle 2 \rangle 2.$ ASSUME: for a contradiction U is open in the metric topology.

$\langle 2 \rangle 3.$ PICK $\epsilon > 0$ such that $B(0, \epsilon) \subseteq U$

$\langle 2 \rangle 4.$ PICK N such that $1/N < \epsilon/2$.

$\langle 2 \rangle 5.$ LET: (x_n) be the sequence with $x_N = \epsilon/2$ and $x_n = 0$ for all other n .

$\langle 2 \rangle 6.$ $d((x_n), 0) = \epsilon/2$

$\langle 2 \rangle 7.$ $(x_n) \notin U$

□

Proposition 20.4.11. *The l^2 -topology on \mathbb{R}^∞ is strictly finer than the uniform topology.*

PROOF:

$\langle 1 \rangle 1.$ ASSUME: for a contradiction $B_d(0, 1) \cap \mathbb{R}^\infty$ is open in the uniform topology.

$\langle 1 \rangle 2.$ PICK $\epsilon > 0$ such that $B_{\bar{\rho}}(0, \epsilon) \cap \mathbb{R}^\infty \subseteq B_d(0, 1) \cap \mathbb{R}^\infty$

$\langle 1 \rangle 3.$ PICK an integer N such that $1/N < \epsilon^2/4$

$\langle 1 \rangle 4.$ LET: (x_n) be the sequence with $x_n = \epsilon/2$ for $n < N$ and $x_n = 0$ for $n \geq N$

$\langle 1 \rangle 5.$ $(x_n) \in \mathbb{R}^\infty$

$\langle 1 \rangle 6.$ $(x_n) \in B_{\bar{\rho}}(0, \epsilon)$

PROOF: Since $\bar{\rho}((x_n), 0) = \epsilon/2$.

$\langle 1 \rangle 7.$ $d((x_n), 0) > 1$

PROOF:

$$\begin{aligned} d((x_n), 0)^2 &= \sum_{n=0}^{\infty} x_n^2 \\ &= N\epsilon^2/4 \\ &> 1 \end{aligned}$$

□

Proposition 20.4.12. *The l^2 -topology on \mathbb{R}^∞ is strictly coarser than the box topology.*

$\langle 1 \rangle 1.$ LET: $U = \prod_n (-1/n, 1/n) \cap \mathbb{R}^\infty$

$\langle 1 \rangle 2.$ ASSUME: for a contradiction U is open in the metric topology.

$\langle 1 \rangle 3.$ PICK $\epsilon > 0$ such that $B(0, \epsilon) \cap \mathbb{R}^\infty \subseteq U \cap \mathbb{R}^\infty$

$\langle 1 \rangle 4.$ PICK N such that $1/N < \epsilon/2$.

⟨1⟩5. LET: (x_n) be the sequence with $x_N = \epsilon/2$ and $x_n = 0$ for all other n .

⟨1⟩6. $d((x_n), 0) = \epsilon/2$

⟨1⟩7. $(x_n) \notin U$

□

Proposition 20.4.13. *The l^2 -topology on the Hilbert cube the same as the product topology.*

PROOF:

⟨1⟩1. For every $(x_n) \in H$ and $\epsilon > 0$, there exists a neighbourhood U of (x_n) in the product topology such that $U \subseteq B((x_n), \epsilon)$.

⟨2⟩1. LET: $(x_n) \in H$

⟨2⟩2. LET: $\epsilon > 0$

⟨2⟩3. PICK N such that $\sum_{i=N+1}^{\infty} 1/i^2 < \epsilon^2/2$

⟨2⟩4. LET: $B' = (\prod_{i=0}^N (x_i - \epsilon/\sqrt{2N}, x_i + \epsilon/\sqrt{2N}) \times \prod_{i=N+1}^{\infty} [0, 1/(i+1)]) \cap H$

PROVE: $B' \subseteq B((x_n), \epsilon)$

⟨2⟩5. LET: $(y_n) \in B'$

⟨2⟩6. $d((x_n), (y_n)) < \epsilon$

PROOF:

$$\begin{aligned} d((x_n), (y_n))^2 &= \sum_{i=0}^{\infty} |x_n - y_n|^2 \\ &< \sum_{i=0}^N \epsilon^2/2N + \sum_{i=N+1}^{\infty} 1/(i+1)1/(i+1)^2 \\ &< \epsilon^2/2 + \epsilon^2/2 \\ &= \epsilon^2 \end{aligned}$$

⟨1⟩2. The product topology is finer than the l^2 -topology.

⟨2⟩1. LET: $(x_n) \in H$ and $\epsilon > 0$

PROVE: $B((x_n), \epsilon) \cap H$ is open in the product topology.

⟨2⟩2. LET: $(y_n) \in B((x_n), \epsilon)$

⟨2⟩3. PICK a neighbourhood U of (y_n) in the product topology such that

$U \subseteq B((y_n), \epsilon - d((x_n), (y_n)))$

⟨2⟩4. $U \subseteq B((x_n), \epsilon)$

□

Definition 20.4.14. Let l_{∞} be the set of all bounded sequences in \mathbb{R} under

$$\|(x_n)\| := \sup_n |x_n|$$

Proposition 20.4.15. *For all $p \geq 1$ we have l_p is not homeomorphic to l_{∞} .*

Proposition 20.4.16. *Let $\| \cdot \|$ be a seminorm on the vector space E . Then $\| \cdot \|$ defines a norm on $E/\{0\}$.*

Proposition 20.4.17. *Let E and F be normed spaces. Any continuous linear map $E \rightarrow F$ is uniformly continuous.*

Definition 20.4.18. 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

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

20.5 Unit Ball

Proposition 20.5.1. *Let n be a positive integer. Every open ball $B(\vec{x}, \epsilon)$ in \mathbb{R}^n is path connected.*

PROOF:

$\langle 1 \rangle 1$. LET: $\vec{y}, \vec{z} \in B(\vec{x}, \epsilon)$

$\langle 1 \rangle 2$. LET: $\vec{p} : [0, 1] \rightarrow B(\vec{x}, \epsilon)$ be the path $\vec{p}(t) = (1-t)\vec{y} + t\vec{z}$.

