

Mathematics

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Contents

1	Primitive Terms and Axioms	7
1.1	Primitive Terms	7
1.2	Injectons, Surjections and Bijections	7
1.3	Axioms	8
2	Sets and Functions	11
2.1	Composition	11
2.1.1	Injectons	11
2.1.2	Surjections	13
2.1.3	Bijections	13
2.2	Identity Function	15
2.2.1	Composition	15
2.2.2	The Empty Set	16
2.2.3	The Singleton	17
2.2.4	The Set Two	17
2.2.5	Subsets	18
2.2.6	Union	19
2.2.7	Intersection	20
2.2.8	Direct Image	20
2.2.9	Inverse Image	20
2.3	Relations	21
2.3.1	Equivalence Relations	21
2.4	Power Set	21
2.4.1	Partitions	21
2.5	Cartesian Product	22
2.6	Quotient Sets	22
2.7	Partitions	22
2.8	Disjoint Union	22
2.9	Natural Numbers	22
2.10	Finite and Infinite Sets	23
2.11	Countable Sets	25

3	Order Theory	29
3.1	Relations	29
3.1.1	Strict Partial Orders	30
3.1.2	Linear Orders	31
3.1.3	Sets of Finite Type	32
3.2	Well Orders	33
4	Category Theory	39
4.1	Categories	39
4.1.1	Monomorphisms	43
4.1.2	Epimorphisms	43
4.1.3	Sections and Retractions	44
4.1.4	Isomorphisms	44
4.1.5	Initial Objects	45
4.1.6	Terminal Objects	45
4.1.7	Zero Objects	46
4.1.8	Triads	46
4.1.9	Cotriads	46
4.1.10	Pullbacks	46
4.1.11	Pushouts	49
4.1.12	Subcategories	52
4.1.13	Opposite Category	52
4.1.14	Groupoids	53
4.1.15	Concrete Categories	53
4.1.16	Power of Categories	53
4.1.17	Arrow Category	53
4.1.18	Slice Category	53
4.2	Functors	56
4.3	Natural Transformations	59
4.4	Bifunctors	60
4.5	Functor Categories	61
5	The Real Numbers	63
5.0.1	Subtraction	65
6	Integers and Rationals	71
6.1	Positive Integers	71
6.1.1	Exponentiation	72
6.2	Integers	73
6.3	Rational Numbers	75
6.4	Algebraic Numbers	76
7	Monoid Theory	77
8	Group Theory	79

<i>CONTENTS</i>	5
9 Ring Theory	81
10 Field Theory	83
11 Linear Algebra	85
12 Topology	87
12.1 Topological Spaces	87
12.1.1 Subspaces	91
12.1.2 Topological Disjoint Union	93
12.1.3 Product Topology	95
12.1.4 Bases	97
12.1.5 Subbases	99
12.1.6 Countability Axioms	100
12.2 Interior	101
12.3 Closure	101
12.3.1 Subspaces	102
12.3.2 Product Topology	102
12.3.3 Interior	103
12.4 Boundary	103
12.5 Limit Points	105
12.6 Continuous Functions	105
12.6.1 Paths	109
12.6.2 Loops	109
12.7 Convergence	109
12.8 Subspaces	109
12.9 Embedding	110
12.10 Open Maps	110
12.11 Quotient Spaces	110
12.12 Connected Spaces	113
12.13 T_1 Spaces	113
12.13.1 Limit Points	114
12.14 Hausdorff Spaces	115
12.15 Separable Spaces	117
12.16 Sequential Compactness	117
12.17 Compactness	117
12.18 Quotient Spaces	118
12.19 Gluing	119
12.20 Metric Spaces	119
12.20.1 Products	120
12.21 Complete Metric Spaces	122
12.22 Manifolds	122
13 Homotopy Theory	123
13.1 Homotopies	123
13.2 Homotopy Equivalence	123

14 Simplicial Complexes	125
14.1 Cell Decompositions	125
14.2 CW-complexes	125
15 Topological Groups	127
15.1 Continuous Actions	127
16 Topological Vector Spaces	129
16.1 Cauchy Sequences	129
16.2 Seminorms	130
16.3 Fréchet Spaces	130
16.4 Normed Spaces	130
16.5 Inner Product Spaces	132
16.6 Banach Spaces	133
16.7 Hilbert Spaces	133
16.8 Locally Convex Spaces	133

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). A function $f : A \rightarrow B$ is *injective* or an *injection* iff, for all $x, y \in A$, if $f(x) = f(y)$ then $x = y$.

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

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

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

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

1.3 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 $f = g$.*

Definition 1.3.3 (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 1.3.4 (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 1.3.5 (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 1.3.6 (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 1.3.7 (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 $a = p(b)$.

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 $p : B \rightarrow A$ is a surjective function such that A is small, then there exists a U -small set C , a surjection $q : C \rightarrow A$, 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:

$$\begin{aligned} (h \circ (g \circ f))(x) &= h((g \circ f)(x)) && \text{(Definition of composition)} \\ &= h(g(f(x))) && \text{(Definition of composition)} \\ &= (h \circ g)(f(x)) && \text{(Definition of composition)} \\ &= ((h \circ g) \circ f)(x) && \text{(Definition of composition)} \end{aligned}$$

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

PROOF: By the Axiom of Extensionality.

□

2.1.1 Injections

Proposition 2.1.2. *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:

$$\begin{aligned} g(f(x)) &= (g \circ f)(x) && \text{(definition of composition)} \\ &= (g \circ f)(y) && (\langle 1 \rangle 7) \\ &= g(f(y)) && \text{(definition of composition)} \end{aligned}$$

 $\langle 1 \rangle 9. f(x) = f(y)$
 PROOF: $\langle 1 \rangle 4, \langle 1 \rangle 8$
 $\langle 1 \rangle 10. x = y$
 PROOF: $\langle 1 \rangle 5, \langle 1 \rangle 9$
 \square

Proposition 2.1.3. *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:

$$\begin{aligned} (g \circ f)(x) &= g(f(x)) && \text{(definition of composition)} \\ &= g(f(y)) && (\langle 1 \rangle 6) \\ &= (g \circ f)(y) && \text{(definition of composition)} \end{aligned}$$

 $\langle 1 \rangle 8. x = y$
 PROOF: $\langle 1 \rangle 4, \langle 1 \rangle 7$
 \square

Proposition 2.1.4. *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, $\langle 1 \rangle 5$

□

2.1.2 Surjections

Proposition 2.1.5. *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 2.1.6. *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 $b = f(a)$.

□

2.1.3 Bijections

Proposition 2.1.7. *The composite of bijections is a bijection.*

PROOF: Propositions 2.1.2 and 2.1.5. \square

Theorem 2.1.8 (Schroeder-Bernstein). *Let A and B be sets. If there exist injections $A \rightarrow B$ and $B \rightarrow A$, 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

Proposition 2.1.9.

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

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

Proposition 2.1.10.

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

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

2.2 Identity Function

Definition 2.2.1 (Identity). For any set A , the *identity* function $\text{id}_A : A \rightarrow A$ is the function defined by $\text{id}_A(a) = a$.

2.2.1 Composition

Proposition 2.2.2. 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 $f(a)$. \square

Proposition 2.2.3. 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: $g(f(x)) = x$

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

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

\square

Proposition 2.2.4. 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:

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

$\langle 2 \rangle 1$. ASSUME: f is surjective.

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

PROOF: Axiom of Choice.

$\langle 2 \rangle 3$. $f \circ g = \text{id}_B$.

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

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

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

$\langle 2 \rangle 3$. LET: $h, k : B \rightarrow X$

$\langle 2 \rangle 4$. ASSUME: $h \circ f = k \circ f$

$\langle 2 \rangle 5$. $h = k$

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

□

Corollary 2.2.4.1. *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 2.2.5. *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 2.2.13.
- ⟨2⟩3. $f \circ g \circ f = f$
- ⟨2⟩4. $g \circ f = \text{id}_A$
PROOF: Proposition 2.1.4.
- ⟨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 2.2.13.
- ⟨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 $g = g \circ f \circ h = h$.

□

2.2.2 The Empty Set

Theorem 2.2.6. *There exists a set which has no elements.*

PROOF:

- ⟨1⟩1. PICK a set A
PROOF: By the Axiom of Infinity, a set exists.
- ⟨1⟩2. LET: $S = \{x \in A : \perp\}$ with injection $i : S \rightarrow A$
PROOF: Axiom of Separation.
- ⟨1⟩3. S has no elements.

□

Theorem 2.2.7. *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 $F(x) = y$.

□

Definition 2.2.8 (Empty Set). The *empty set* \emptyset is the set with no elements.

2.2.3 The Singleton

Theorem 2.2.9. *There exists a set that has exactly one element.*

PROOF:

$\langle 1 \rangle 1$. PICK a set A that has an element.

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

$\langle 1 \rangle 2$. PICK $a \in A$

$\langle 1 \rangle 3$. PICK a set S and injection $i : S \rightarrow A$ such that, for all $x \in A$, there exists $s \in S$ such that $s = x$ if and only if $x = a$

$\langle 1 \rangle 4$. S has exactly one element.

□

Theorem 2.2.10. *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.

□

Definition 2.2.11 (Singleton). Let 1 be the set that has exactly one element.
 Let $*$ be its element.

Proposition 2.2.12. *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 $X = 1$. □

2.2.4 The Set Two

Proposition 2.2.13. *Let $f : A \rightarrow B$. Then f is surjective if and only if, for any set X and functions $g, h : B \rightarrow X$, if $g \circ f = h \circ f$ then $g = h$.*

PROOF:

- <1>1. If f is surjective then, for any set X and functions $g, h : B \rightarrow X$, if $g \circ f = h \circ f$ then $g = h$.
 <2>1. ASSUME: f is surjective.
 <2>2. LET: X be a set.
 <2>3. LET: $g, h : B \rightarrow X$
 <2>4. ASSUME: $g \circ f = h \circ f$
 <2>5. LET: $b \in B$
 PROVE: $g(b) = h(b)$
 <2>6. PICK $a \in A$ such that $f(a) = b$
 <2>7. $g(b) = h(b)$
 PROOF: $g(b) = g(f(a)) = h(f(a)) = h(b)$
 <1>2. If, 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.
 <2>1. ASSUME: For any set X and functions $g, h : B \rightarrow X$, if $g \circ f = h \circ f$ then $g = h$.
 <2>2. LET: $b \in B$
 <2>3. LET: $h : B \rightarrow 2$ be the function that maps everything to 1.
 <2>4. LET: $k : B \rightarrow 2$ be the function that maps b to 0 and everything else to 1.
 <2>5. $h \neq k$
 <2>6. $h \circ f \neq k \circ f$
 <2>7. PICK $a \in A$ such that $h(f(a)) \neq k(f(a))$
 <2>8. $f(a) = b$

□

2.2.5 Subsets

Definition 2.2.14 (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 2.2.15. 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 2.2.16. 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 2.2.17. 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 2.2.18 (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 2.2.19. If $a \in (S, i)$ and $(S, i) = (T, j)$ then $a \in (T, j)$.

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

Definition 2.2.20 (Union). Given subsets S and T of A , the *union* is the subset $\{x \in A : x \in S \vee x \in T\}$.

Definition 2.2.21 (Intersection). Given subsets S and T of A , the *intersection* is the subset $\{x \in A : x \in S \wedge x \in T\}$.

Proposition 2.2.22 (Distributive Law).

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

Proposition 2.2.23 (Distributive Law).

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

Definition 2.2.24. Given a set A , we write \emptyset for the subset $(\emptyset, !)$ where $!$ is the unique function $\emptyset \rightarrow A$.

Proposition 2.2.25.

$$S \cup \emptyset = S$$

Proposition 2.2.26.

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

Definition 2.2.27 (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 2.2.28.

$$\emptyset \subseteq S$$

Definition 2.2.29 (Disjoint). Subsets S and T of A are *disjoint* iff $S \cap T = \emptyset$.

Definition 2.2.30 (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 2.2.31 (De Morgan's Law).

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

Proposition 2.2.32 (De Morgan's Law).

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

2.2.6 Union

Definition 2.2.33 (Union). Given $\mathcal{A} \in \mathcal{PPX}$, its *union* is

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

2.2.7 Intersection

Definition 2.2.34 (Intersection). Given $\mathcal{A} \in \mathcal{PP}X$, its *intersection* is

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

2.2.8 Direct Image

Definition 2.2.35 (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 2.2.36.

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

Example 2.2.37. 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 2.2.38. 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 $f(S) - f(T) = \emptyset$.

2.2.9 Inverse Image

Definition 2.2.39 (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 2.2.40. 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. $(g \circ f)^{-1}(S) = f^{-1}(g^{-1}(S))$

2.3 Relations

Definition 2.3.1 (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 2.3.2 (Reflexive). A relation R on a set A is *reflexive* iff $\forall a \in A. aRa$.

Definition 2.3.3 (Symmetric). A relation R on a set A is *symmetric* iff, whenever xRy , then yRx .

Definition 2.3.4 (Transitive). A relation R on a set A is *transitive* iff, whenever xRy and yRz , then xRz .

