Mathematics

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Chapter 1

Primitive Terms and Axioms

1.1 Primitive Terms

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

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

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

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

1.2 Axioms

Axiom Schema 1.2.1 (Choice)**.** *Let $P[X, Y, x, y]$ be a formula where X and Y are set variables, $x : \mathrm{El}(X)$ and $y : \mathrm{El}(Y)$. Then the following is an axiom.*

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

Axiom 1.2.2 (Pairing)**.** *For any sets A and B, there exists a set $A \times B$, the* Cartesian product *of A and B, and functions $\pi_1 : A \times B \to A$ and $\pi_2 : A \times B \to B$ such that, for all $a : \mathrm{El}(A)$ and $b : \mathrm{El}(B)$, there exists a unique $(a, b) : \mathrm{El}(A \times B)$ such that $\pi_1(a, b) = a$ and $\pi_2(a, b) = b$.*

Definition 1.2.3 (Injective)**.** A function $f : A \to B$ is *injective* or an *injection* iff, for all $x, y : \mathrm{El}(A)$, if $f(x) = f(y)$ then $x = y$.

Axiom Schema 1.2.4 (Separation)**.** *For every property $P[X, x]$ where X is a set variable and $x : \mathrm{El}(X)$, the following is an axiom:*

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

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

Axiom 1.2.5 (Infinity)**.** *There exists a set $\mathbb{N}$, an element $0 : \mathrm{El}\,(\mathbb{N})$, and a function $s : \mathbb{N} \to \mathbb{N}$ such that:*

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

1.3 Consequences of the Axioms

1.3.1 Definitions

Definition 1.3.1. Let $f, g : A \to B$. We say f and g are *equal*, $f = g$, iff $\forall x : \mathrm{El}\,(A)\,.f(x) = g(x)$.

Definition 1.3.2 (Surjective)**.** A function $f : A \to B$ is *surjective* iff, for all $y : \mathrm{El}\,(B)$, there exists $x : \mathrm{El}\,(A)$ such that $f(x) = y$.

Definition 1.3.3 (Bijective)**.** A function $f : A \to B$ 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 $P(C)$".

Definition 1.3.4 (Composition)**.** Given $f : A \to B$ and $g : B \to C$, let $g \circ f$ be the function such that $\forall a : \mathrm{El}\,(A)\,.(g \circ f)(a) = g(f(a))$.

1.3.2 The Empty Set

Theorem 1.3.5. *There exists a set which has no elements.*

PROOF:
$\langle 1 \rangle$1. PICK a set A
PROOF: By the Axiom of Infinity, a set exists.
$\langle 1 \rangle$2. LET: $S = \{x : \mathrm{El}\,(A) \mid \bot\}$ with injection $i : S \to A$
PROOF: Axiom of Separation.
$\langle 1 \rangle$3. S has no elements.
□

Theorem 1.3.6. *If E and E' have no elements then $E \approx E'$.*

PROOF:

⟨1⟩1. LET: E and E' have no elements.
⟨1⟩2. PICK a function $F : E \to E'$.
PROOF: Axiom of Choice since vacuously $\forall x : \mathrm{El}\,(E)\,.\exists y : \mathrm{El}\,(E')\,.\top$.
⟨1⟩3. F is injective.
PROOF: Vacuously, for all $x, y : \mathrm{El}\,(E)$, if $F(x) = F(y)$ then $x = y$.
⟨1⟩4. F is surjective.
PROOF: Vacuously, for all $y : \mathrm{El}\,(E)$, there exists $x : \mathrm{El}\,(E)$ such that $F(x) = y$.
□

Definition 1.3.7 (Empty Set)**.** The *empty set* $\varnothing$ is the set with no elements.

1.3.3 The Singleton

Theorem 1.3.8. *There exists a set that has exactly one element.*

PROOF:
⟨1⟩1. PICK a set A that has an element.
PROOF: By the Axiom of Infinity, there exists a set that has an element.
⟨1⟩2. PICK $a : \mathrm{El}\,(A)$
⟨1⟩3. PICK a set S and injection $i : S \rightarrowtail A$ such that, for all $x : \mathrm{El}\,(A)$, there exists $s : \mathrm{El}\,(S)$ such that $s = x$ if and only if $x = a$
⟨1⟩4. S has exactly one element.
□

Theorem 1.3.9. *If A and B both have exactly one element then $A \approx B$.*

PROOF:
⟨1⟩1. LET: A and B both have exactly one element a and b respectively.
⟨1⟩2. LET: $F : A \to B$ be the function such that, for all $x : \mathrm{El}\,(A)$, we have $(x = a \wedge F(x) = b)$
⟨1⟩3. F is a bijection.
□

Definition 1.3.10 (Singleton)**.** Let 1 be the set that has exactly one element. Let $*$ be its element.

1.3.4 Subsets

Definition 1.3.11 (Subset)**.** A *subset* of a set A consists of a set S and an injection $i : S \rightarrowtail A$. We write $(S, i) : \mathrm{Sub}(A)$.