$\langle 2 \rangle 1$. LET: $t \in [0, 1]$

PROVE: $\vec{p}(t) \in B(\vec{x}, \epsilon)$

$\langle 2 \rangle 2$. $d(\vec{p}(t), \vec{x}) < \epsilon$

PROOF:

$$\begin{aligned} d(\vec{p}(t), \vec{x}) &= \|(1-t)\vec{y} + t\vec{z} - \vec{x}\| \\ &= \|(1-t)(\vec{y} - \vec{x}) + t(\vec{z} - \vec{x})\| \\ &\leq (1-t)\|\vec{y} - \vec{x}\| + t\|\vec{z} - \vec{x}\| \\ &< (1-t)\epsilon + t\epsilon \\ &= \epsilon \end{aligned}$$

$\langle 1 \rangle 3$. \vec{p} is a path from \vec{x} to \vec{y} .

□

Proposition 20.5.2. *Let n be a positive integer. Every closed ball $B(\vec{x}, \epsilon)$ in \mathbb{R}^n is path connected.*

PROOF:

$\langle 1 \rangle 1$. LET: $\vec{y}, \vec{z} \in \overline{B(\vec{x}, \epsilon)}$

$\langle 1 \rangle 2$. LET: $\vec{p} : [0, 1] \rightarrow \overline{B(\vec{x}, \epsilon)}$ be the path $\vec{p}(t) = (1-t)\vec{y} + t\vec{z}$.

$\langle 2 \rangle 1$. LET: $t \in [0, 1]$

PROVE: $\vec{p}(t) \in \overline{B(\vec{x}, \epsilon)}$

$\langle 2 \rangle 2$. $d(\vec{p}(t), \vec{x}) \leq \epsilon$

PROOF:

$$\begin{aligned} d(\vec{p}(t), \vec{x}) &= \|(1-t)\vec{y} + t\vec{z} - \vec{x}\| \\ &= \|(1-t)(\vec{y} - \vec{x}) + t(\vec{z} - \vec{x})\| \\ &\leq (1-t)\|\vec{y} - \vec{x}\| + t\|\vec{z} - \vec{x}\| \\ &\leq (1-t)\epsilon + t\epsilon \\ &= \epsilon \end{aligned}$$

$\langle 1 \rangle 3$. \vec{p} is a path from \vec{x} to \vec{y} .

□

20.6 Unit Sphere

Definition 20.6.1 (Unit Sphere). Let n be a positive integer. The *unit sphere* S^{n-1} is

$$S^{n-1} := \{\vec{x} \in \mathbb{R}^n : \|\vec{x}\| = 1\} .$$

Proposition 20.6.2. For $n > 1$, the unit sphere S^{n-1} is path connected.

PROOF: The map $g : \mathbb{R}^n - \{\vec{0}\} \rightarrow S^{n-1}$ defined by $g(\vec{x}) = \vec{x}/\|\vec{x}\|$ is continuous and surjective. Hence S^{n-1} is the continuous image of a path connected space. \square

20.7 Inner Product Spaces

Definition 20.7.1 (Inner Product). Given $\vec{x}, \vec{y} \in \mathbb{R}^n$, define

$$\vec{x} \cdot \vec{y} = x_1 y_1 + \cdots + x_n y_n .$$

Proposition 20.7.2.

$$\vec{x} \cdot (\vec{y} + \vec{z}) = \vec{x} \cdot \vec{y} + \vec{x} \cdot \vec{z}$$

PROOF:

$$\begin{aligned} \vec{x} \cdot (\vec{y} + \vec{z}) &= x_1(y_1 + z_1) + \cdots + x_n(y_n + z_n) \\ &= x_1 y_1 + x_1 z_1 + \cdots + x_n y_n + x_n z_n \\ &= \vec{x} \cdot \vec{y} + \vec{x} \cdot \vec{z} \end{aligned} \quad \square$$

Proposition 20.7.3. For all $\vec{x}, \vec{y} \in \mathbb{R}^n$ we have

$$|\vec{x} \cdot \vec{y}| \leq \|\vec{x}\| \|\vec{y}\| .$$

PROOF:

- $\langle 1 \rangle 1$. ASSUME: w.l.o.g. $\vec{x} \neq \vec{0} \neq \vec{y}$
- $\langle 1 \rangle 2$. LET: $a = 1/\|\vec{x}\|$
- $\langle 1 \rangle 3$. LET: $b = 1/\|\vec{y}\|$
- $\langle 1 \rangle 4$. $\|a\vec{x} + b\vec{y}\| \geq 0$
- $\langle 1 \rangle 5$. $a^2\|\vec{x}\|^2 + 2ab\vec{x} \cdot \vec{y} + b^2\|\vec{y}\|^2 \geq 0$
- $\langle 1 \rangle 6$. $ab\vec{x} \cdot \vec{y} \geq -1$
- $\langle 1 \rangle 7$. $\|a\vec{x} - b\vec{y}\| \geq 0$
- $\langle 1 \rangle 8$. $ab\vec{x} \cdot \vec{y} \leq 1$
- $\langle 1 \rangle 9$. $|\vec{x} \cdot \vec{y}| \leq 1/ab$

\square

Proposition 20.7.4. Let $(x_n), (y_n)$ be sequences of real numbers. If $\sum_{n=0}^{\infty} x_n^2$ and $\sum_{n=0}^{\infty} y_n^2$ converge then $\sum_{n=0}^{\infty} |x_n y_n|$ converges.

PROOF:

$$\begin{aligned} \sum_{n=0}^N |x_n y_n| &\leq \sqrt{\sum_{n=0}^N x_n^2 \sum_{n=0}^N y_n^2} && \text{(Proposition 20.7.3)} \\ &\leq \sqrt{\sum_{n=0}^{\infty} x_n^2 \sum_{n=0}^{\infty} y_n^2} && \square \end{aligned}$$

Proposition 20.7.5. *If E is an inner product space then $\|x\| = \sqrt{\langle x, x \rangle}$ is a norm on E .*

20.8 Banach Spaces

Definition 20.8.1 (Banach Space). A *Banach space* is a complete normed space.

Example 20.8.2. 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 20.8.3. *The completion of a normed space is a Banach space.*

Proposition 20.8.4. *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 20.8.5. *$L^p(\mathbb{R}^n)$ is a Banach space.*

Proposition 20.8.6. *$C(\mathbb{R})$ is first countable but not second countable.*

PROOF: For every sequence of 0s and 1s $s = (s_n)$, let f_s be a continuous bounded function whose value at n is s_n . Then the set of all f_s is an uncountable discrete set in $C(\mathbb{R})$. Hence $C(\mathbb{R})$ is not second countable.

It is first countable because it is metrizable. \square

20.9 Hilbert Spaces

Definition 20.9.1 (Hilbert Space). A *Hilbert space* is a complete inner product space.

Example 20.9.2. 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 20.9.3. *The completion of an inner product space is a Hilbert space.*

An infinite dimensional Hilbert space with the weak topology is not first countable.