2.3.1 Equivalence Relations

Definition 2.3.5 (Equivalence Relation). A relation R on a set A is an *equivalence relation* iff it is reflexive, symmetric and transitive.

Definition 2.3.6 (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 2.3.7. *Two equivalence classes are either disjoint or equal.*

2.4 Power Set

Definition 2.4.1 (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 $a \in A$ for $S(a) = 1$.

Definition 2.4.2 (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 $S \cap T = \emptyset$.

2.4.1 Partitions

Definition 2.4.3 (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.

2.5 Cartesian Product

Definition 2.5.1 (Cartesian Product). Let A and B be sets. The *Cartesian product* of A and B , $A \times B$, is the tabulation of the relation $A \bowtie B$ 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 $\pi_2(a, b) = b$.

2.6 Quotient Sets

Proposition 2.6.1. 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 $\phi \circ \pi = p$.

2.7 Partitions

Definition 2.7.1 (Partition). A *partition* of a set X is a set of pairwise disjoint subsets of X whose union is X .

2.8 Disjoint Union

Theorem 2.8.1. 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 2.8.2 (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 $f \upharpoonright S = f \circ i$.

2.9 Natural Numbers

Theorem 2.9.1 (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:

⟨1⟩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

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

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

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

⟨2⟩2. $P[0]$

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

⟨2⟩3. For any natural number n , if $P[n]$ then $P[n+1]$.

⟨3⟩1. ASSUME: $P[n]$

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

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

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

⟨3⟩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 $g' = g$.

□

2.10 Finite and Infinite Sets

Definition 2.10.1 (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 2.10.2. 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 2.10.3. 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: $P[n]$

- $\langle 2 \rangle 3$. LET: A be a set.
 $\langle 2 \rangle 4$. ASSUME: $A \approx \{m \in \mathbb{N} : m < n + 1\}$
 $\langle 2 \rangle 5$. LET: B be a proper subset of A .
 $\langle 2 \rangle 6$. CASE: $B = \emptyset$
 PROOF: Then $B \not\approx \{m \in \mathbb{N} : m < n + 1\}$ but $B \approx \{k \in \mathbb{N} : k < 0\}$.
 $\langle 2 \rangle 7$. CASE: $B \neq \emptyset$
 $\langle 3 \rangle 1$. PICK $b_0 \in B$
 $\langle 3 \rangle 2$. $A - \{b_0\} \approx \{m \in \mathbb{N} : m < n\}$
 $\langle 3 \rangle 3$. $B - \{b_0\}$ is a proper subset of $A - \{b_0\}$
 $\langle 3 \rangle 4$. $B - \{b_0\} \not\approx \{m \in \mathbb{N} : m < n\}$
 $\langle 3 \rangle 5$. $B \approx \{m \in \mathbb{N} : m < n + 1\}$
 $\langle 3 \rangle 6$. PICK $m < n$ such that $B - \{b_0\} \approx \{k \in \mathbb{N} : k < m\}$
 $\langle 3 \rangle 7$. $m + 1 < n + 1$
 $\langle 3 \rangle 8$. $B \approx \{k \in \mathbb{N} : k < m + 1\}$

□

Corollary 2.10.3.1. *If A is finite then there is no bijection between A and a proper subset of A .*

Corollary 2.10.3.2. *\mathbb{N} is infinite.*

Corollary 2.10.3.3. *The cardinality of a finite set is unique.*

Corollary 2.10.3.4. *A subset of a finite set is finite.*

Corollary 2.10.3.5. *If A is finite and B is a proper subset of A then $|B| < |A|$.*

Corollary 2.10.3.6. *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 2.10.3.7. *A finite union of finite sets is finite.*

Corollary 2.10.3.8. *A finite Cartesian product of finite sets is finite.*

Theorem 2.10.4. *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 $s(n) = n + 1$.
 $\langle 2 \rangle 3$. $f \circ s \circ f^{-1} : A \approx A - \{f(0)\}$

⟨1⟩2. $2 \Rightarrow 3$

PROOF: Corollary 2.10.3.1.

⟨1⟩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 .

□

2.11 Countable Sets

Definition 2.11.1 (Countable). A set A is *countably infinite* iff $A \approx \mathbb{N}$.

Proposition 2.11.2. $\mathbb{N} \times \mathbb{N}$ 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 2.11.3. Every infinite subset of \mathbb{N} is countably infinite.

PROOF:

⟨1⟩1. LET: C be an infinite subset of \mathbb{N}

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

⟨1⟩3. h is injective.

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

⟨1⟩4. h is surjective.

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

⟨2⟩2. LET: $c \in C$

⟨2⟩3. $c \leq h(c)$

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

⟨2⟩5. $c \in C - \{h(m) : m < n\}$

⟨2⟩6. $h(n) \leq c$

⟨2⟩7. $h(n) = c$

□

Definition 2.11.4 (Countable). A set is *countable* iff it is either finite or countably infinite; otherwise it is *uncountable*.

Proposition 2.11.5. 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:

- ⟨1⟩1. $1 \Rightarrow 2$
 - ⟨2⟩1. ASSUME: B is countable.
 - ⟨2⟩2. CASE: B is finite.
 - ⟨3⟩1. PICK a natural number n and bijection $f : \{m \in \mathbb{N} : m < n\} \approx B$
 - ⟨3⟩2. PICK $b \in B$
 - ⟨3⟩3. Extend f to a surjection $g : \mathbb{N} \twoheadrightarrow B$ by setting $g(m) = b$ for $m \geq n$.
 - ⟨2⟩3. CASE: B is countably infinite.
 - PROOF: Then there exists a bijection $\mathbb{N} \approx B$.
- ⟨1⟩2. $2 \Rightarrow 3$
 - PROOF: Given a surjection $f : \mathbb{N} \twoheadrightarrow B$, define $g : B \rightarrow \mathbb{N}$ by $g(b)$ is the smallest number such that $f(g(b)) = b$.
- ⟨1⟩3. $3 \Rightarrow 1$
 - ⟨2⟩1. LET: $f : B \rightarrow \mathbb{N}$ be injective.
 - ⟨2⟩2. $f(B)$ is countable.
 - ⟨2⟩3. $B \approx f(B)$
 - ⟨2⟩4. B is countable.

□

Corollary 2.11.5.1. *A subset of a countable set is countable.*

Corollary 2.11.5.2. $\mathbb{N} \times \mathbb{N}$ is countably infinite.

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

Corollary 2.11.5.3. *The Cartesian product of two countable sets is countable.*

Theorem 2.11.6. *A countable union of countable sets is countable.*

PROOF:

- ⟨1⟩1. LET: A be a set.
- ⟨1⟩2. LET: $\mathcal{B} \subseteq \mathcal{P}A$ be a countable set of countable sets such that $\bigcup \mathcal{B} = A$
- ⟨1⟩3. PICK a surjection $B : \mathbb{N} \twoheadrightarrow \mathcal{B}$
- ⟨1⟩4. ASSUME: w.l.o.g. each $B(n)$ is nonempty.
- ⟨1⟩5. For $n \in \mathbb{N}$, PICK a surjective function $g_n : \mathbb{N} \twoheadrightarrow B(n)$
- ⟨1⟩6. LET: $h : \mathbb{N} \times \mathbb{N} \rightarrow A$ be the function $h(m, n) = g_m(n)$
- ⟨1⟩7. h is surjective.

□

Theorem 2.11.7. $2^{\mathbb{N}}$ is uncountable.

PROOF:

- ⟨1⟩1. LET: $f : \mathbb{N} \rightarrow 2^{\mathbb{N}}$
 - PROVE: f is not surjective.
- ⟨1⟩2. Define $g : \mathbb{N} \rightarrow 2$ by $g(n) = 1 - f(n)(n)$.
- ⟨1⟩3. For all $n \in \mathbb{N}$ we have $g(n) \neq f(n)(n)$.
- ⟨1⟩4. For all $n \in \mathbb{N}$ we have $g \neq f(n)$.

□

Theorem 2.11.8. *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 $a \notin f(a)$.

□

Corollary 2.11.8.1. *For any set A , there is no injective function $\mathcal{P}A \rightarrow A$.*

Chapter 3

Order Theory

3.1 Relations

Definition 3.1.1 (Reflexive). A relation $R \subseteq A \times A$ is *reflexive* iff, for all $a \in A$, we have $(a, a) \in R$.

Definition 3.1.2 (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 3.1.3 (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 3.1.4 (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 3.1.5 (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 3.1.6 (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 3.1.7 (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 3.1.8 (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 3.1.9 (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 3.1.10 (Supremum). 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 3.1.11 (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 3.1.12. *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.

□

3.1.1 Strict Partial Orders

Definition 3.1.13 (Strict Partial Order). A *strict partial order* on a set A is a relation on A that is irreflexive and transitive.

Proposition 3.1.14. 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.*

3.1.2 Linear Orders

Definition 3.1.15 (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 3.1.16 (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 3.1.17 (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 3.1.18 (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 3.1.19 (Maximum Principle). *Every poset has a maximal linearly ordered subset.*

PROOF:

$\langle 1 \rangle 1$. LET: (A, \leq) be a poset.

$\langle 1 \rangle 2$. PICK a well ordering \preceq of A .

PROOF: Well Ordering Theorem.

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

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

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

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

$\langle 1 \rangle 5$. B is linearly ordered by \leq .

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

$\langle 2 \rangle 2$. ASSUME: w.l.o.g. $x \preceq y$

$\langle 2 \rangle 3$. y is \preceq -comparable with x

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

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

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

$\langle 2 \rangle 3$. $x \in B$

□

Theorem 3.1.20 (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:

$\langle 1 \rangle 1$. PICK a maximal linearly ordered subset B of A .

PROOF: Maximal Principle

$\langle 1 \rangle 2$. PICK an upper bound c for B .

PROVE: c is maximal.

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

$\langle 1 \rangle 4$. ASSUME: $c \leq x$

PROVE: $x = c$

$\langle 1 \rangle 5$. x is an upper bound for B .

$\langle 1 \rangle 6$. $x \in B$

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

$\langle 1 \rangle 7$. $x \leq c$

PROOF: $\langle 1 \rangle 2$

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

□

Corollary 3.1.20.1 (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 3.1.21 (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 3.1.22 (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

$$(a, b] := \{x \in X : a < x \leq b\}$$

$$[a, b) := \{x \in X : a \leq x < b\}$$

Definition 3.1.23 (Open Ray). Let X be a linearly ordered set and $a \in X$. The *open rays* $(a, +\infty)$ and $(-\infty, a)$ are defined by:

$$(a, +\infty) := \{x \in X : a < x\}$$

$$(-\infty, a) := \{x \in X : x < a\}$$

Definition 3.1.24 (Closed Ray). Let X be a linearly ordered set and $a \in X$. The *closed rays* $[a, +\infty)$ and $(-\infty, a]$ are defined by:

$$[a, +\infty) := \{x \in X : a \leq x\}$$

$$(-\infty, a] := \{x \in X : x \leq a\}$$

Definition 3.1.25 (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 $c \in Y$.

3.1.3 Sets of Finite Type

Definition 3.1.26 (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 3.1.27 (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.

□

3.2 Well Orders

Definition 3.2.1 (Well Ordered Set). A *well ordered set* is a linearly ordered set such that every nonempty subset has a least element.

Proposition 3.2.2. *Any subset of a well ordered set is well ordered.*

Proposition 3.2.3. *The product of two well ordered sets is well ordered under the dictionary order.*

Theorem 3.2.4 (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 3.2.11.

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

$\langle 3 \rangle 1$. 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:

$$\begin{aligned}
 h(x) &= c(X - \{y \in T_2 : y < h(x)\}) && \langle 1 \rangle 3 \\
 &= c(X - \{y \in T_2 : y < x\}) && \langle 3 \rangle 4 \\
 &= c(X - \{y \in T_1 : y < x\}) && \langle 3 \rangle 2 \\
 &= x && \langle 1 \rangle 3
 \end{aligned}$$

$\langle 1 \rangle 5$. 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 .

□

Proposition 3.2.5. *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.

□

Proposition 3.2.6. *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. □

Proposition 3.2.7. *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. □

Theorem 3.2.8 (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. □

Proposition 3.2.9. *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. □

Theorem 3.2.10 (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:

⟨1⟩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 $h(x) = \rho(h \upharpoonright (-\infty, x))$.

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

⟨2⟩1. LET: $x \in J$

⟨2⟩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 $h(y) = k(y)$

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

⟨2⟩4. $h \upharpoonright (-\infty, x) = k \upharpoonright (-\infty, x)$

PROOF: By ⟨2⟩2.

⟨2⟩5. $h(x) = k(x)$

PROOF: By ⟨2⟩3, each is the least element of the set in ⟨2⟩4.

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

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

Corollary 3.2.10.1 (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 $B - h((-\infty, x))$. \square

Proposition 3.2.11. *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:

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

$\langle 2 \rangle 1. \text{ ASSUME: } 1$

$\langle 2 \rangle 2. h(J)$ is closed downwards.