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

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

Proposition 1.3.13. *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 1.3.14. *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 1.3.15 (Membership)**.** Given $(S, i) : \mathrm{Sub}(A)$ and $a \in A$, we write $a \in (S, i)$ for $\exists s : \mathrm{El}\,(S)\,.i(s) = a$.

Proposition 1.3.16. *If $a \in (S, i)$ and $(S, i) = (T, j)$ then $a \in (T, j)$.*

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

1.4 Composition

Definition 1.4.1 (Composite)**.** Let $\phi : A \looparrowright B$ and $\psi : B \looparrowright C$. The *composite* $\psi \circ \phi : A \looparrowright C$ is the relation such that $a(\psi \circ \phi)c$ iff there exists b such that $a\phi b$ and $b\psi c$.

Definition 1.4.2 (Identity)**.** For any set A, the *identity* function $\mathrm{id}_A : A \to A$ is the function defined by $\mathrm{id}_A(a) = a$.

Theorem 1.4.3. *Composition of relations is associative, and the identity function is an identity for composition. The composite of functions is a function. The composite of injective functions is injective. The composite of surjective functions is surjective. The composite of bijections is a bijection. A function $f : A \to B$ is a bijection iff there exists a function $f^{-1} : B \to A$ such that $f^{-1}f = \mathrm{id}_A$ and $ff^{-1} = \mathrm{id}_B$, in which case f^{-1} is unique.*

1.5 Axioms Part Two

Axiom 1.5.1 (Power Set)**.** *For any set A, there exists a set $\mathcal{P}A$, the* power set *of A, and a relation $\in : A \looparrowright \mathcal{P}A$, called* membership*, such that, for any subset S of A, there exists a unique $\overline{S} \in \mathcal{P}A$ such that, for all $x \in A$, we have $x \in \overline{S}$ if and only if $x \in S$.*

We usually write just S for $\overline{S}$.

Axiom Schema 1.5.2 (Collection)**.** *Let $P[X, Y, x]$ be a formula with set variables X and Y and an element variable $x \in X$. Then the following is an axiom.*

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

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

Definition 1.5.3 (Universe)**.** Let $E : U \looparrowright X$ be a relation. Let us say that a set A is *small* iff there exists $u \in U$ such that $A \approx \{x \in X : uEx\}$.

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

- $\mathbb{N}$ is U-small.
- For any U-small sets A and B and relation $R : A \looparrowright B$, the tabulation of R is U-small.
- If A is U-small then so is $\mathcal{P}A$
- Let $f : A \to B$ be a function. If B is U-small and $f^{-1}(b)$ is U-small for all $b \in B$, then A is U-small.
- If $p : B \twoheadrightarrow A$ is a surjective function such that A is U-small, then there exists a U-small set C, a surjection $q : C \twoheadrightarrow A$, and a function $f : C \to B$ such that $q = pf$.

Axiom 1.5.4 (Universe)**.** *There exists a universe.*

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

1.6 Cartesian Product

Definition 1.6.1 (Cartesian Product)**.** Let A and B be sets. The *Cartesian product* of A and B, $A \times B$, is the tabulation of the relation $A \looparrowright B$ that holds for all $a \in A$ and $b \in B$. The associated functions $\pi_1 : A \times B \to A$ and $\pi_2 : A \times B \to B$ are called the *projections*.

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

1.7 Quotient Sets

Proposition 1.7.1. *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 $x, y : \mathrm{El}(X)$, we have $x \sim y$ if and only if $\pi(x) = \pi(y)$.*

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

1.8 Partitions

Definition 1.8.1 (Partition)**.** A *partition* of a set X is a set of pairwise disjoint subsets of X whose union is X.

Chapter 2

Category Theory

2.1 Categories

Definition 2.1.1. A *category* $\mathcal{C}$ consists of:

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

such that:

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

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

Definition 2.1.2. Let **Set** be the category of small sets and functions.

Proposition 2.1.3. *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: $i, j : A \to A$ be identity morphisms on A.
$\langle 1 \rangle 4$. $i = j$

PROOF:

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

□

Definition 2.1.4. Given $f : A \to B$ and an object C, define the function $f^* : \mathcal{C}[B, C] \to \mathcal{C}[A, C]$ by $f^*(g) = g \circ f$.

Definition 2.1.5. Given $f : A \to B$ and an object C, define the function $f_* : \mathcal{C}[C, A] \to \mathcal{C}[C, B]$ by $f_*(g) = f \circ g$.

2.1.1 Sections and Retractions

Definition 2.1.6 (Section, Retraction)**.** Let $r : A \to B$ and $s : B \to A$. Then r is a *retraction* of s, and s is a *section* of r, iff $rs = \mathrm{id}_B$.