20.10 Locally Convex Spaces

Definition 20.10.1 (Locally Convex Space). A topological vector space is *locally convex* iff every neighbourhood of 0 includes a convex neighbourhood of 0.

Proposition 20.10.2. *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 20.10.3. *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 20.10.4. 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 Dieudonné, J. A., Treatise on Analysis, Vol. II, New York and London: Academic Press, 1970, p. 76.

Definition 20.10.5 (Thom Space). Let E be a vector bundle with a Riemannian metric, $DE = \{x \in E : \|x\| \leq 1\}$ its disc bundle and $SE := \{v \in E : \|v\| = 1\}$ its sphere bundle. The *Thom space* of E is the quotient space DE/SE .

Part VII

Probability Theory

Chapter 21

Discrete Random Variables

Definition 21.0.1 (Discrete random variable). Let Ω be a countable set. A *discrete random variable* X that takes values in Ω is a function

$$X : \Omega \rightarrow [0, 1]$$

such that

$$\sum_{a \in \Omega} X(a) = 1 \ .$$

We write $P(X = a)$ for $X(a)$, and call this the *probability* that X takes value a .

Definition 21.0.2 (Expected Value). Let X be a discrete random variable that takes values in a real vector space Ω . The *expected value* of X is

$$\langle X \rangle = \sum_{a \in \Omega} P(X = a)a \ .$$

Definition 21.0.3 (Variance). The *variance* of X is

$$\langle (X - \langle X \rangle)^2 \rangle \ .$$

Proposition 21.0.4. *The variance of X is $\langle X^2 \rangle - \langle X \rangle^2$.*

PROOF:

$$\begin{aligned} \langle (X - \langle X \rangle)^2 \rangle &= \sum_{a \in \Omega} (a - \langle X \rangle)^2 P(X = a) \\ &= \sum_{a \in \Omega} (a^2 - 2a\langle X \rangle + \langle X \rangle^2) P(X = a) \\ &= \sum_{a \in \Omega} a^2 P(X = a) - 2\langle X \rangle \sum_{a \in \Omega} a P(X = a) + \langle X \rangle^2 \sum_{a \in \Omega} P(X = a) \\ &= \langle X^2 \rangle - 2\langle X \rangle^2 + \langle X \rangle^2 \\ &= \langle X^2 \rangle - \langle X \rangle^2 \end{aligned}$$

□

Corollary 21.0.4.1.

$$\langle X^2 \rangle \geq \langle X \rangle^2$$

PROOF: For all $a \in \Omega$ we have $(a - \langle X \rangle)^2 \geq 0$, so the variance of X must be ≥ 0 . \square

Definition 21.0.5 (Standard Deviation). The *standard deviation* of X , denoted σ_X , is the square root of the variance.

Chapter 22

Continuous Random Variables

Definition 22.0.1 (Continuous random variable). A *continuous random variable* X that takes values in \mathbb{R} is an integrable function

$$\rho : \mathbb{R} \rightarrow [0, 1]$$

such that

$$\int \rho = 1 \quad .$$

Given a measurable set $S \subseteq \mathbb{R}$, *probability* that X takes a value in S is

$$\int_S \rho \quad .$$

Example 22.0.2. A *Gaussian distribution* is

$$\rho(x) = \sqrt{\frac{\lambda}{\pi}} e^{-\lambda(x-a)^2}$$

for some λ and a .

Definition 22.0.3 (Expected Value). Let X be a discrete random variable that takes values in a real vector space Ω . The *expected value* of X is

$$\langle X \rangle = \int x \rho(x) dx$$

Example 22.0.4. The Gaussian distribution

$$\rho(x) = \sqrt{\frac{\lambda}{\pi}} e^{-\lambda(x-a)^2}$$

has expected value a .

Definition 22.0.5 (Variance). The *variance* of X is

$$\langle (X - \langle X \rangle)^2 \rangle .$$

Proposition 22.0.6. The variance of X is $\langle X^2 \rangle - \langle X \rangle^2$.

PROOF:

$$\begin{aligned} \langle (X - \langle X \rangle)^2 \rangle &= \int (x - \langle X \rangle)^2 \rho(x) dx \\ &= \int (x^2 - 2x\langle X \rangle + \langle X \rangle^2) \rho(x) dx \\ &= \int x^2 \rho(x) dx - 2\langle X \rangle \int x \rho(x) dx + \langle X \rangle^2 \int \rho(x) dx \\ &= \langle X^2 \rangle - 2\langle X \rangle^2 + \langle X \rangle^2 \\ &= \langle X^2 \rangle - \langle X \rangle^2 \end{aligned} \quad \square$$

Corollary 22.0.6.1.

$$\langle X^2 \rangle \geq \langle X \rangle^2$$

PROOF: For all $x \in \mathbb{R}$ we have $(x - \langle X \rangle)^2 \geq 0$, so the variance of X must be ≥ 0 . \square

Example 22.0.7. The Gaussian distribution

$$\rho(x) = \sqrt{\frac{\lambda}{\pi}} e^{-\lambda(x-a)^2}$$

has variance $\frac{1}{2\lambda}$.

Definition 22.0.8 (Standard Deviation). The *standard deviation* of X , denoted σ_X , is the square root of the variance.

Example 22.0.9. The Gaussian distribution

$$\rho(x) = \sqrt{\frac{\lambda}{\pi}} e^{-\lambda(x-a)^2}$$

has standard deviation $1/\sqrt{2\lambda}$.

Part VIII

Quantum Theory

Chapter 23

The Postulates of Quantum Mechanics

Axiom 23.0.1 (Principle of Superposition). *For any physical system S , there exists a complex inner product space V such that the states of S correspond to the one-dimensional subspaces of V . We call the elements of this subspace the state vectors that correspond to the state.*

Definition 23.0.2 (Observable). An *observable* of a physical system is a physical quantity that can be measured by an experiment whose value is a real number.

Definition 23.0.3 (Eigenstate). Let S be a physical system. Let E be an observable of S . Let $\alpha \in \mathbb{R}$. A state s of S is an *eigenstate* of E with *eigenvalue* α iff the probability is 1 that, if we measure E when the system is in state s , then the outcome will be α .