$\langle 2 \rangle 3. \text{ LET: } \alpha \in J$

$\langle 2 \rangle 4. h(\alpha) \in E - h((-\infty, \alpha))$

PROOF: If $\beta < \alpha$ then $h(\beta) < h(\alpha)$.

$\langle 2 \rangle 5. \text{ For all } y \in E - h((-\infty, \alpha)) \text{ we have } h(\alpha) \leq y$

$\langle 3 \rangle 1. \text{ ASSUME: for a contradiction } y < h(\alpha)$

$\langle 3 \rangle 2. y \in h(J)$

$\langle 3 \rangle 3. \text{ PICK } \beta \in J \text{ such that } h(\beta) = y$

$\langle 3 \rangle 4. h(\beta) < h(\alpha)$

$\langle 3 \rangle 5. \beta < \alpha$

$\langle 3 \rangle 6. \text{ Q.E.D.}$

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

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

$\langle 2 \rangle 1. \text{ ASSUME: } 2$

$\langle 2 \rangle 2. h$ is strictly monotone.

$\langle 3 \rangle 1. \text{ LET: } \alpha, \beta \in J \text{ with } \alpha < \beta$

$\langle 3 \rangle 2. h(\alpha) \neq h(\beta)$

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

$\langle 3 \rangle 3. h(\alpha) \leq h(\beta)$

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

$\langle 3 \rangle 4. h(\alpha) < h(\beta)$

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

$\langle 3 \rangle 1. \text{ ASSUME: } h(J) \neq E$

$\langle 3 \rangle 2. \text{ LET: } e \text{ be least in } E - h(J)$

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

$\langle 3 \rangle 3. h(J) \subseteq (-\infty, e)$

$\langle 4 \rangle 1. \text{ LET: } \alpha \in J$

$\langle 4 \rangle 2. h(\alpha) \neq e$

PROOF: $e \notin h(J)$

$\langle 4 \rangle 3. h(\alpha) \leq e$

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

$\langle 4 \rangle 4. h(\alpha) < e$

$\langle 3 \rangle 4. (-\infty, e) \subseteq h(J)$

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

□

Chapter 4

Category Theory

4.1 Categories

Definition 4.1.1. 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 4.1.2. Let **Set** be the category of small sets and functions.

Definition 4.1.3. Let **LPos** be the category of linearly ordered sets and monotone functions.

Proposition 4.1.4. Any finite linearly ordered set is isomorphic to $\{m \in \mathbb{N} : m < n\}$ for some n .

PROOF:

$\langle 1 \rangle$ 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 4.1.4.1. *Any finite linearly ordered set is well ordered.*

Proposition 4.1.5. *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 3.2.11.

□

Proposition 4.1.6. *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 4.1.7. *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 4.1.8 (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 4.1.9. *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 4.1.10. *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 4.1.11. *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 4.1.12. 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 4.1.13. *A category is a poset iff, for any two objects, there exists at most one morphism between them.*

Proposition 4.1.14. *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 4.1.15. *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 4.1.15.1. *Let A be a linearly ordered set. If every countable subset of A is well ordered, then A is well ordered.*

Definition 4.1.16. 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 4.1.17. Given $f : A \rightarrow B$ and an object C , define the function $f_* : \mathcal{C}[C, A] \rightarrow \mathcal{C}[C, B]$ by $f_*(g) = f \circ g$.

4.1.1 Monomorphisms

Definition 4.1.18 (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 $x = y$.

4.1.2 Epimorphisms

Definition 4.1.19 (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 $x = y$.

4.1.3 Sections and Retractions

Definition 4.1.20 (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 4.1.21. *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 4.1.22. *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 4.1.23. *Every retraction is epic.*

PROOF: Dual. \square

4.1.4 Isomorphisms

Definition 4.1.24 (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 4.1.25. *The inverse of an isomorphism is unique.*

PROOF: From Proposition 4.1.21. \square

Proposition 4.1.26. *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 4.1.27. 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 4.1.28.

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

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

4.1.5 Initial Objects

Definition 4.1.29 (Initial Object). An object I is *initial* iff, for any object X , there exists exactly one morphism $I \rightarrow X$.

Proposition 4.1.30. *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 4.1.31. *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

4.1.6 Terminal Objects

Definition 4.1.32 (Terminal Object). An object T is *terminal* iff, for any object X , there exists exactly one morphism $X \rightarrow T$.

Proposition 4.1.33. *1 is terminal in Set.*

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

Proposition 4.1.34. *If T and T' are terminal objects, then there exists a unique isomorphism $T \cong T'$.*

PROOF: Dual to Proposition 4.1.31. \square

4.1.7 Zero Objects

Definition 4.1.35 (Zero Object). An object Z is a *zero object* iff it is an initial object and a terminal object.

Definition 4.1.36 (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 4.1.37. *There is no zero object in **Set**.*

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

4.1.8 Triads

Definition 4.1.38 (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.

4.1.9 Cotriads

Definition 4.1.39 (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.

4.1.10 Pullbacks

Definition 4.1.40 (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 4.1.41. *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 4.1.42. *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 4.1.43. *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 4.1.44. *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: $(Z, z) \in \mathcal{C} \backslash A$

$\langle 1 \rangle 2$. 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 4.1.45. 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 4.1.46. 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

4.1.11 Pushouts

Definition 4.1.47 (Pushout). A diagram

$$\begin{array}{ccc} W & \xrightarrow{\xi} & X \\ \eta \downarrow & & \downarrow \alpha \\ Y & \xrightarrow{\beta} & M \end{array} \quad (4.1)$$

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 4.1.48. 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 4.1.41. □

Proposition 4.1.49. 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 4.1.42.

Proposition 4.1.50. The diagram (4.1) is a pushout in \mathcal{C} iff it is a pullback in \mathcal{C}^{op} .

PROOF: Immediate from definitions. □

Proposition 4.1.51. The pushout of an isomorphism is an isomorphism.

PROOF: Dual to Proposition 4.1.43. \square

Proposition 4.1.52. *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 4.1.45. \square

Proposition 4.1.53. *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 4.1.44. \square

Proposition 4.1.54. *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 4.1.55. Let $u : A \rightarrow X$ 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 4.1.56. 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 4.1.57 (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 4.1.58 (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.

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

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

4.1.12 Subcategories

Definition 4.1.59 (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 $\mathcal{C}'[A, B] = \mathcal{C}[A, B]$.

4.1.13 Opposite Category

Definition 4.1.60 (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 4.1.61. An object is initial in \mathcal{C} iff it is terminal in \mathcal{C}^{op} .

PROOF: Immediate from definitions. \square

Proposition 4.1.62. An object is terminal in \mathcal{C} iff it is initial in \mathcal{C}^{op} .

PROOF: Immediate from definitions. \square

Corollary 4.1.62.1. If T and T' are terminal objects in \mathcal{C} then there exists a unique isomorphism $T \cong T'$.

4.1.14 Groupoids

Definition 4.1.63 (Groupoid). A *groupoid* is a category in which every morphism is an isomorphism.

4.1.15 Concrete Categories

Definition 4.1.64 (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 $\text{id}_{|A|} \in \mathcal{C}[A, A]$.

4.1.16 Power of Categories

Definition 4.1.65. 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 $f_j : X_j \rightarrow Y_j$

4.1.17 Arrow Category

Definition 4.1.66 (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 $vf = gu$.

4.1.18 Slice Category

Definition 4.1.67 (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 4.1.68. *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 4.1.69. *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 4.1.70. *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 4.1.71 (Pointed Sets). The *category of pointed sets* is **Set** $\setminus 1$.

Definition 4.1.72. 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 4.1.73. *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 4.1.68. □

Proposition 4.1.74. *id_A is terminal in \mathcal{C}/A .*

PROOF: Dual to Proposition 4.1.69. □

Proposition 4.1.75. *If A is initial in \mathcal{C} then id_A is the zero object in \mathcal{C}/A .*

PROOF: Dual to Proposition 4.1.70. □

Definition 4.1.76. 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 4.1.77. *$(A, \text{id}_A, \text{id}_A)$ 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 4.1.78 (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 4.1.79 (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 4.1.80 (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 4.1.81. *Set has products and coproducts.*

Proposition 4.1.82. *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 4.1.83. *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 4.1.84. *A product in \mathcal{C} constitutes a product in \mathcal{C}/A .*

Proposition 4.1.85. *A coproduct in \mathcal{C} constitutes a product in \mathcal{C}/A .*

4.2 Functors

Definition 4.2.1 (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 4.2.2. *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 4.2.3 (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 4.2.4. 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 4.2.4.1. 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 4.2.5 (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 4.2.6 (Category of Categories). Let **Cat** be the category of small categories and functors.

Definition 4.2.7 (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 4.2.8. 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 4.2.9. *If A is terminal in \mathcal{C} then $\mathcal{C}/A \cong \mathcal{C}$.*

PROOF: Dual. \square

Proposition 4.2.10.

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

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 4.2.11 (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 4.2.12 (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 4.2.13 (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 4.2.14. 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 4.2.15. 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.

$$\begin{array}{ccccc}
 X \vee Y & \xrightarrow{\quad} & 1 & & \\
 \downarrow & \searrow & \downarrow & \searrow & \\
 X \times Y & \xrightarrow{\quad} & X \wedge Y & & \\
 & \searrow & \downarrow & \searrow & \\
 & & X' \vee Y' & \xrightarrow{\quad} & 1 \\
 f \times g \swarrow & & \downarrow & & \downarrow \\
 & & X' \times Y' & \xrightarrow{\quad} & X' \wedge Y'
 \end{array}$$

Definition 4.2.16 (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 4.2.17. Extend \vee_B to a functor $\mathbf{Set}_B^B \times \mathbf{Set}_B^B \rightarrow \mathbf{Set}_B^B$.

Definition 4.2.18. Extend \wedge_B to a functor $\mathbf{Set}_B^B \times \mathbf{Set}_B^B \rightarrow \mathbf{Set}_B^B$.

Definition 4.2.19 (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 4.2.20 (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 4.2.21 (Fully Faithful). A functor $F : \mathcal{C} \rightarrow \mathcal{D}$ is *fully faithful* iff it is full and faithful.

Definition 4.2.22 (Full Embedding). A functor $F : \mathcal{C} \rightarrow \mathcal{D}$ is a *full embedding* iff it is fully faithful and injective on objects.

4.3 Natural Transformations

Definition 4.3.1 (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 4.3.2 (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 4.3.3 (Inverse). Let $\tau : F \cong G$. The *inverse* natural isomorphism $\tau^{-1} : G \cong F$ is defined by $(\tau^{-1})_X = \tau_X^{-1}$.

4.4 Bifunctors

Definition 4.4.1 (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 4.4.2. $\vee : \mathbf{Set}_* \times \mathbf{Set}_* \rightarrow \mathbf{Set}_*$ is commutative.

PROOF: Since the pushout of f and g is the pushout of g and f . \square

Proposition 4.4.3. $\wedge : \mathbf{Set}_* \times \mathbf{Set}_* \rightarrow \mathbf{Set}_*$ 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 4.4.4. $\vee_B : \mathbf{Set}_B^B \times \mathbf{Set}_B^B \rightarrow \mathbf{Set}_B^B$ is commutative.

Proposition 4.4.5. $\wedge_B : \mathbf{Set}_B^B \times \mathbf{Set}_B^B \rightarrow \mathbf{Set}_B^B$ is commutative.

Definition 4.4.6 (Associative). A bifunctor \square is *associative* iff $\square \circ (\square \times \text{id}) \cong \square \circ (\text{id} \times \square)$.

Proposition 4.4.7. $\vee : \mathbf{Set}_* \times \mathbf{Set}_* \rightarrow \mathbf{Set}_*$ 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 4.4.8. $\wedge : \mathbf{Set}_* \times \mathbf{Set}_* \rightarrow \mathbf{Set}_*$ 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 4.4.9. $\vee_B : \mathbf{Set}_B^B \times \mathbf{Set}_B^B \rightarrow \mathbf{Set}_B^B$ is associative.

Proposition 4.4.10. $\wedge_B : \mathbf{Set}_B^B \times \mathbf{Set}_B^B \rightarrow \mathbf{Set}_B^B$ is associative.

Proposition 4.4.11. 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 4.4.12. *In a category with binary products and binary coproducts, then \times distributes over $+$.*

Proposition 4.4.13. *In $\mathbf{Set}/*$, we have \times does not distribute over \vee .*

Proposition 4.4.14. *In $\mathbf{Set}/*$, we have \wedge distributes over \vee .*

Proposition 4.4.15. *In \mathbf{Set}/B , we have \times_B distributes over $+_B$.*

Proposition 4.4.16. *In \mathbf{Set}/B^B , we have \wedge_B distributes over \vee_B .*

4.5 Functor Categories

Definition 4.5.1 (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 4.5.2 (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 4.5.3 (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 4.5.3.1. *The Yoneda embedding is fully faithful.*

Corollary 4.5.3.2. *Given objects A and B in \mathcal{C} , we have $A \cong B$ if and only if $\mathcal{C}[-, A] \cong \mathcal{C}[-, B]$.*

Chapter 5

The Real Numbers

Theorem 5.0.1. *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 5.0.2 (Subtraction). We write $x - y$ for $x + (-y)$.

Definition 5.0.3. Given real numbers x and y with $y \neq 0$, we write x/y for xy^{-1} .

Theorem 5.0.4. *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 5.0.5.

$$\forall x \in \mathbb{R}. 0x = 0$$

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 5.0.4, $\langle 1 \rangle 2$.

□

Theorem 5.0.6.

$$-0 = 0$$

PROOF: Since $0 + 0 = 0$. □

Theorem 5.0.7.

$$\forall x \in \mathbb{R}. -(-x) = x$$

PROOF: Since $-x + x = 0$. □

Theorem 5.0.8.

$$\forall x, y \in \mathbb{R}. x(-y) = -(xy)$$

PROOF:

$$\begin{aligned}
 x(-y) + xy &= x((-y) + y) && \text{(Distributive Law)} \\
 &= x0 && \text{(Definition of } -y) \\
 &= 0 && \text{(Theorem 5.0.5)} \quad \square
 \end{aligned}$$

Theorem 5.0.9.

$$\forall x \in \mathbb{R}. (-1)x = -x$$

PROOF:

$$\begin{aligned}
 (-1)x &= -(1 \cdot x) && \text{(Theorem 5.0.8)} \\
 &= -x && \text{(Definition of 1)} \quad \square
 \end{aligned}$$

5.0.1 Subtraction

Theorem 5.0.10.

$$\forall x, y, z \in \mathbb{R}. x(y - z) = xy - xz$$

PROOF:

$$\begin{aligned} x(y - z) &= x(y + (-z)) && \text{(Definition of subtraction)} \\ &= xy + x(-z) && \text{(Distributive Law)} \\ &= xy + (-(xz)) && \text{(Theorem 5.0.8)} \\ &= xy - xz && \text{(Definition of subtraction)} \quad \square \end{aligned}$$

Theorem 5.0.11.

$$\forall x, y \in \mathbb{R}. -(x + y) = -x - y$$

PROOF:

$$\begin{aligned} -(x + y) &= (-1)(x + y) && \text{(Theorem 5.0.9)} \\ &= (-1)x + (-1)y && \text{(Distributive Law)} \\ &= -x + (-y) && \text{(Theorem 5.0.9)} \\ &= -x - y && \text{(Definition of subtraction)} \quad \square \end{aligned}$$

Theorem 5.0.12.

$$\forall x, y \in \mathbb{R}. -(x - y) = -x + y$$

PROOF:

$$\begin{aligned} -(x - y) &= -(x + (-y)) && \text{(Definition of subtraction)} \\ &= -x - (-y) && \text{(Theorem 5.0.11)} \\ &= -x + (-(-y)) && \text{(Definition of subtraction)} \\ &= -x + y && \text{(Theorem 5.0.7)} \quad \square \end{aligned}$$

Definition 5.0.13 (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 5.0.14. 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:

$$\begin{aligned} y &= y1 && \text{(Definition of 1)} \\ &= y(x \cdot 1/x) && \text{(Definition of } 1/x, \langle 1 \rangle 2) \\ &= (yx)1/x && \text{(Associativity of Multiplication)} \\ &= (xy)1/x && \text{(Commutativity of Multiplication)} \\ &= x \cdot 1/x && (\langle 1 \rangle 3) \\ &= 1 && \text{(Definition of } 1/x, \langle 1 \rangle 2) \end{aligned}$$

□

Definition 5.0.15 (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 5.0.16. For any real number x , if $x \neq 0$ then $x/x = 1$.

PROOF: Immediate from definitions. □

Theorem 5.0.17.

$$\forall x \in \mathbb{R}. x/1 = x$$

PROOF:

⟨1⟩1. LET: $x \in \mathbb{R}$

⟨1⟩2. $1/1 = 1$

PROOF: Since $1 \cdot 1 = 1$.

⟨1⟩3. $x/1 = x$

PROOF: Since $x/1 = x \cdot 1/1 = x \cdot 1 = x$.

□

Theorem 5.0.18. For any real numbers x and y , if $x \neq 0$ and $y \neq 0$ then $xy \neq 0$.

PROOF:

⟨1⟩1. LET: $x, y \in \mathbb{R}$

⟨1⟩2. ASSUME: $xy = 0$ and $x \neq 0$

PROVE: $y = 0$

⟨1⟩3. $y = 0$

PROOF:

$$\begin{aligned} y &= 1y && \text{(Definition of 1)} \\ &= (1/x)xy && \text{(Definition of } 1/x, \langle 1 \rangle 2) \\ &= (1/x)0 && \text{(\langle 1 \rangle 2)} \\ &= 0 && \text{(Theorem 5.0.5)} \end{aligned}$$

□

Theorem 5.0.19. 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 5.0.19.1. For any real numbers x, y, z, w with $y \neq 0 \neq w$, we have $(x/y)(z/w) = (xz)/(yw)$.

Theorem 5.0.20. 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 5.0.21. For any real number x , if $x \neq 0$ then $1/x \neq 0$.

PROOF: Since $x \cdot 1/x = 1 \neq 0$. \square

Theorem 5.0.22. For any real numbers w, z , if $w \neq 0 \neq z$ then $1/(w/z) = z/w$.

PROOF: Since $(z/w)(w/z) = (wz)/(wz) = 1$. \square

Theorem 5.0.23. For any real numbers a, x and y , if $y \neq 0$ then $(ax)/y = a(x/y)$

PROOF: Since $ya(x/y) = ax$. \square

Theorem 5.0.24. 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 5.0.23.

$\langle 1 \rangle 2.$ $x/(-y) = -(x/y)$

PROOF: Since $(-y)(-(x/y)) = y(x/y) = x$.

\square

Theorem 5.0.25. 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 5.0.25.1. For any real numbers x and y , if $x > 0$ and $y > 0$ then $x + y > 0$.

Theorem 5.0.26. For any real numbers x and y , if $x > 0$ and $y > 0$ then $xy > 0$.

PROOF:

$$\begin{aligned} xy &> 0y && \text{(Monotonicity of Multiplication)} \\ &= 0 && \text{(Theorem 5.0.5)} \end{aligned} \quad \square$$

Theorem 5.0.27. 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 5.0.28. *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.

□

Theorem 5.0.29. *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 5.0.27, $\langle 1 \rangle 3$.

$\langle 1 \rangle 5$. $x(-z) > y(-z)$

PROOF: $\langle 1 \rangle 2$, $\langle 1 \rangle 4$, Monotonicity of Multiplication.

$\langle 1 \rangle 6$. $-(xz) > -(yz)$

PROOF: Theorem 5.0.8, $\langle 1 \rangle 5$.

$\langle 1 \rangle 7$. $xz < yz$

PROOF: Theorem 5.0.27, $\langle 1 \rangle 6$.

□

Theorem 5.0.30. *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 5.0.29.

□

Theorem 5.0.31.

$$0 < 1$$

PROOF: By Theorem 5.0.30 since $1 = 1 \cdot 1$. □

Definition 5.0.32 (Positive). A real number x is *positive* iff $x > 0$.

We write \mathbb{R}_+ for the set of positive reals.

Theorem 5.0.33. *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 5.0.29. □

Corollary 5.0.33.1. *For any real number x , if $x > 0$ then $1/x > 0$.*

PROOF: Since $x \cdot 1/x = 1$ is positive. □

Theorem 5.0.34. 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. \square

Theorem 5.0.35. 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 $1/2 > 0$. \square

Corollary 5.0.35.1. \mathbb{R} is a linear continuum.

Definition 5.0.36 (Negative). A real number x is *negative* iff $x < 0$.

We write $\overline{\mathbb{R}}_+$ for the set of nonnegative reals.

Theorem 5.0.37. 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

$$(x+h)^2 < x^2 + h(2x+1) .$$

$\langle 2 \rangle 1$. LET: x and h be real numbers.

$\langle 2 \rangle 2$. ASSUME: $0 \leq h < 1$

$\langle 2 \rangle 3$. $(x+h)^2 < x^2 + h(2x+1)$

PROOF:

$$\begin{aligned} (x+h)^2 &= x^2 + 2hx + h^2 \\ &< x^2 + 2hx + h & (\langle 2 \rangle 2) \\ &= x^2 + h(2x+1) \end{aligned}$$

$\langle 1 \rangle 3$. For any real numbers x and h , if $h > 0$ then

$$(x-h)^2 > x^2 - 2hx .$$

$\langle 2 \rangle 1$. LET: x and h be real numbers.

$\langle 2 \rangle 2$. ASSUME: $h > 0$

$\langle 2 \rangle 3$. $(x-h)^2 > x^2 - 2hx$

PROOF:

$$\begin{aligned} (x-h)^2 &= x^2 - 2hx + h^2 \\ &> x^2 - 2hx & (\langle 2 \rangle 2) \end{aligned}$$

$\langle 1 \rangle 4$. For any positive real x , if $x^2 < a$ then there exists $h > 0$ such that

$$(x+h)^2 < a.$$

$\langle 2 \rangle 1$. LET: x be a positive real.

$\langle 2 \rangle 2$. ASSUME: $x^2 < a$

$\langle 2 \rangle 3$. LET: $h = \min((a-x^2)/(2x+1), 1/2)$

$\langle 2 \rangle 4$. $0 < h < 1$

$\langle 2 \rangle 5$. $(x+h)^2 < a$

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:

$$(x - h)^2 > x^2 - 2hx$$

$$= a$$

(⟨2⟩3)

⟨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 $b^2 < a$

⟨3⟩2. PICK $h > 0$ such that $(b + h)^2 < a$

PROOF: ⟨1⟩4

⟨3⟩3. $b + h \in B$

⟨3⟩4. Q.E.D.

PROOF: This contradicts ⟨1⟩9.

⟨2⟩2. $b^2 \leq a$

⟨3⟩1. ASSUME: for a contradiction $b^2 > a$

⟨3⟩2. PICK $h > 0$ such that $(b - h)^2 > a$

PROOF: ⟨1⟩5

⟨3⟩3. PICK $x \in B$ such that $b - h < x$

PROOF: ⟨1⟩9

⟨3⟩4. $(b - h)^2 < x^2 < a$

⟨3⟩5. Q.E.D.

PROOF: This contradicts ⟨3⟩2

⟨1⟩11. For any positive reals b and c , if $b^2 = c^2$ then $b = c$.

⟨2⟩1. LET: b and c be positive reals.

⟨2⟩2. ASSUME: $b^2 = c^2$

⟨2⟩3. $b^2 - c^2 = 0$

⟨2⟩4. $(b - c)(b + c) = 0$

⟨2⟩5. $b - c = 0$ or $b + c = 0$

⟨2⟩6. $b + c \neq 0$

PROOF: Since $b + c > 0$

⟨2⟩7. $b - c = 0$

⟨2⟩8. $b = c$

□

Theorem 5.0.38. *The set of real numbers is uncountable.*

Chapter 6

Integers and Rationals

6.1 Positive Integers

Definition 6.1.1 (Inductive). A set of real numbers A is *inductive* iff $1 \in A$ and $\forall x \in A. x + 1 \in A$.

Definition 6.1.2 (Positive Integer). The set \mathbb{Z}_+ of *positive integers* is the intersection of the set of inductive sets.

Proposition 6.1.3. *Every positive integer is positive.*

PROOF: The set of positive reals is inductive. \square

Proposition 6.1.4. *1 is the least element of \mathbb{Z}_+ .*

PROOF: Since $\{x \in \mathbb{R} : x \geq 1\}$ is inductive. \square

Proposition 6.1.5. *\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 6.1.6 (Principle of Induction). *If A is an inductive set of positive integers then $A = \mathbb{Z}_+$.*

PROOF: Immediate from definitions. \square

Theorem 6.1.7 (Well-Ordering Property). *\mathbb{Z}_+ is well ordered.*

PROOF: Construct the obvious order isomorphism $\omega \cong \mathbb{Z}_+$. \square

Theorem 6.1.8 (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.

□

6.1.1 Exponentiation

Definition 6.1.9. 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 6.1.10. 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 6.1.11. 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:

$$\begin{aligned} (a^n)^{m+1} &= (a^n)^m a^n \\ &= a^{nm} a^n \\ &= a^{nm+n} && \text{(Theorem 6.1.10)} \\ &= a^{n(m+1)} \end{aligned}$$

□

Theorem 6.1.12. *For any real numbers a and b and positive integer m ,*

$$a^m b^m = (ab)^m .$$

PROOF: Induction on m . □

6.2 Integers

Definition 6.2.1 (Integer). The set \mathbb{Z} of *integers* is

$$\mathbb{Z} = \mathbb{Z}_+ \cup \{0\} \cup \{-x : x \in \mathbb{Z}_+\} .$$

Proposition 6.2.2. *The sum, difference and product of two integers is an integer.*

PROOF: Easy. □

Example 6.2.3. $1/2$ is not an integer.