Axiom 23.0.4. *Let E be an observable of a physical system S . Let $\alpha \in \mathbb{R}$. The state vectors corresponding to the eigenstates of E form a subspace of the Hilbert space associated with S , called the eigenspace of α .*

Axiom 23.0.5 (Projection Postulate). *Let S be a physical system with associated state space V . Let E be an observable of S . Let V_α be the eigenspace of V with eigenvalue α . Let $P_\alpha : V \rightarrow V_\alpha$ be the projection operator. If S is in a state with normalised state vector $|\psi\rangle$, and we measure E on S , then the probability of getting the value α is*

$$p_E(\alpha|\psi) = \frac{\langle\psi|P_\alpha|\psi\rangle}{\langle\psi|\psi\rangle}$$

and after the experiment, the state of the system is $P_\alpha|\psi\rangle$.

Proposition 23.0.6. *Let E be an observable of a physical system S . Then eigenstates of E with different eigenvalues are orthogonal.*

PROOF:

- $\langle 1 \rangle 1$. LET: $|\psi\rangle$ a normalised eigenstate with eigenvalue β and $\alpha \neq \beta$.
 $\langle 1 \rangle 2$. The probability of measuring α if the system is in state $|\psi\rangle$ is 0.
 $\langle 1 \rangle 3$. $\langle \psi | P_\alpha | \psi \rangle = 0$
 $\langle 1 \rangle 4$. $P_\alpha |\psi\rangle = 0$
 $\langle 1 \rangle 5$. $|\psi\rangle$ is orthogonal to every eigenvector with eigenvalue α .
 \square

Proposition 23.0.7. *Let E be an observable of a physical system S with state space V . Assume E has countably many outcomes $\alpha_1, \alpha_2, \dots$ and, for any state vector $|\psi\rangle$, we have*

$$\sum_{n=1}^{\infty} P_{\alpha_n} |\psi\rangle \text{ converges.}$$

Then the eigenvectors of E span V .

PROOF:

- $\langle 1 \rangle 1$. LET: $|\psi\rangle \in V$
 $\langle 1 \rangle 2$. LET: $|\psi'\rangle = |\psi\rangle - \sum_{n=1}^{\infty} P_{\alpha_n} |\psi\rangle$
 $\langle 1 \rangle 3$. ASSUME: for a contradiction $|\psi'\rangle \neq 0$
 $\langle 1 \rangle 4$. LET: $|\phi\rangle = |\psi'\rangle / \| |\psi'\rangle \|$
 $\langle 1 \rangle 5$. For all n we have $P_{\alpha_n} |\phi\rangle = 0$

PROOF:

$$\begin{aligned}
 P_{\alpha_n} |\psi'\rangle &= P_{\alpha_n} |\psi\rangle - \sum_{m=1}^{\infty} P_{\alpha_n} P_{\alpha_m} |\psi\rangle \\
 &= P_{\alpha_n} |\psi\rangle - P_{\alpha_n} |\psi\rangle \quad (\text{Proposition 23.0.6}) \\
 &= 0
 \end{aligned}$$

- $\langle 1 \rangle 6$. For all n , the probability of measuring α_n if the system is in state $|\phi\rangle$ is 0.
 $\langle 1 \rangle 7$. Q.E.D.

PROOF: This is a contradiction.

\square

Definition 23.0.8. For any observable E of a physical system with state space V , pick an orthonormal basis \mathcal{B} of normalised eigenvectors of E . The operator that represents E is $\hat{E} : V \rightarrow V$ where, for $|\phi\rangle \in \mathcal{B}$, if α is the eigenvalue of $|\phi\rangle$ then

$$\hat{E} |\phi\rangle = \alpha |\phi\rangle .$$

Proposition 23.0.9. *For any observable E , the operator \hat{E} is Hermitian.*

PROOF:

- $\langle 1 \rangle 1$. LET: $\hat{\phi} = \sum_n c_n \hat{\psi}_n$ and $\hat{\psi} = \sum_n d_n \hat{\psi}_n$ be any two state vectors, where the $\hat{\psi}_n$ are the basis vectors with eigenvalues α_n .
 $\langle 1 \rangle 2$. $\langle \phi | \hat{E} | \psi \rangle = \langle \psi | \hat{E} | \phi \rangle$

PROOF:

$$\begin{aligned}
 \langle \phi | \hat{E} | \psi \rangle &= \sum_m \sum_n \overline{c_m} d_n \langle \psi_m | \hat{E} | \psi_n \rangle \\
 &= \sum_m \sum_n \overline{c_m} d_n \alpha_n \langle \psi_m | \psi_n \rangle \\
 &= \sum_n \overline{c_n} d_n \alpha_n \\
 \langle \psi | \hat{E} | \phi \rangle &= \sum_n \overline{d_n} c_n \alpha_n \quad \text{similarly}
 \end{aligned}$$

□

Definition 23.0.10. Let E be an observable and $f : \mathbb{R} \rightarrow \mathbb{R}$. Then $f(E)$ is the observable that consists of performing the experiment to obtain the value of E and then applying f to it.

Proposition 23.0.11. $\widehat{E^n} = \hat{E}^n$

PROOF: Since if $|\phi\rangle$ is an eigenstate with eigenvalue α then $\hat{E}^n |\phi\rangle = \alpha^n |\phi\rangle$. □

Corollary 23.0.11.1. For any real polynomial p we have $\widehat{p(E)} = p(\hat{E})$.

Chapter 24

The Wave Function

24.1 The Schrödinger Equation

Definition 24.1.1 (Planck's constant). *Planck's constant* is

$$h = 6.62607015 \times 10^{-34} \text{ Js} .$$

Definition 24.1.2 (Reduced Planck's constant). The *reduced Planck's constant* is

$$\hbar = h/2\pi .$$

Consider a particle of mass m moving in one dimension under a force given by a potential energy function $V(x, t) : \mathbb{R} \times [0, +\infty) \rightarrow [0, +\infty]$. Associated with the particle is a *wave function* $\Psi(x, t) : \mathbb{R} \times [0, +\infty) \rightarrow \mathbb{C}$ that is differentiable in t , twice differentiable in x , satisfies the (*time-dependent*) *Schrödinger equation*: for all x and t ,

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} + V(x, t)\Psi(x, t)$$

and satisfies

$$\int_{-\infty}^{\infty} |\Psi(x, 0)|^2 dx = 1 .$$

Proposition 24.1.3.

$$\frac{\partial}{\partial t} |\Psi(x, t)|^2 = \frac{i\hbar}{2m} \frac{\partial}{\partial x} \left(\Psi^*(x, t) \frac{\partial \Psi}{\partial x} - \frac{\partial \Psi^*}{\partial x} \Psi(x, t) \right)$$

PROOF:

$\langle 1 \rangle 1.$

$$\frac{\partial \Psi}{\partial t} = \frac{i\hbar}{2m} \frac{\partial^2 \Psi}{\partial x^2} - \frac{i}{\hbar} V(x, t)\Psi(x, t)$$

PROOF: Schrödinger equation.