Proposition 6.2.4. *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 6.2.5. *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 6.2.6. *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 6.2.7 (Even). An integer n is *even* iff $n/2$ is an integer; otherwise, n is *odd*.

Theorem 6.2.8. *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 6.2.6.

⟨1⟩2. $2n < m < 2n + 2$

⟨1⟩3. $m = 2n + 1$

□

Theorem 6.2.9. *The product of two odd integers is odd.*

PROOF: $(2m + 1)(2n + 1) = 2(2mn + m + n) + 1$. \square

Corollary 6.2.9.1. *If p is an odd integer and n is a positive integer then p^n is an odd integer.*

Definition 6.2.10 (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 6.2.11 (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 6.2.12. \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

6.3 Rational Numbers

Definition 6.3.1 (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 6.3.2. $\sqrt{2}$ 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 6.2.9.

$\langle 1 \rangle 7$. 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 6.2.9.

$\langle 1 \rangle 12$. Q.E.D.

PROOF: $\langle 1 \rangle 3$, $\langle 1 \rangle 6$ and $\langle 1 \rangle 11$ form a contradiction.

□

Theorem 6.3.3. \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.

□

6.4 Algebraic Numbers

Definition 6.4.1 (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 6.4.2. 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 6.4.2.1. The set of transcendental numbers is uncountable.

Chapter 7

Monoid Theory

Definition 7.0.1 (Monoid). A *monoid* is a category with one object.

Definition 7.0.2. 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 7.0.3. *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 8

Group Theory

Definition 8.0.1. Let **Grp** be the category of small groups and group homomorphisms.

Definition 8.0.2. 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 8.0.3. *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 8.0.4. 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 8.0.5. *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 8.0.6. **Grp** has products.

Definition 8.0.7 (Free Product). The product of a family of groups in **Grp** is called the *free product*.

Proposition 8.0.8. **Ab** has products given by direct sums.

Chapter 9

Ring Theory

Definition 9.0.1. Let **Ring** be the concrete category of rings and ring homomorphisms.

Definition 9.0.2 (Spectrum). Let R be a commutative ring. The *spectrum* of R , $\text{spec } R$, is the set of all prime ideals of R .

Definition 9.0.3 (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 9.0.4. For any ring R , let $R - \mathbf{Mod}$ be the category of small R -modules and R -module homomorphisms.

Proposition 9.0.5. $R - \mathbf{Mod}$ has products and coproducts.

Chapter 10

Field Theory

Proposition 10.0.1. *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 11

Linear Algebra

Definition 11.0.1 (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 11.0.2 (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

$$\alpha_1 = \cdots = \alpha_n = 0 .$$

Proposition 11.0.3. *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 11.0.4. *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 11.0.3.

□

Definition 11.0.5. For any field K , we write \mathbf{Vect}_K for $K - \mathbf{Mod}$.

Dual space functor $\mathbf{Vect}_K^{\text{op}} \rightarrow \mathbf{Vect}_K$.

Chapter 12

Topology

12.1 Topological Spaces

Definition 12.1.1 (Topological Space). Let X be a set and $\mathcal{O} \subseteq \mathcal{P}X$. Then we say (X, \mathcal{O}) is a *topological space* iff:

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

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

Definition 12.1.2 (Discrete Topology). For any set X , the power set $\mathcal{P}X$ is called the *discrete* topology on X .

Proposition 12.1.3. *For any set X , the discrete topology on X is a topology on X .*

Definition 12.1.4 (Indiscrete Topology). For any set X , the *indiscrete* or *trivial* topology on X is $\{\emptyset, X\}$.

Proposition 12.1.5. *For any set X , the indiscrete topology on X is a topology on X .*

Definition 12.1.6 (Cofinite Topology). For any set X , the *cofinite* topology is $\{X - U : U \subseteq X \text{ is finite}\}$.

Definition 12.1.7 (Cocountable Topology). For any set X , the *cocountable* topology is $\{X - U : U \subseteq X \text{ is countable}\}$.

Definition 12.1.8 (Sierpiński Two-Point Space). The *Sierpiński two-point space* is $\{0, 1\}$ under the topology $\{\emptyset, \{1\}, \{0, 1\}\}$.

Proposition 12.1.9. *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 $x \in V \subseteq U$.*

Proposition 12.1.10. *The intersection of a set of topologies on a set X is a topology on X .*

Definition 12.1.11 (Closed Set). *Let X be a topological space and $A \subseteq X$. Then A is closed iff $X - A$ is open.*

Proposition 12.1.12. *A set B is open if and only if $X - B$ is closed.*

Proposition 12.1.13. *Let X be a set and $\mathcal{C} \subseteq \mathcal{P}X$. Then there exists a topology \mathcal{O} on X such that \mathcal{C} is the set of closed sets if and only if:*

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

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

Theorem 12.1.14. *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: Straightforward.

Theorem 12.1.15. *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: $dz + n \in S(a_1, b_1) \cap S(a_2, b_2)$

⟨3⟩5. $dz + n \in S(a_1, b_1)$

PROOF:

$$\begin{aligned} dz + n &= a_1 kz + a_1 c + b_1 \\ &= a_1(kz + c) + b_1 \end{aligned}$$

⟨3⟩6. $dz + n \in S(a_2, b_2)$

PROOF: Similar.

⟨1⟩3. For all $a \in \mathbb{Z} - \{0\}$ and $b \in \mathbb{Z}$ we have $S(a, b)$ is closed.

⟨2⟩1. LET: $a \in \mathbb{Z} - \{0\}$ and $b \in \mathbb{Z}$

⟨2⟩2. LET: $n \in \mathbb{Z} - S(a, b)$

⟨2⟩3. $n \in S(a, n) \subseteq \mathbb{Z} - S(a, b)$

⟨3⟩1. LET: $x \in S(a, n)$

⟨3⟩2. ASSUME: for a contradiction $x \in S(a, b)$

⟨3⟩3. PICK m such that $x = am + b$

⟨3⟩4. PICK l such that $x = al + n$

⟨3⟩5. $n = a(m - l) + b$

⟨3⟩6. $n \in S(a, b)$

⟨3⟩7. Q.E.D.

PROOF: This contradicts ⟨2⟩2.

⟨1⟩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.

⟨1⟩5. No nonempty finite set is open.

⟨2⟩1. LET: U be a nonempty open set

⟨2⟩2. PICK $n \in U$

⟨2⟩3. There exist a, b such that $n \in S(a, b) \subseteq U$

⟨2⟩4. U is infinite.

⟨1⟩6. $\mathbb{Z} - \{1, -1\}$ is not closed.

⟨1⟩7. $\bigcup_{p \text{ prime}} S(p, 0)$ is not closed.

⟨1⟩8. The union of finitely many closed sets is closed.

⟨1⟩9. There are infinitely many primes.

□

Proposition 12.1.16. *In a discrete topological space, every set is closed.*

PROOF: Immediate from definitions. □

Proposition 12.1.17. *In a linearly ordered set under the order topology, every closed interval and closed ray is closed.*

PROOF:

⟨1⟩1. LET: X be a linearly ordered set under the order topology.

⟨1⟩2. Every closed interval in X is closed.

PROOF: Since $X - [a, b] = (-\infty, a) \cup (b, +\infty)$.

⟨1⟩3. Every closed ray in X is closed.

PROOF: Since $X - [a, +\infty) = (-\infty, a)$ and $X - (-\infty, a] = (a, +\infty)$.

□

Proposition 12.1.18. *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:

$$\begin{aligned}
 A \text{ is closed in } Y &\Leftrightarrow Y - A \text{ is open in } Y \\
 &\Leftrightarrow \exists U \text{ open in } X. Y - A = U \cap Y \\
 &\Leftrightarrow \exists C \text{ closed in } X. Y - A = Y - C \\
 &\Leftrightarrow \exists C \text{ closed in } X. A = Y \cap C \quad \square
 \end{aligned}$$

Proposition 12.1.19. *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:

$\langle 1 \rangle 1$. PICK C closed in X such that $A = C \cap Y$.

$\langle 1 \rangle 2$. A is closed in X .

PROOF: It is the intersection of two closed sets in X .

\square

Definition 12.1.20 (Neighbourhood). Let X be a topological space, $Sx \in X$ 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 12.1.21. *A set B is open if and only if it is a neighbourhood of each of its points.*

Proposition 12.1.22. *Let X be a set and $\mathcal{N} : X \rightarrow \mathcal{P}X$. Then there exists a topology \mathcal{O} on X such that, for all $x \in X$, we have \mathcal{N}_x is the set of neighbourhoods of x , if and only if:*

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

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

Definition 12.1.23 (Exterior Point). Let X be a topological space, $x \in X$ and $B \subseteq X$. Then x is an *exterior point* of B iff $B - X$ is a neighbourhood of x .

Definition 12.1.24 (Boundary Point). Let X be a topological space, $x \in X$ and $B \subseteq X$. Then x is a *boundary point* of B iff it is neither an interior point nor an exterior point of B .

Definition 12.1.25 (Interior). Let X be a topological space and $B \subseteq X$. The *interior* of B , B° , is the set of all interior points of B .

Proposition 12.1.26. *The interior of B is the union of all the open sets included in B .*

Definition 12.1.27 (Closure). Let X be a topological space and $B \subseteq X$. The *closure* of B , \overline{B} , is the set of all points that are not exterior points of B .

Proposition 12.1.28. *The closure of B is the intersection of all the closed sets that include B .*

Proposition 12.1.29. *A set B is open iff $X - B = \overline{X - B}$.*

Proposition 12.1.30 (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 $\mathcal{O} = \{U : X - U = \overline{X - U}\}$.

Definition 12.1.31 (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 $\mathcal{T} \subseteq \mathcal{T}'$.

12.1.1 Subspaces

Definition 12.1.32 (Subspace). Let X be a topological space and $X_0 \subseteq X$. The *subspace topology* on X_0 is $\mathcal{T}_0 = \{U \cap X_0 : U \text{ is open in } X\}$.

We prove this is a topology.

PROOF:

- ⟨1⟩1. For all $\mathcal{U} \subseteq \mathcal{T}_0$ we have $\bigcup \mathcal{U} \in \mathcal{T}_0$.
 ⟨2⟩1. LET: $\mathcal{U} \subseteq \mathcal{T}_0$
 ⟨2⟩2. LET: $\mathcal{V} = \{U \text{ open in } X : U \cap X_0 \in \mathcal{U}\}$.
 ⟨2⟩3. $\bigcup \mathcal{V}$ is open in X .
 PROVE: $\bigcup \mathcal{U} = \bigcup \mathcal{V} \cap X_0$
 ⟨2⟩4. $\bigcup \mathcal{U} \subseteq \bigcup \mathcal{V} \cap X_0$
 ⟨3⟩1. LET: $x \in \bigcup \mathcal{U}$
 ⟨3⟩2. PICK $U \in \mathcal{U}$ such that $x \in U$
 ⟨3⟩3. PICK V open in X such that $U = V \cap X_0$
 ⟨3⟩4. $x \in V \in \mathcal{V}$
 ⟨3⟩5. $x \in \bigcup \mathcal{V}$

- 1

Theorem 12.1.34. *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.*

⟨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 12.1.35. *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 12.1.36. *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 12.1.37. *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 $y \in B \cap Y \subseteq V$

□

12.1.2 Topological Disjoint Union

Definition 12.1.38 (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 12.1.39. *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.

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

$\langle 2 \rangle 2$. LET: $\{U_{\alpha}\}_{\alpha \in A}$ be a family with each U_{α} open in X_{α} .

$\langle 2 \rangle 3$. For all $\alpha \in A$, we have $\kappa_{\alpha}^{-1}(\coprod_{\alpha \in A} U_{\alpha})$ is open in X_{α} .

PROOF: Since $\kappa_{\alpha}^{-1}(\coprod_{\alpha \in A} U_{\alpha}) = U_{\alpha}$.

$\langle 1 \rangle 5$. If, for all $\alpha \in A$, the injection $\kappa_{\alpha} : X_{\alpha} \rightarrow (P, \mathcal{T})$ is continuous, then $\mathcal{T} \subseteq \mathcal{T}_c$.

$\langle 2 \rangle 1$. ASSUME: For all $\alpha \in A$, the injection $\kappa_{\alpha} : X_{\alpha} \rightarrow (P, \mathcal{T})$ is continuous.

$\langle 2 \rangle 2$. LET: $U \in \mathcal{T}$

$\langle 2 \rangle 3$. For all $\alpha \in A$, we have $\kappa_{\alpha}^{-1}(U)$ is open in X_{α} .

$\langle 2 \rangle 4$. $U = \coprod_{\alpha \in A} \kappa_{\alpha}^{-1}(U) \in \mathcal{T}_c$

□

Theorem 12.1.40. *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:

$\langle 1 \rangle 1$. LET: $X = \coprod_{\alpha \in A} X_{\alpha}$

$\langle 1 \rangle 2$. LET: \mathcal{T}_c be the coproduct topology.

- $\langle 1 \rangle 3$. 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.
- $\langle 2 \rangle 1$. LET: Z be a topological space.
- $\langle 2 \rangle 2$. LET: $f : X \rightarrow Z$
- $\langle 2 \rangle 3$. 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.
- $\langle 2 \rangle 4$. If $\forall \alpha \in A. f \circ \kappa_\alpha$ is continuous then f is continuous.
- $\langle 3 \rangle 1$. ASSUME: $\forall \alpha \in A. f \circ \kappa_\alpha$ is continuous.
- $\langle 3 \rangle 2$. LET: U be open in Z
- $\langle 3 \rangle 3$. For all $\alpha \in A$ we have $\kappa_\alpha^{-1}(f^{-1}(U))$ is open in X_α
- $\langle 3 \rangle 4$. $f^{-1}(U) = \coprod_{\alpha \in A} \kappa_\alpha^{-1}(f^{-1}(U))$
- $\langle 3 \rangle 5$. $f^{-1}(U)$ is open in X
- $\langle 1 \rangle 4$. 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 $\mathcal{T} = \mathcal{T}_c$.
- $\langle 2 \rangle 1$. LET: \mathcal{T} be a topology on X .
- $\langle 2 \rangle 2$. 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.
- $\langle 2 \rangle 3$. $\mathcal{T} \subseteq \mathcal{T}_c$
- $\langle 3 \rangle 1$. For all $\alpha \in A$ we have $\kappa_\alpha : X_\alpha \rightarrow (X, \mathcal{T})$ is continuous.
- PROOF: From $\langle 2 \rangle 1$ since id_X is continuous.
- $\langle 3 \rangle 2$. $\mathcal{T} \subseteq \mathcal{T}_c$
- PROOF: Proposition 12.1.39.
- $\langle 2 \rangle 4$. $\mathcal{T}_c \subseteq \mathcal{T}$
- $\langle 3 \rangle 1$. LET: $f : (X, \mathcal{T}) \rightarrow (X, \mathcal{T}_c)$ be the identity function.
- $\langle 3 \rangle 2$. $f \circ \kappa_\alpha$ is continuous for all α .
- $\langle 3 \rangle 3$. f is continuous.
- PROOF: $\langle 2 \rangle 1$
- $\langle 3 \rangle 4$. $\mathcal{T}_c \subseteq \mathcal{T}$

□

12.1.3 Product Topology

Definition 12.1.41 (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.

Proposition 12.1.42. 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 12.1.43. 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 12.1.44. *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 12.1.45. 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 12.1.46. 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:

$$f \text{ is continuous} \Leftrightarrow \iota \circ f : Z \rightarrow \prod_{i \in I} X_i \text{ is continuous} \quad (\text{Theorem 12.1.34})$$

$$\Leftrightarrow \forall i \in I. \pi_i \circ \iota \circ f : Z \rightarrow X_i \text{ is continuous} \quad (\text{Theorem 12.1.44})$$

$$\Leftrightarrow \forall i \in I. \iota_i \circ \pi_i \circ f : Z \rightarrow X_i \text{ is continuous}$$

$$\Leftrightarrow \forall i \in I. \pi_i \circ f : Z \rightarrow Y_i \text{ is continuous} \quad (\text{Theorem 12.1.34})$$

where ι_i is the inclusion $Y_i \rightarrow X_i$.

□

12.1.4 Bases

Definition 12.1.47 (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.

Proposition 12.1.48. Let X be a set. The set of all one-element subsets of X is a basis for the discrete topology on X .

Proposition 12.1.49. *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 12.1.50. *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 $X \times Y$.

Definition 12.1.51 (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 12.1.52. *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 12.1.53. *Let X be a linearly ordered set. The open rays in X form a subbasis for the order topology.*

Definition 12.1.54 (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 12.1.55 (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.

Definition 12.1.56 (Ordered Square). The *ordered square* I_o^2 is the set $[0, 1]^2$ under the order topology induced by the dictionary order.

Proposition 12.1.57. *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 12.1.58. 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 12.1.59. 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 12.1.60. 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 12.1.61. 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 12.1.62. 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 12.1.62.1. 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.

12.1.5 Subbases

Definition 12.1.63 (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 12.1.64. *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 12.1.65. *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 12.1.66. *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:

<1>1. Every element of \mathcal{S} is open.

PROOF: Since $\pi_1^{-1}(U) = U \times Y$ and $\pi_2^{-1}(V) = X \times V$.

<1>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 12.1.67 (Space with Basepoint). A *space with basepoint* is a pair (X, x) where X is a topological space and $x \in X$.

12.1.6 Countability Axioms

Definition 12.1.68 (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} .

Definition 12.1.69 (First Countable). A topological space is *first countable* iff every point has a countable neighbourhood basis.

Definition 12.1.70 (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 12.1.71. *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:

<1>1. For all $\lambda \in \Lambda$, PICK U_λ open in X_λ such that $\emptyset \neq U_\lambda \neq X_\lambda$.

<1>2. For all $\lambda \in \Lambda$, PICK $x_\lambda \in U_\lambda$.

<1>3. ASSUME: for a contradiction B is a countable neighbourhood basis for $(x_\lambda)_{\lambda \in \Lambda}$.

⟨1⟩4. PICK $\lambda \in \Lambda$ such that, for all $U \in B$, we have $\pi_\lambda(U) = X_\lambda$

⟨1⟩5. There is no $U \in \lambda$ such that $U \subseteq \pi_\lambda^{-1}(U_\lambda)$

⟨1⟩6. Q.E.D.

PROOF: This is a contradiction.

□

12.2 Interior

Definition 12.2.1 (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 .

12.3 Closure

Definition 12.3.1 (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 12.3.2. 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:

$$\begin{aligned} x \in \bar{A} &\Leftrightarrow \text{for every closed set } C, \text{ if } A \subseteq C \text{ then } x \in C \\ &\Leftrightarrow \text{for every open set } U, \text{ if } A \subseteq X - U \text{ then } x \in X - U \\ &\Leftrightarrow \text{for every open set } U, \text{ if } A \cap U = \emptyset \text{ then } x \notin U \\ &\Leftrightarrow \text{for every open set } U, \text{ if } x \in U \text{ then } A \text{ intersects } U \quad \square \end{aligned}$$

Proposition 12.3.3. 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 12.3.4. Let X be a topological space. Let $A, B \subseteq X$. Then $\overline{A \cup B} = \bar{A} \cup \bar{B}$.

PROOF:

⟨1⟩1. $\overline{A \cup B} \subseteq \bar{A} \cup \bar{B}$

PROOF: Since $\bar{A} \cup \bar{B}$ is a closed set that includes $A \cup B$.

⟨1⟩2. $\bar{A} \cup \bar{B} \subseteq \overline{A \cup B}$

PROOF: Since $\bar{A} \subseteq \overline{A \cup B}$ and $\bar{B} \subseteq \overline{A \cup B}$ by Proposition 12.3.3.

□

Proposition 12.3.5. Let X be a topological space. Let $\mathcal{A} \subseteq \mathcal{P}X$. Then

$$\bigcup \{\bar{A} : A \in \mathcal{A}\} \subseteq \overline{\bigcup \mathcal{A}}.$$

PROOF: For all $A \in \mathcal{A}$ we have $\bar{A} \subseteq \overline{\bigcup \mathcal{A}}$ by Proposition 12.3.3. □

Example 12.3.6. The converse does not always hold. In \mathbb{R} , let $\mathcal{A} = \{\{x\} : 0 < x < 1\}$. Then $\bigcup\{\bar{A} : A \in \mathcal{A}\} = (0, 1)$ but $\bigcup \mathcal{A} = [0, 1]$.

Proposition 12.3.7. *Let X be a topological space. Let $\mathcal{A} \subseteq \mathcal{P}X$. Then $\overline{\bigcap \mathcal{A}} \subseteq \bigcap\{\bar{A} : A \in \mathcal{A}\}$.*

PROOF: Since $\overline{\bigcap \mathcal{A}} \subseteq \bar{A}$ for all $A \in \mathcal{A}$ by Proposition 12.3.3. \square

Example 12.3.8. 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 $\bigcap A \cap \bigcap B = \mathbb{R}$.

Proposition 12.3.9. *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 $x \in \bar{A}$ if and only if, for all $B \in \mathcal{B}$, if $x \in B$ then B intersects A .*

PROOF:

$\langle 1 \rangle 1$. If $x \in \bar{A}$ then, for all $B \in \mathcal{B}$, if $x \in B$ then B intersects A .

PROOF: Proposition 12.3.2 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 $x \in \bar{A}$.

$\langle 2 \rangle 1$. 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 .

\square

12.3.1 Subspaces

Proposition 12.3.10. *Let X be a topological space. Let Y be a subspace of X . Let $A \subseteq Y$. Let \bar{A} be the closure of A in X . Then the closure of A in Y is $\bar{A} \cap Y$.*

PROOF:

$\langle 1 \rangle 1$. $\bar{A} \cap Y$ is the closed in Y .

PROOF: Since \bar{A} is closed in X .

$\langle 1 \rangle 2$. For any closed set B in Y , if $A \subseteq B$ then $\bar{A} \cap Y \subseteq B$.

$\langle 2 \rangle 1$. LET: B be closed in Y .

$\langle 2 \rangle 2$. ASSUME: $A \subseteq B$

$\langle 2 \rangle 3$. PICK C closed in X such that $B = C \cap Y$.

$\langle 2 \rangle 4$. $A \subseteq C$

$\langle 2 \rangle 5$. $\bar{A} \subseteq C$

$\langle 2 \rangle 6$. $\bar{A} \cap Y \subseteq B$

\square

12.3.2 Product Topology

Proposition 12.3.11. *Let X and Y be topological spaces. Let $A \subseteq X$ and $B \subseteq Y$. Then $\overline{A \times B} = \bar{A} \times \bar{B}$.*

PROOF:

$$\langle 1 \rangle 1. \overline{A \times B} \subseteq \overline{A} \times \overline{B}$$

PROOF: Since $\overline{A \times B}$ is a closed set that includes $A \times B$ by Proposition 12.1.42.

$$\langle 1 \rangle 2. \overline{A} \times \overline{B} \subseteq \overline{A \times B}$$

$\langle 2 \rangle 1.$ LET: $x \in \overline{A}$ and $y \in \overline{B}$.

$\langle 2 \rangle 2.$ LET: U be an open set that contains (x, y) .

$\langle 2 \rangle 3.$ PICK open sets V in X and W in Y such that $(x, y) \in V \times W \subseteq U$.

$\langle 2 \rangle 4.$ V intersects A and W intersects B .

$\langle 2 \rangle 5.$ U intersects $A \times B$.

□

12.3.3 Interior

Proposition 12.3.12. *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 12.3.13. *Let X be a topological space and $A \subseteq X$. Then*

$$X - \overline{A} = (X - A)^\circ$$

PROOF: Dual. □

12.4 Boundary

Definition 12.4.1 (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 12.4.2. *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 12.4.3. *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 12.4.4. *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 12.4.3.

$\langle 2 \rangle 3.$ $\overline{A} = A = A^\circ$

$\langle 1 \rangle 2.$ 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 12.4.5. *Let X be a topological space. Let $U \subseteq X$. Then U is open if and only if $\partial U = \overline{U} - U$.*

PROOF:

$\langle 1 \rangle 1.$ If U is open then $\partial U = \overline{U} - U$

PROOF: If U is open then

$$\begin{aligned} \partial U &= \overline{U} \cap \overline{X - U} \\ &= \overline{U} \cap (X - U^\circ) \\ &= \overline{U} - U^\circ \\ &= \overline{U} - U \end{aligned}$$

$\langle 1 \rangle 2$. If $\partial U = \overline{U} - U$ then U is open.

$\langle 2 \rangle 1$. ASSUME: $\partial U = \overline{U} - U$

$\langle 2 \rangle 2$. $\overline{U} - U^\circ = \overline{U} - U$

$\langle 2 \rangle 3$. $U \subseteq U^\circ$

$\langle 2 \rangle 4$. $U = U^\circ$

□

12.5 Limit Points

Definition 12.5.1 (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 12.5.2. 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:

$\langle 1 \rangle 1$. $\overline{A} \subseteq A \cup A'$

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

$\langle 2 \rangle 2$. ASSUME: $x \notin A$

PROVE: $x \in A'$

$\langle 2 \rangle 3$. LET: U be a neighbourhood of x .

$\langle 2 \rangle 4$. PICK $y \in U \cap A$

PROOF: Proposition 12.3.2.

$\langle 2 \rangle 5$. $y \neq x$

$\langle 1 \rangle 2$. $A \subseteq \overline{A}$

PROOF: Immediate from the definition of \overline{A} .

$\langle 1 \rangle 3$. $A' \subseteq \overline{A}$

PROOF: From Proposition 12.3.2.

□

Corollary 12.5.2.1. A set is closed if and only if it contains all its limit points.

12.6 Continuous Functions

Definition 12.6.1 (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 12.6.2. 1. id_X is continuous

2. The composite of two continuous functions is continuous.

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

4. If $f : X + Y \rightarrow Z$, then f is continuous iff $f \circ \kappa_1 : X \rightarrow Z$ and $f \circ \kappa_2 : Y \rightarrow Z$ are continuous.
5. If $f : Z \rightarrow X \times Y$, then f is continuous iff $\pi_1 \circ f$ and $\pi_2 \circ f$ are continuous.