$\langle 1 \rangle 2.$

$$\frac{\partial \Psi^*}{\partial t} = -\frac{i\hbar}{2m} \frac{\partial^2 \Psi^*}{\partial x^2} + \frac{i}{\hbar} V(x, t) \Psi(x, t)^*$$

PROOF: Taking complex conjugates in $\langle 1 \rangle 1.$

$\langle 1 \rangle 3.$

$$\frac{\partial}{\partial t} |\Psi(x, t)|^2 = \frac{i\hbar}{2m} \frac{\partial}{\partial x} \left(\Psi^*(x, t) \frac{\partial \Psi}{\partial x} - \frac{\partial \Psi^*}{\partial x} \Psi(x, t) \right)$$

PROOF:

$$\begin{aligned} \frac{\partial}{\partial t} |\Psi(x, t)|^2 &= \frac{\partial}{\partial t} (\Psi(x, t)^* \Psi(x, t)) \\ &= \Psi^* \frac{\partial \Psi}{\partial t} + \frac{\partial \Psi^*}{\partial t} \Psi \\ &= \frac{i\hbar}{2m} \left(\Psi^* \frac{\partial^2 \Psi}{\partial x^2} - \frac{\partial^2 \Psi^*}{\partial x^2} \Psi \right) \quad (\langle 1 \rangle 1, \langle 1 \rangle 2) \\ &= \frac{i\hbar}{2m} \frac{\partial}{\partial x} \left(\Psi^*(x, t) \frac{\partial \Psi}{\partial x} - \frac{\partial \Psi^*}{\partial x} \Psi(x, t) \right) \end{aligned}$$

□

Proposition 24.1.4. For all $t \in [0, +\infty)$ we have

$$\int_{-\infty}^{\infty} |\Psi(x, t)|^2 dx = 1 \quad .$$

PROOF:

$\langle 1 \rangle 1.$

$$\frac{d}{dt} \int_{-\infty}^{\infty} |\Psi(x, t)|^2 dx = 0$$

PROOF:

$$\begin{aligned} \frac{d}{dt} \int_{-\infty}^{\infty} |\Psi(x, t)|^2 dx &= \int_{-\infty}^{\infty} \frac{\partial}{\partial t} |\Psi(x, t)|^2 dx \\ &= \frac{i\hbar}{2m} \left[\Psi^* \frac{\partial \Psi}{\partial x} - \frac{\partial \Psi^*}{\partial x} \Psi \right]_{-\infty}^{\infty} \quad (\text{Proposition 24.1.3}) \\ &= 0 \quad (\Psi \rightarrow 0 \text{ as } x \rightarrow \pm\infty) \end{aligned}$$

$\langle 2 \rangle 1.$ $\int_{-\infty}^{\infty} |\Psi(x, t)|^2 dx$ is constant.

□

24.2 Statistical Interpretation

Born's statistical interpretation of the wave function:

The *position* on the particle at time t is a random variable x with probability density function $|\Psi(x, t)|^2$ at time t .

Proposition 24.2.1. The expected value of position is

$$\langle x \rangle = \int_{-\infty}^{+\infty} x |\Psi(x, t)|^2 dx = \int_{-\infty}^{+\infty} \Psi(x, t)^* x \Psi(x, t) dx$$

PROOF: Immediate from definitions. \square

24.3 Momentum

Associated with any *observable* quantity Q is a linear operator

$$\hat{Q} : \mathcal{C}(\mathbb{R}, \mathbb{C}) \rightarrow \mathcal{C}(\mathbb{R}, \mathbb{C}) \ .$$

The *expected value* of Q at time t is then

$$\langle Q \rangle = \int_{-\infty}^{+\infty} \Psi(x, t)^* \hat{Q}(\lambda x, \Psi(x, t)) dx \ .$$

Position x is represented by the operator \hat{x} , multiplication by x .

Momentum p is represented by the operator $\hat{p} = -i\hbar \frac{\partial}{\partial x}$.

Kinetic energy T is represented by

$$\hat{T} = \frac{\hat{p}^2}{2m} = -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} \ .$$

Proposition 24.3.1 (Ehrenfest's Theorem). 1.

$$\langle p \rangle = m \frac{d\langle x \rangle}{dt}$$

2.

$$\frac{d\langle p \rangle}{dt} = \left\langle -\frac{\partial V}{\partial x} \right\rangle$$

PROOF:

$$\begin{aligned}
m \frac{d\langle x \rangle}{dt} &= m \frac{d}{dt} \int_{-\infty}^{+\infty} x |\Psi|^2 dx \\
&= m \int_{-\infty}^{+\infty} x \frac{\partial}{\partial t} |\Psi|^2 dx \\
&= \frac{i\hbar}{2} \int_{-\infty}^{+\infty} x \frac{\partial}{\partial x} \left(\Psi^* \frac{\partial \Psi}{\partial x} - \frac{\partial \Psi^*}{\partial x} \Psi \right) dx && \text{(Proposition 24.1.3)} \\
&= -\frac{i\hbar}{2} \int_{-\infty}^{+\infty} \left(\Psi^* \frac{\partial \Psi}{\partial x} - \frac{\partial \Psi^*}{\partial x} \Psi \right) dx \\
&\quad + \left[x \left(\Psi^* \frac{\partial \Psi}{\partial x} - \frac{\partial \Psi^*}{\partial x} \Psi \right) \right]_{-\infty}^{+\infty} && \text{(integrating by parts)} \\
&= -\frac{i\hbar}{2} \int_{-\infty}^{+\infty} \left(\Psi^* \frac{\partial \Psi}{\partial x} - \frac{\partial \Psi^*}{\partial x} \Psi \right) dx \\
&= -i\hbar \int_{-\infty}^{+\infty} \Psi^* \frac{\partial \Psi}{\partial x} dx && \text{(integrating by parts)} \\
&= \langle p \rangle \\
\frac{d\langle p \rangle}{dt} &= -i\hbar \frac{d}{dt} \int_{-\infty}^{+\infty} \Psi(x, t)^* \frac{\partial \Psi}{\partial x} dx \\
&= -i\hbar \int_{-\infty}^{+\infty} \frac{\partial}{\partial t} \left(\Psi(x, t)^* \frac{\partial \Psi}{\partial x} \right) dx \\
&= -i\hbar \int_{-\infty}^{+\infty} \left(\Psi^* \frac{\partial^2 \Psi}{\partial t \partial x} + \frac{\partial \Psi^*}{\partial t} \frac{\partial \Psi}{\partial x} \right) dx \\
&\quad \frac{\partial \Psi}{\partial t} = \frac{i\hbar}{2m} \frac{\partial^2 \Psi}{\partial x^2} - \frac{i}{\hbar} V \Psi && \text{(Schrödinger equation)} \\
\therefore \frac{\partial^2 \Psi}{\partial x \partial t} &= \frac{i\hbar}{2m} \frac{\partial^3 \Psi}{\partial x^3} - \frac{i}{\hbar} \frac{\partial V}{\partial x} \Psi - \frac{i}{\hbar} V \frac{\partial \Psi}{\partial x} \\
\frac{\partial \Psi^*}{\partial t} &= -\frac{i\hbar}{2m} \frac{\partial^2 \Psi^*}{\partial x^2} + \frac{i}{\hbar} V \Psi^* \\
\therefore \Psi^* \frac{\partial^2 \Psi}{\partial t \partial x} + \frac{\partial \Psi^*}{\partial t} \frac{\partial \Psi}{\partial x} &= \frac{i\hbar}{2m} \Psi^* \frac{\partial^3 \Psi}{\partial x^3} - \frac{i}{\hbar} \frac{\partial V}{\partial x} \Psi^* \Psi - \frac{i}{\hbar} V \Psi^* \frac{\partial \Psi}{\partial x} \\
&\quad - \frac{i\hbar}{2m} \frac{\partial^2 \Psi^*}{\partial x^2} \frac{\partial \Psi}{\partial x} + \frac{i}{\hbar} V \Psi^* \frac{\partial \Psi}{\partial x} \\
\therefore \frac{d\langle p \rangle}{dt} &= \frac{\hbar^2}{2m} \int_{-\infty}^{+\infty} \left(\Psi^* \frac{\partial^3 \Psi}{\partial x^3} - \frac{\partial^2 \Psi^*}{\partial x^2} \frac{\partial \Psi}{\partial x} \right) dx \\
&\quad + \int_{-\infty}^{+\infty} \Psi^* \left(-\frac{\partial V}{\partial x} \right) \Psi dx \\
&= -\frac{\hbar^2}{2m} \int_{-\infty}^{+\infty} \left(\frac{\partial \Psi^*}{\partial x} \frac{\partial^2 \Psi}{\partial x^3} + \frac{\partial^2 \Psi^*}{\partial x^2} \frac{\partial \Psi}{\partial x} \right) dx \\
&\quad + \left[\Psi^* \frac{\partial^2 \Psi}{\partial x^2} \right]_{-\infty}^{+\infty} + \left\langle -\frac{\partial V}{\partial x} \right\rangle \\
&= -\frac{\hbar^2}{2m} \left[\frac{\partial \Psi^*}{\partial x} \frac{\partial \Psi}{\partial x} \right]_{-\infty}^{+\infty} + \left\langle \bullet - \frac{\partial V}{\partial x} \right\rangle \\
&= \left\langle -\frac{\partial V}{\partial x} \right\rangle
\end{aligned}$$

Proposition 24.3.2 (Canonical Commutation Relation).

$$[\hat{x}, \hat{p}] = i\hbar$$

PROOF:

$$\begin{aligned} [\hat{x}, \hat{p}]\psi &= -i\hbar x \frac{d\psi}{dx} + i\hbar \frac{d}{dx}(x\psi) \\ &= -i\hbar \left(x \frac{d\psi}{dx} - x \frac{d\psi}{dx} - \psi \right) \\ &= i\hbar \psi \end{aligned} \quad \square$$

24.4 The Time-Independent Schrödinger Equation

Definition 24.4.1 (Hamiltonian). Assume that the potential V does not vary with t . The *Hamiltonian* or *total energy* H is the quantity with operator

$$\begin{aligned} \hat{H} &= \frac{\hat{p}^2}{2m} + V(t)\hat{I} \\ &= -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} + V(x)\hat{I} \end{aligned}$$

Definition 24.4.2 (Time-independent Schrödinger equation). Assume that the potential V does not vary with t . Let $E \geq 0$. The *time-independent Schrödinger equation* with *energy* E is

$$\hat{H}\psi = E\psi$$

i.e.

$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V(x)\psi(x) = E\psi(x) \quad .$$

Proposition 24.4.3. Let $\psi : \mathbb{R} \rightarrow \mathbb{C}$. Then

$$\Psi(x, t) = \psi(x)e^{-\frac{iEt}{\hbar}}$$

is a solution to the time-dependent Schrödinger equation iff ψ is a solution to the time-independent Schrödinger equation.

PROOF:

$$\begin{aligned} i\hbar \frac{\partial \Psi}{\partial t} &= i\hbar \psi \left(-\frac{iE}{\hbar} \right) e^{-\frac{iEt}{\hbar}} \\ &= E\psi e^{-\frac{iEt}{\hbar}} \\ -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} + V\Psi &= e^{-\frac{iEt}{\hbar}} \left(-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V\psi \right) \end{aligned}$$

and these are equal iff the time-independent equation holds. \square

Proposition 24.4.4 (Solutions to the Time-Independent Equation are Stationary States). *Let the wave function of the particle be*

$$\Psi(x, t) = \psi(x)e^{-\frac{iEt}{\hbar}}$$

For any quantity Q , the expectation value $\langle Q \rangle$ is constant in t .

PROOF:

$$\begin{aligned}\langle Q \rangle &= \int_{-\infty}^{+\infty} \Psi^*(x, t) \hat{Q}(\lambda x, \Psi(x, t))(x) dx \\ &= \int_{-\infty}^{+\infty} \psi^*(x) e^{\frac{iEt}{\hbar}} \hat{Q}(\lambda x, \psi(x) e^{-\frac{iEt}{\hbar}}) dx \\ &= \int_{-\infty}^{+\infty} \psi^*(x) \hat{Q}(\psi)(x) dx\end{aligned}$$

since \hat{Q} is linear. \square

Corollary 24.4.4.1. *If the wave function is given by $\psi(x)e^{-\frac{iEt}{\hbar}}$ then $\langle p \rangle = 0$.*

Proposition 24.4.5. *If the wave function is given by $\psi(x)e^{-\frac{iEt}{\hbar}}$ then $\langle H \rangle = E$ and $\sigma_H = 0$.*

PROOF:

$$\begin{aligned}\langle H \rangle &= \int \psi^* \hat{H} \psi dx \\ &= \int \psi^* E \psi dx \quad (\text{time-independent Schrödinger equation}) \\ &= E \int |\psi|^2 dx \\ &= E \\ \langle H^2 \rangle &= \int \psi^* \hat{H}^2 \psi dx \\ &= E^2 \int \psi^* \psi dx \\ &= E^2 \\ \therefore \sigma_H^2 &= \langle H^2 \rangle - \langle H \rangle^2 \\ &= 0\end{aligned} \quad \square$$

Example 24.4.6 (The Infinite Square Well). *The infinite square well with size a ($a > 0$) is a particle moving under the potential*

$$V(x) = \begin{cases} 0 & \text{if } 0 \leq x \leq a, \\ \infty & \text{otherwise} \end{cases}$$

The normalizable solutions to the time-independent equation are

$$\psi_n(x) = \sqrt{\frac{2}{a}} \sin \frac{n\pi}{a} x$$

with associated energy

$$E_n = \frac{n^2 \pi^2 \hbar^2}{2ma^2} .$$

24.5 The Quantum Harmonic Oscillator

The *quantum harmonic oscillator* with frequency ω is a particle of mass m moving under the potential

$$V(x) = \frac{1}{2}m\omega^2 x^2 .$$

Proposition 24.5.1. *The Hamiltonian operator for the quantum harmonic oscillator is*

$$\hat{H} = \frac{1}{2m} (\hat{p}^2 + (m\omega x)^2) .$$

PROOF: Immediate from definitions. \square

Definition 24.5.2 (Ladder Operators). The *raising operator* \hat{a}_+ is

$$\hat{a}_+ = \frac{1}{\sqrt{2\hbar m\omega}} (-i\hat{p} + m\omega\hat{x})$$

The *lowering operator* \hat{a}_- is

$$\hat{a}_- = \frac{1}{\sqrt{2\hbar m\omega}} (i\hat{p} + m\omega\hat{x})$$

Together, these are called the *ladder operators*.

Proposition 24.5.3.

$$[\hat{a}_-, \hat{a}_+] = 1$$

Proposition 24.5.4.

$$\hat{H} = \hbar\omega(\hat{a}_-\hat{a}_+ - \frac{1}{2}) = \hbar\omega(\hat{a}_+\hat{a}_- + \frac{1}{2})$$

Proposition 24.5.5. *If ψ is a solution to the time-independent Schrödinger equation with energy E , then $\hat{a}_+\psi$ is a solution with energy $E + \hbar\omega$, and $\hat{a}_-\psi$ is a solution with energy $E - \hbar\omega$.*

Proposition 24.5.6. *For any integrable functions $f, g : \mathbb{R} \rightarrow \mathbb{C}$,*

$$\int_{-\infty}^{+\infty} f^*(\hat{a}_\pm g) dx = \int_{-\infty}^{+\infty} (\hat{a}_\mp f)^* g dx$$

PROOF:

$$\begin{aligned}
 \int_{-\infty}^{+\infty} f^*(\hat{a}_{\pm}g)dx &= \frac{1}{\sqrt{2\hbar m\omega}} \int_{-\infty}^{+\infty} f^*(\mp\hbar\frac{d}{dx} + m\omega x)g dx \\
 &= \frac{1}{\sqrt{2\hbar m\omega}} \left[\mp \int f^* \frac{dg}{dx} dx + \int m\omega f^* x g dx \right] \\
 &= \frac{1}{\sqrt{2\hbar m\omega}} \left[\pm \int \frac{df^*}{dx} g dx + \int m\omega f^* x g dx \right] \quad (\text{integrating by parts}) \\
 &= \frac{1}{\sqrt{2\hbar m\omega}} \int ((\pm\hbar\frac{d}{dx} + m\omega x)f^*)g dx \\
 &= \int (a_{\mp}pf)^* g dx \quad \square
 \end{aligned}$$

Proposition 24.5.7. *The normalized solutions to the time-independent Schrödinger equation are*

$$\psi_n(x) = \frac{1}{\sqrt{n!}} (\hat{a}_+)^n \psi_0$$

with energies

$$E_n = \left(n + \frac{1}{2}\right) \hbar\omega$$

where

$$\psi_0(x) = \left(\frac{m\omega}{\pi\hbar}\right)^{\frac{1}{4}} e^{-\frac{m\omega}{2\hbar}x^2}.$$

PROOF:

<1>1. $\psi(x) = e^{-\frac{m\omega}{2\hbar}x^2}$ is a solution with energy $\frac{1}{2}\hbar m\omega$.

PROOF:

$$\begin{aligned}
 \frac{d\psi}{dx} &= -\frac{m\omega}{\hbar}x\psi \\
 \therefore \frac{d^2\psi}{dx^2} &= -\frac{m\omega}{\hbar} \left(x \frac{d\psi}{dx} + \psi \right) \\
 &= \frac{m^2\omega^2}{\hbar^2}x^2\psi - \frac{m\omega}{\hbar}\psi \\
 \therefore \hat{H}\psi &= -\frac{\hbar^2}{2m} \frac{m^2\omega^2}{\hbar^2}x^2\psi - \frac{\hbar^2}{2m} \frac{m\omega}{\hbar}\psi + \frac{1}{2}m\omega^2x^2\psi \\
 &= \frac{1}{2}\hbar m\omega\psi
 \end{aligned}$$

<1>2. For this ψ we have $\int |\psi|^2 dx = \sqrt{\frac{\pi\hbar}{m\omega}}$.

PROOF:

$$\begin{aligned}
 \int |\psi|^2 dx &= \int e^{-\frac{m\omega}{\hbar}x^2} dx \\
 &= \sqrt{\frac{\pi\hbar}{m\omega}}
 \end{aligned}$$

<1>3. ψ_0 is a normalized solution.

<1>4. For all n we have $(\hat{a}_+)^n \psi_0$ is a solution with energy E_n .

PROOF: Proposition 24.5.5.

⟨1⟩5. $\hat{a}_- \hat{a}_+ \chi_n = (n+1)\chi - n$

PROOF: Since from Proposition 24.5.4 we have

$$\hbar\omega \hat{a}_- \hat{a}_+ \chi_n - \frac{1}{2}\chi_n = (n + \frac{1}{2})\hbar\omega \chi_n$$

⟨1⟩6. For all n , we have $\int |(\hat{a}_+)^n \psi_0|^2 dx = n!$.

PROOF:

⟨2⟩1. LET: $\chi_n = (\hat{a}_+)^n \psi_0$

⟨2⟩2. ASSUME: as induction hypothesis $\int |\chi_n|^2 dx = n!$.