Proposition 12.6.3. *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 .
4. For all $x \in X$ and neighbourhood V of $f(x)$, there exists a neighbourhood U of x such that $f(U) \subseteq V$.

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: $x \in \overline{A}$

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: $\overline{A} = A$

$\langle 2 \rangle 4.$ $f(A) \subseteq B$

$\langle 2 \rangle 5.$ $\overline{A} \subseteq A$

$\langle 3 \rangle 1.$ LET: $x \in \overline{A}$

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

PROOF:

$$f(x) \in f(\overline{A})$$

$$\subseteq \overline{f(A)} \quad (\langle 2 \rangle 1)$$

$$\subseteq \overline{B} \quad (\langle 2 \rangle 4)$$

$$= B \quad (\langle 2 \rangle 2)$$

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

$\langle 2 \rangle 1.$ 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 .
 $\langle 1 \rangle 4$. $1 \Rightarrow 4$
 PROOF: Take $U = f^{-1}(V)$.
 $\langle 1 \rangle 5$. $4 \Rightarrow 1$
 $\langle 2 \rangle 1$. ASSUME: 4
 $\langle 2 \rangle 2$. LET: V be open in Y .
 $\langle 2 \rangle 3$. LET: $x \in f^{-1}(V)$
 $\langle 2 \rangle 4$. V is a neighbourhood of $f(x)$
 $\langle 2 \rangle 5$. PICK a neighbourhood U of x such that $f(U) \subseteq V$
 $\langle 2 \rangle 6$. $x \in U \subseteq f^{-1}(V)$
 \square

Proposition 12.6.4. *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:

- $\langle 1 \rangle 1$. 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 .
 $\langle 1 \rangle 2$. If, for all $B \in \mathcal{B}$, we have $f^{-1}(B)$ is open in X , then f is continuous.
 $\langle 2 \rangle 1$. ASSUME: For all $B \in \mathcal{B}$, we have $f^{-1}(B)$ is open in X .
 $\langle 2 \rangle 2$. LET: U be open in Y .
 $\langle 2 \rangle 3$. LET: $x \in f^{-1}(U)$
 $\langle 2 \rangle 4$. PICK $B \in \mathcal{B}$ such that $f(x) \in B \subseteq U$.
 $\langle 2 \rangle 5$. $x \in f^{-1}(B) \subseteq f^{-1}(U)$
 \square

Proposition 12.6.5. *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:

- $\langle 1 \rangle 1$. If f is continuous then, for all $V \in \mathcal{S}$, we have $f^{-1}(V)$ is open in X .
 PROOF: Immediate from definitions.
 $\langle 1 \rangle 2$. If, for all $V \in \mathcal{S}$, we have $f^{-1}(V)$ is open in X , then f is continuous.
 $\langle 2 \rangle 1$. ASSUME: For all $V \in \mathcal{S}$, we have $f^{-1}(V)$ is open in X .
 $\langle 2 \rangle 2$. 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 $f^{-1}(V_1 \cap \dots \cap V_n) = f^{-1}(V_1) \cap \dots \cap f^{-1}(V_n)$.
 $\langle 2 \rangle 3$. Q.E.D.
 PROOF: By Proposition 12.6.4 since the set of all finite intersections of elements of \mathcal{S} forms a basis for the topology on Y .
 \square

Proposition 12.6.6. *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 12.6.6.

□

Definition 12.6.7 (Homeomorphism). Let X and Y be topological spaces. A *homeomorphism* between X and Y is a bijection $f : X \approx Y$ such that f and f^{-1} are continuous.

Definition 12.6.8 (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 12.6.9. Let **Top** be the category of small topological spaces and continuous functions.

Proposition 12.6.10. \emptyset is initial in **Top**.

Proposition 12.6.11. 1 is terminal in **Top**.

Forgetful functor **Top** \rightarrow **Set**.

Basepoint preserving continuous functor.

Proposition 12.6.12. 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 $\Phi(f^{-1}(1)) = f$.

□

12.6.1 Paths

Definition 12.6.13 (Path). A *path* in a topological space X is a continuous function $[0, 1] \rightarrow X$.

12.6.2 Loops

Definition 12.6.14 (Loop). A *loop* in a topological space X is a path $\alpha : [0, 1] \rightarrow X$ such that $\alpha(0) = \alpha(1)$.

12.7 Convergence

Definition 12.7.1 (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 $\forall n \geq n_0. x_n \in U$.

Convergence in a product space is pointwise convergence.

If $f : X \rightarrow Y$ is continuous and $x_n \rightarrow l$ in X then $f(x_n) \rightarrow f(l)$ in Y .

Example 12.7.2. 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 12.7.3. *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.*

12.8 Subspaces

Definition 12.8.1 (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 12.8.2. 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. □

12.9 Embedding

Definition 12.9.1 (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 .

12.10 Open Maps

Definition 12.10.1 (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 12.10.2. 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:

$\langle 1 \rangle 1$. π_1 is an open map.

$\langle 2 \rangle 1$. LET: U be open in $X \times Y$.

$\langle 2 \rangle 2$. LET: $x \in \pi_1(U)$

$\langle 2 \rangle 3$. PICK y such that $(x, y) \in U$

$\langle 2 \rangle 4$. 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.

□

12.11 Quotient Spaces

Definition 12.11.1 (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:

$\langle 1 \rangle 1$. For all $\mathcal{U} \subseteq \mathcal{T}$ we have $\bigcup \mathcal{U} \in \mathcal{T}$.

PROOF: Since $\pi^{-1}(\bigcup \mathcal{U}) = \bigcup \{\pi^{-1}(U) : U \in \mathcal{U}\}$.

$\langle 1 \rangle 2$. For all $U, V \in \mathcal{T}$ we have $U \cap V \in \mathcal{T}$.

PROOF: Since $\pi^{-1}(U \cap V) = \pi^{-1}(U) \cap \pi^{-1}(V)$.

$\langle 1 \rangle 3$. $X \in \mathcal{T}$

PROOF: Since $X = \pi^{-1}(Y)$.

□

Proposition 12.11.2. 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. □

Definition 12.11.3 (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 .

Theorem 12.11.4. 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:

$\langle 1 \rangle 1$. 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.

$\langle 2 \rangle 1$. Give S the quotient topology.

$\langle 2 \rangle 2$. LET: Z be a topological space.

$\langle 2 \rangle 3$. LET: $f : S \rightarrow Z$

$\langle 2 \rangle 4$. If f is continuous then $f \circ \pi$ is continuous.

PROOF: The composite of two continuous functions is continuous.

$\langle 2 \rangle 5$. If $f \circ \pi$ is continuous then f is continuous.

$\langle 3 \rangle 1$. ASSUME: $f \circ \pi$ is continuous.

$\langle 3 \rangle 2$. LET: U be open in Z .

$\langle 3 \rangle 3$. $\pi^{-1}(f^{-1}(U))$ is open in X .

$\langle 3 \rangle 4$. $f^{-1}(U)$ 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 $\langle 2 \rangle 1$).

□

Corollary 12.11.4.1. Let $\pi : X \rightarrow S$ 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 $\pi^{-1}(s)$.

Proposition 12.11.5. 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 12.11.6 (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 12.11.7 (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 12.11.8 (Möbius Band). The *Möbius band* is the quotient of $[0, 1]^2$ by \sim where $(0, y) \sim (1, 1 - y)$.

Definition 12.11.9 (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 12.11.10. \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 12.11.11. Let $\{X_i\}_{i \in I}$ be a family of topological spaces and $\{Y_i\}_{i \in I}$ a family of sets. Let $q_i : X_i \rightarrow Y_i$ 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 $\prod_{i \in I} q_i : \prod_{i \in I} X_i \rightarrow \prod_{i \in I} Y_i$.

PROOF:

- ⟨1⟩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 .
- ⟨1⟩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.
- ⟨1⟩3. For $n \in \mathbb{Z}_+$,
 LET: $c_n = \sqrt{2}/n$
- ⟨1⟩4. For $n \in \mathbb{Z}_+$,
 LET: $U_n = \{(x, y) \in \mathbb{Q} \times \mathbb{R} : n - 1/4 < x < n + 1/4 \text{ and } ((y > x + c_n - n \text{ and } y > -x + c_n + n) \text{ or } (y < x + c_n - n \text{ and } y < -x + c_n + n))\}$
- ⟨1⟩5. For all $n \in \mathbb{Z}_+$, U_n is open in $\mathbb{R} \times \mathbb{Q}$
- ⟨1⟩6. For all $n \in \mathbb{Z}_+$ we have $\{n\} \times \mathbb{Q} \subseteq U_n$
- ⟨1⟩7. LET: $U = \bigcup_{n \in \mathbb{Z}_+} U_n$
- ⟨1⟩8. U is open in $\mathbb{R} \times \mathbb{Q}$.
- ⟨1⟩9. U is saturated with respect to $p \times \text{id}_{\mathbb{Q}}$.
- ⟨1⟩10. LET: $U' = (p \times \text{id}_{\mathbb{Q}})(U)$
- ⟨1⟩11. ASSUME: for a contradiction U' is open in $X^* \times \mathbb{Q}$.

12.12 Connected Spaces

Definition 12.12.1 (Connected). A topological space is *connected* iff it is not the union of two nonempty open disjoint subsets.

Proposition 12.12.2. *The continuous image of a connected space is connected.*

Proposition 12.12.3. *Let X be a topological space and $A, B \subseteq X$. If $X = A \cup B$, $A \cap B \neq \emptyset$, and A and B are connected, then X is connected.*

Proposition 12.12.4. *If X and Y are nonempty topological spaces, then $X \times Y$ is connected if and only if X and Y are connected.*

Definition 12.12.5 (Path-connected). A topological space X is *path-connected* iff, for any points $a, b \in X$, there exists a continuous function $\alpha : [0, 1] \rightarrow X$, called a *path*, such that $\alpha(0) = a$ and $\alpha(1) = b$.

Proposition 12.12.6. *The continuous image of a path connected space is path connected.*

Proposition 12.12.7. *Let X be a topological space and $A, B \subseteq X$. If $X = A \cup B$, $A \cap B \neq \emptyset$, and A and B are path connected, then X is path connected.*

Proposition 12.12.8. *If X and Y are nonempty topological spaces, then $X \times Y$ is path connected if and only if X and Y are path connected.*

12.13 T_1 Spaces

Definition 12.13.1 (T_1). A topological space is T_1 iff every one-point set is closed.

Proposition 12.13.2. *A topological space is T_1 iff every finite set is closed.*

PROOF: Since the union of finitely many closed sets is closed. \square

Proposition 12.13.3. *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:

- $\langle 1 \rangle 1$. 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 .
- $\langle 2 \rangle 1$. ASSUME: X is T_1 .
- $\langle 2 \rangle 2$. LET: $x, y \in X$
- $\langle 2 \rangle 3$. ASSUME: $x \neq y$
- $\langle 2 \rangle 4$. $X - \{y\}$ is a neighbourhood of x that does not contain y .
- $\langle 2 \rangle 5$. $X - \{x\}$ is a neighbourhood of y that does not contain x .
- $\langle 1 \rangle 2$. 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 .
- $\langle 2 \rangle 1$. 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 .
- $\langle 2 \rangle 2$. LET: $x \in X$
PROVE: $\{x\}$ is closed.
- $\langle 2 \rangle 3$. LET: $y \in X - \{x\}$
- $\langle 2 \rangle 4$. PICK a neighbourhood U of y that does not contain x .
- $\langle 2 \rangle 5$. $y \in U \subseteq X - \{x\}$

\square

12.13.1 Limit Points

Proposition 12.13.4. *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:

- $\langle 1 \rangle 1$. If l is a limit point of A then every neighbourhood of l contains infinitely many points of A .
- $\langle 2 \rangle 1$. ASSUME: l is a limit point of A .
- $\langle 2 \rangle 2$. LET: U be a neighbourhood of l .
- $\langle 2 \rangle 3$. ASSUME: for a contradiction $U \cap A - \{l\}$ is finite.
- $\langle 2 \rangle 4$. $U \cap A - \{l\}$ is closed.
- PROOF: Since X is T_1 .
- $\langle 2 \rangle 5$. $U - (A - \{l\})$ is a neighbourhood of l .
- $\langle 2 \rangle 6$. $U - (A - \{l\})$ intersects A .
- $\langle 2 \rangle 7$. 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.

□

12.14 Hausdorff Spaces

Definition 12.14.1 (Hausdorff). A topological space is a *Hausdorff* space or a T_2 space iff any two distinct points have disjoint neighbourhoods.