⟨2⟩3. $\int |\chi_{n+1}|^2 dx = (n+1)!$

PROOF:

$$\begin{aligned} \int |\chi_{n+1}|^2 dx &= \int (\hat{a}_+ \chi_n)^* (\hat{a}_+ \chi_n) dx \\ &= \int \chi_n^* (\hat{a}_- \hat{a}_+ \chi_n) dx && \text{(Proposition 24.5.6)} \\ &= (n+1) \int \chi_n^* \chi_n dx && (\langle 1 \rangle 5) \\ &= (n+1)n! && (\langle 1 \rangle 3) \\ &= (n+1)! \end{aligned}$$

⟨1⟩7. For all n , ψ_n is a normalized solution.

⟨1⟩8. For all $n > 0$, $\hat{a}_- \psi_n = \sqrt{n} \psi_{n-1}$

PROOF: Using ⟨1⟩5.

⟨1⟩9. For any non-zero solution ψ , if $\hat{a}_- \psi$ has energy ≤ 0 then ψ is a constant multiplied by ψ_0 .

PROOF:

⟨2⟩1. ASSUME: $\hat{a}_- \psi$ has energy ≤ 0

⟨2⟩2. $\hat{a}_- \psi = 0$

⟨2⟩3.

$$\hbar \frac{d\psi}{dx} + m\omega x \psi = 0$$

⟨2⟩4.

$$\frac{1}{\psi} \frac{d\psi}{dx} = -\frac{m\omega}{\hbar} x$$

⟨2⟩5. $\ln \psi = -\frac{m\omega}{2\hbar} x^2$ plus a constant.

⟨2⟩6. $\psi = e^{-\frac{m\omega}{2\hbar} x^2}$ multiplied by a constant.

⟨1⟩10. For any solution ψ with energy > 0 , there exists n such that ψ is a constant multiplied by ψ_n .

⟨2⟩1. LET: n be least such that $(\hat{a}_-)^{n+1} \psi$ has non-positive energy.

⟨2⟩2. $(\hat{a}_-)^n \psi$ is a constant multiplied by ψ_0 .

⟨2⟩3. ψ is a constant multiplied by $(\hat{a}_+)^n \psi_0$.

⟨2⟩4. ψ is a constant multiplied by ψ_n .

□

Definition 24.5.8. We call ψ_0 the *ground state* of the quantum harmonic oscillator, and the other ψ_n the *excited states*.

Proposition 24.5.9.

$$x = \sqrt{\frac{\hbar}{2m\omega}}(\hat{a}_+ + \hat{a}_-)$$

PROOF: Straightforward calculation. \square

Proposition 24.5.10.

$$\hat{p} = i\sqrt{\frac{\hbar m\omega}{2}}(\hat{a}_+ - \hat{a}_-)$$

PROOF: Straightforward calculation. \square

Proposition 24.5.11. *If $m \neq n$ then*

$$\int \psi_m^* \psi_n dx = 0$$

PROOF: We have

$$\int \psi_m^* \hat{a}_+ \hat{a}_- \psi_n dx = n \int \psi_m^* \psi_n dx$$

and

$$\begin{aligned} \int \psi_m^* \hat{a}_+ \hat{a}_- \psi_n dx &= \int \hat{a}_+ \hat{a}_- \psi_m^* \psi_n dx && \text{(Proposition 24.5.6)} \\ &= m \int \psi_m^* \psi_n dx \end{aligned}$$

Therefore either $m = n$ or $\int \psi_m^* \psi_n dx = 0$. \square

Proposition 24.5.12. *For the n th excited state of the quantum harmonic oscillator we have:*

$$\begin{aligned} \langle x \rangle &= 0 \\ \langle p \rangle &= 0 \\ \sigma_x &= \sqrt{\left(n + \frac{1}{2}\right) \frac{\hbar}{m\omega}} \\ \sigma_p &= \sqrt{\left(n + \frac{1}{2}\right) \hbar m\omega} \\ \langle T \rangle &= \frac{1}{2} \hbar \omega \left(n + \frac{1}{2}\right) \\ \langle V \rangle &= \frac{1}{2} \hbar \omega \left(n + \frac{1}{2}\right) \end{aligned}$$

PROOF: These follow from

$$\begin{aligned}
 \langle x^2 \rangle &= \int_{-\infty}^{+\infty} \psi_n^* x^2 \psi_n dx \\
 &= \frac{\hbar}{2m\omega} \int_{-\infty}^{+\infty} \psi_n^* [\hat{a}_+^2 + \hat{a}_+ \hat{a}_- + \hat{a}_- \hat{a}_+ + \hat{a}_-^2] \psi_n dx \\
 &= \frac{\hbar}{2m\omega} \left[\int_{-\infty}^{+\infty} a \psi_n^* \psi_{n+2} dx + n \int \psi_n^* \psi_n dx + (n+1) \int \psi_n^* \psi_n dx + \int b \psi_n^* \psi_{n-2} dx \right] \\
 &= \frac{\hbar}{2m\omega} (2n+1)
 \end{aligned}$$

and $\langle p^2 \rangle = \frac{\hbar m \omega}{2} (2n+1)$ similar. \square

Proposition 24.5.13. *The n th excited state is*

$$\psi_n(x) = \left(\frac{m\omega}{\pi\hbar} \right)^{\frac{1}{4}} \frac{1}{\sqrt{2^n n!}} H_n(\xi) e^{-\frac{\xi^2}{2}}$$

where H_n is the n th Hermite polynomial and

$$\xi = \sqrt{\frac{m\omega}{\hbar}} x .$$

PROOF: From Proposition 24.5.7 by induction. \square

24.6 The Free Particle

Proposition 24.6.1. *The solutions to the time-independent Schrödinger equation with $V = 0$ are*

$$Ae^{i(kx - \frac{\hbar k^2}{2m}t)}$$

Proposition 24.6.2. *The normalized solutions to the time-dependent Schrödinger equation with $V = 0$ are the wave packets*

$$\Psi(x, t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} \phi(k) e^{i(kx - \frac{\hbar k^2}{2m}t)} dk$$

where $\phi : \mathbb{R} \rightarrow \mathbb{C}$ is a function such that

$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} \phi(k) dk = 1 .$$

Proposition 24.6.3. *Let a particle moving under potential $V = 0$ have initial wave function $\Psi(x, 0)$. Then we have*

$$\Psi(x, t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} \phi(k) e^{i(kx - \frac{\hbar k^2}{2m}t)} dk$$

where

$$\phi(k) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} \Psi(x, 0) e^{-ikx} dx .$$

PROOF: We have $\phi(k)$ is the inverse Fourier transform of $\Phi(x, t)$ hence of $\Phi(x, 0)$.
 \square