Proposition 12.14.2. *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 12.14.3. 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 12.14.4. *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 12.14.5. *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 12.14.6. *The disjoint union of two Hausdorff spaces is Hausdorff.*

Proposition 12.14.7. *The product of two Hausdorff spaces is Hausdorff.*

PROOF:

- <1>1. LET: X and Y be Hausdorff spaces.
 - <1>2. LET: $(x_1, y_1), (x_2, y_2) \in X \times Y$ with $(x_1, y_1) \neq (x_2, y_2)$
 - <1>3. ASSUME: w.l.o.g. $x_1 \neq x_2$
 - <1>4. PICK disjoint open sets U, V in X with $x_1 \in U$ and $x_2 \in V$.
 - <1>5. $U \times Y$ and $V \times Y$ are disjoint open sets in $X \times Y$ with $(x_1, y_1) \in U \times Y$ and $(x_2, y_2) \in V \times Y$.
-

Proposition 12.14.8. *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.

□

Proposition 12.14.9. *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 12.14.10. The converse does not hold. If X is an infinite set under the cofinite topology, then X is T_1 but not Hausdorff.

Proposition 12.14.11. *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 12.14.12. *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

12.15 Separable Spaces

Definition 12.15.1 (Separable). A topological space is *separable* iff it has a countable dense subset.

Every second countable space is separable.

12.16 Sequential Compactness

Definition 12.16.1 (Sequentially Compact). A topological space is *sequentially compact* iff every sequence has a convergent subsequence.

12.17 Compactness

Definition 12.17.1 (Compact). A topological space is *compact* iff every open cover has a finite subcover.

Proposition 12.17.2. *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 12.17.2.1. *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 12.17.3. *The continuous image of a compact space is compact.*

Proposition 12.17.4. *A closed subspace of a compact space is compact.*

Proposition 12.17.5. *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 12.17.6. *A compact subspace of a Hausdorff space is closed.*

Proposition 12.17.7. *A continuous bijection from a compact space to a Hausdorff space is a homeomorphism.*

Proposition 12.17.8. *A first countable compact space is sequentially compact.*

12.18 Quotient Spaces

Definition 12.18.1 (Quotient Space). Let X be a topological space and \sim an equivalence relation on X . The *quotient topology* on X/\sim is defined by: $U \in \mathcal{P}X$ is open in X/\sim if and only if $\pi^{-1}(U)$ is open in X .

Proposition 12.18.2. *Let X and Y be topological spaces. Let \sim be an equivalence relation on X . Let $f : X/\sim \rightarrow Y$. Then f is continuous if and only if $f \circ \pi$ is continuous.*

Proposition 12.18.3. *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 12.18.4. *A quotient of a connected space is connected.*

Proposition 12.18.5. *A quotient of a path connected space is path connected.*

Proposition 12.18.6. *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 12.18.7. 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 12.18.8 (Cone). Let X be a topological space. The *cone over X* is the space $(X \times [0, 1])/(X \times \{1\})$.

Definition 12.18.9 (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 12.18.10 (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 12.18.11 (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 12.18.12. $D^n/S^{n-1} \cong S^n$

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.

□

12.19 Gluing

Definition 12.19.1 (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 12.19.2. Y is a subspace of $Y \cup_\phi X$.

Definition 12.19.3. 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 12.19.4 (Möbius Strip). The *Möbius strip* is $([-1, 1] \times [0, 1])/\alpha$ where $\alpha(x) = -x$.

Definition 12.19.5 (Klein Bottle). The *Klein bottle* is $(S^1 \times [0, 1])/\alpha$ where $\alpha(z) = \bar{z}$.

Proposition 12.19.6. 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.

□

12.20 Metric Spaces

Definition 12.20.1 (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 12.20.2 (Ball). Let X be a metric space. Let $x \in X$ and $r > 0$. The *ball* with *centre* x and *radius* r is

$$B(x, r) = \{y \in X \mid d(x, y) < r\} .$$

Definition 12.20.3 (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.

Definition 12.20.4 (Metrizable). A topological space is *metrizable* iff there exists a metric that induces its topology.

Proposition 12.20.5. *Every metrizable space is Hausdorff.*

Every metrizable space is first countable.

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.

12.20.1 Products

Definition 12.20.6 (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:

$\langle 1 \rangle 1.$ $d((x_1, y_1), (x_2, y_2)) \geq 0$

PROOF: Immediate from definition.

$\langle 1 \rangle 2.$ $d((x_1, y_1), (x_2, y_2)) = 0$ 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 $y_1 = y_2$.

$\langle 1 \rangle 3.$ $d((x_1, y_1), (x_2, y_2)) = d((x_2, y_2), (x_1, y_1))$

PROOF: Since $\sqrt{d(x_1, x_2)^2 + d(y_1, y_2)^2} = \sqrt{d(x_2, x_1)^2 + d(y_2, y_1)^2}$.

$\langle 1 \rangle 4.$ 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 12.20.7. *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: $d((x', y'), (a, b)) < \epsilon$

⟨2⟩3. $d((x', y'), (x, y)) < \epsilon - d((x, y), (a, b))$

PROOF:

$$\begin{aligned}
d((x', y'), (x, y)) &= \sqrt{d(x', x)^2 + d(y', y)^2} \\
&< \sqrt{(\epsilon - d((x, y), (a, b)))^2/2 + (\epsilon - d((x, y), (a, b)))^2/2} \\
&= \epsilon - d((x, y), (a, b))
\end{aligned}$$

⟨2⟩4. $d((x', y'), (a, b)) < \epsilon$

PROOF:

$$\begin{aligned}
d((x', y'), (a, b)) &\leq d((x', y'), (x, y)) + d((x, y), (a, b)) \quad (\text{Triangle Inequality}) \\
&< \epsilon \quad (\langle 2 \rangle 3)
\end{aligned}$$

⟨1⟩2. If U is open in X and V is open in Y then $U \times V$ is open under the Euclidean metric.

⟨2⟩1. LET: $(x, y) \in U \times V$

⟨2⟩2. PICK $\delta, \epsilon > 0$ such that $B(x, \delta) \subseteq U$ and $B(y, \epsilon) \subseteq V$

PROVE: $B((x, y), \min(\delta, \epsilon)) \subseteq U \times V$

⟨2⟩3. LET: $(x', y') \in B((x, y), \min(\delta, \epsilon))$

⟨2⟩4. $d(x', x) < \delta$

⟨3⟩1. $d((x', y'), (x, y)) < \min(\delta, \epsilon)$

⟨3⟩2. $d(x', x)^2 + d(y', y)^2 < \delta^2$

⟨3⟩3. $d(x', x)^2 < \delta^2$

⟨2⟩5. $d(y', y) < \epsilon$

PROOF: Similar.

⟨2⟩6. $(x', y') \in U \times V$

□

12.21 Complete Metric Spaces

Definition 12.21.1 (Complete). A metric space is *complete* iff every Cauchy sequence converges.

Example 12.21.2. \mathbb{R} is complete.

Proposition 12.21.3. *The product of two complete metric spaces is complete.*

Proposition 12.21.4. *Every compact metric space is complete.*

Proposition 12.21.5. *Let X be a complete metric space and $A \subseteq X$. Then A is complete if and only if A is closed.*

Definition 12.21.6 (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 12.21.7. *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 $\phi(\lim_{n \rightarrow \infty} i_1(x_n)) = \lim_{n \rightarrow \infty} i_2(x_n)$. \square

Theorem 12.21.8. *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 $d(x_n, y_n) \rightarrow 0$. \square

12.22 Manifolds

Definition 12.22.1 (Manifold). An *n -dimensional manifold* is a second countable Hausdorff space locally homeomorphic to \mathbb{R}^n .

Chapter 13

Homotopy Theory

13.1 Homotopies

Definition 13.1.1 (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 13.1.2. 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 13.1.3. 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 13.1.4. 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.

13.2 Homotopy Equivalence

Definition 13.2.1 (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 13.2.2 (Contractible). A topological space X is *contractible* iff $X \simeq 1$.

Example 13.2.3. \mathbb{R}^n is contractible.

Example 13.2.4. D^n is contractible.

Definition 13.2.5 (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 13.2.6 (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 13.2.7. $\{0\}$ is a strong deformation retract of \mathbb{R}^n and of D^n .

Example 13.2.8. S^1 is a strong deformation retract of the torus $S^1 \times D^2$.

Example 13.2.9. S^{n-1} is a strong deformation retract of $D^n - \{0\}$.

Example 13.2.10. For any topological space X , the singleton consisting of the vertex is a strong deformation retract of the cone over X .

Chapter 14

Simplicial Complexes

Definition 14.0.1 (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 14.0.2 (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 14.0.3 (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 .

14.1 Cell Decompositions

Definition 14.1.1 (n -cell). An n -cell is a topological space homeomorphic to \mathbb{R}^n .

Definition 14.1.2 (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 14.1.3 (n -skeleton). Given a cell decomposition of X , the n -skeleton X^n is the union of all the cells of dimension $\leq n$.

14.2 CW-complexes

Definition 14.2.1 (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 14.2.2. *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 15

Topological Groups

Definition 15.0.1 (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 15.0.2. $GL(n, \mathbb{R})$ and $GL(n, \mathbb{C})$ are topological groups.

Proposition 15.0.3. Any subgroup of a topological group is a topological group under the subspace topology.

Definition 15.0.4 (Homogeneous Space). A *homogeneous space* is a topological space of the form G/H , where G is a topological group and H is a normal subgroup of G , under the quotient topology.

Proposition 15.0.5. Let G be a topological group and H a normal subgroup of G . Then G/H is Hausdorff if and only if H is closed.

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

15.1 Continuous Actions

Definition 15.1.1 (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 15.1.2 (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 15.1.3. *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 15.1.4 (Stabilizer). Let X be a G -space and $x \in X$. The *stabilizer* of x is $G_x := \{g \in G : gx = x\}$.

Proposition 15.1.5. *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: Proposition 12.18.2.

□

Chapter 16

Topological Vector Spaces

Definition 16.0.1 (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 16.0.2. *Every topological vector space is a topological group under addition.*

PROOF: Immediate from the definition. \square

Theorem 16.0.3. *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 16.0.4. *Let E be a topological vector space and E_0 a subspace of E . Then $\overline{E_0}$ is a subspace of E .*

Definition 16.0.5. Let E be a topological vector space. The topological space associated with E is $E/\overline{\{0\}}$.

16.1 Cauchy Sequences

Definition 16.1.1 (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 16.1.2 (Complete Topological Vector Space). A topological vector space is *complete* iff every Cauchy sequence converges.

16.2 Seminorms

Definition 16.2.1 (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 16.2.2. The function that maps (x_1, \dots, x_n) to $|x_i|$ is a seminorm on \mathbb{R}^n .

Definition 16.2.3. 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 16.2.4. 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 $x = 0$.

16.3 Fréchet Spaces

Definition 16.3.1 (Pre-Fréchet Space). A *pre-Fréchet space* is a Hausdorff topological vector space whose topology is generated by a countable set of seminorms.

Proposition 16.3.2. 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 16.3.3 (Fréchet Space). A *Fréchet space* is a complete pre-Fréchet space.

16.4 Normed Spaces

Definition 16.4.1 (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 16.4.2. 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 16.4.3 (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 $x_1 = \dots = x_n = 0$.

□

Definition 16.4.4 (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 16.4.5. *The 2-norm on \mathbb{R}^n induces the standard metric.*

PROOF: Immediate from definitions. \square

Definition 16.4.6. 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 16.4.7. *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>.

Definition 16.4.8. Let l_∞ be the set of all bounded sequences in \mathbb{R} under

$$\|(x_n)\| := \sup_n |x_n|$$

Proposition 16.4.9. *For all $p \geq 1$ we have l_p is not homeomorphic to l_∞ .*

Proposition 16.4.10. *Let $\| \cdot \|$ be a seminorm on the vector space E . Then $\| \cdot \|$ defines a norm on $E/\{0\}$.*

Proposition 16.4.11. *Let E and F be normed spaces. Any continuous linear map $E \rightarrow F$ is uniformly continuous.*

Definition 16.4.12. 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

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

16.5 Inner Product Spaces

Proposition 16.5.1. *If E is an inner product space then $\|x\| = \sqrt{\langle x, x \rangle}$ is a norm on E .*

16.6 Banach Spaces

Definition 16.6.1 (Banach Space). A *Banach space* is a complete normed space.

Example 16.6.2. 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 16.6.3. *The completion of a normed space is a Banach space.*

Proposition 16.6.4. *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 16.6.5. $L^p(\mathbb{R}^n)$ is a Banach space.

Proposition 16.6.6. $C(\mathbb{R})$ 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

16.7 Hilbert Spaces

Definition 16.7.1 (Hilbert Space). A *Hilbert space* is a complete inner product space.

Example 16.7.2. 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 16.7.3. *The completion of an inner product space is a Hilbert space.*

An infinite dimensional Hilbert space with the weak topology is not first countable.

16.8 Locally Convex Spaces

Definition 16.8.1 (Locally Convex Space). A topological vector space is *locally convex* iff every neighbourhood of 0 includes a convex neighbourhood of 0.

Proposition 16.8.2. *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 16.8.3. *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 16.8.4. 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 Dieudonne, J. A., Treatise on Analysis, Vol. II, New York and London: Academic Press, 1970, p. 76.

Definition 16.8.5 (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 .