Proposition 2.1.7. *Let $f : A \to B$ and $r, s : B \to A$. If r is a retraction of f and s is a section of f then $r = s$.*

PROOF:

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

2.1.2 Isomorphisms

Definition 2.1.8 (Isomorphism)**.** A morphism $f : A \to B$ is an *isomorphism*, $f : A \cong B$, iff there exists a morphism $f^{-1} : B \to A$ 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 2.1.9. *The inverse of an isomorphism is unique.*

PROOF: From Proposition 2.1.7. □

Proposition 2.1.10. *If $f : A \cong B$ then $f^{-1} : B \cong A$ and $(f^{-1})^{-1} = f$.*

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

Isomorphism.
Define the opposite category.
Slice categories

Definition 2.1.11. 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 $u : B \to X$ and $p : X \to B$

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

Proposition 2.1.12.

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

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

2.1.3 Initial Objects

Definition 2.1.13 (Initial Object)**.** An object I is *initial* iff, for any object X, there exists exactly one morphism $I \to X$.

Proposition 2.1.14. *The empty set is initial in* **Set***.*

Proof: For any set A, the nowhere-defined function is the unique function $\emptyset \to A$. □

Proposition 2.1.15. *If I and I' are initial objects, then there exists a unique isomorphism $I \cong I'$.*

Proof:
$\langle 1 \rangle$1. Let: $i : I \to I'$ be the unique morphism $I \to I'$.
$\langle 1 \rangle$2. Let: $i^{-1} : I' \to I$ be the unique morphism $I' \to I$.
$\langle 1 \rangle$3. $ii^{-1} = \mathrm{id}_{I'}$
Proof: There is only one morphism $I' \to I'$.
$\langle 1 \rangle$4. $i^{-1}i = \mathrm{id}_I$
Proof: There is only one morphism $I \to I$.
□

2.1.4 Terminal Objects

Definition 2.1.16 (Terminal Object)**.** An object T is *terminal* iff, for any object X, there exists exactly one morphism $X \to T$.

Proposition 2.1.17. *1 is terminal in* **Set***.*

Proof: For any set A, the constant function to $*$ is the only function $A \to 1$. □

2.1.5 Zero Objects

Definition 2.1.18 (Zero Object)**.** An object Z is a *zero object* iff it is an initial object and a terminal object.

Definition 2.1.19 (Zero Morphism)**.** Let $\mathcal{C}$ be a category with a zero object Z. Let $A, B \in \mathcal{C}$. The *zero morphism* $A \to B$ is the unique morphism $A \to Z \to B$.

Proposition 2.1.20. *There is no zero object in* **Set***.*

Proof: Since $\emptyset \not\approx 1$. □

2.1.6 Triads

Definition 2.1.21 (Triad)**.** Let $\mathcal{C}$ be a category. A *triad* consists of objects X, Y, M and morphisms $\alpha : X \to M$, $\beta : Y \to M$. We call M the *codomain* of the triad.

2.1.7 Cotriads

Definition 2.1.22 (Cotriad)**.** Let $\mathcal{C}$ be a category. A *cotriad* consists of objects X, Y, W and morphisms $\xi : W \to X$, $\eta : W \to Y$. We call W the *domain* of the triad.

2.1.8 Pullbacks

Definition 2.1.23 (Pullback)**.** A diagram

$$\begin{tikzcd} W \arrow[r, "\xi"] \arrow[d, "\eta"'] & X \arrow[d, "\alpha"] \\ Y \arrow[r, "\beta"'] & M \end{tikzcd}$$

is a *pullback* iff $\alpha\xi = \beta\eta$ and, for every object Z and morphism $f : Z \to X$ and $g : Z \to Y$ such that $\alpha f = \beta g$, there exists a unique $h : Z \to W$ 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 2.1.24. *If $\xi : W \to X$ and $\eta : W \to Y$ form a pullback of $\alpha : X \to M$ and $\beta : Y \to M$, and $\xi' : W' \to X$ and $\eta' : W' \to Y$ 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: $\phi : W \to W'$ be the unique morphism such that $\eta'\phi = \eta$ and $\xi'\phi = \xi$.
$\langle 1\rangle$2. Let: $\phi^{-1} : W' \to W$ be the unique morphism such that $\eta\phi^{-1} = \eta'$ and $\xi\phi^{-1} = \xi'$.
$\langle 1\rangle$3. $\phi\phi^{-1} = \mathrm{id}_{W'}$
Proof: Each is the unique $x : W' \to W'$ such that $\eta' x = \eta'$ and $\xi' x = \xi'$.
$\langle 1\rangle$4. $\phi^{-1}\phi = \mathrm{id}_W$
Proof: Each is the unique $x : W \to W$ such that $\eta x = \eta$ and $\xi x = \xi$.
□

Proposition 2.1.25. *For any morphism $h : A \to B$, the following diagram is a pullback diagram.*

$$\begin{tikzcd} A \arrow[r, "h"] \arrow[d, equal] & B \arrow[d, equal] \\ A \arrow[r, "h"'] & B \end{tikzcd}$$

PROOF:
⟨1⟩1. LET: Z be an object.
⟨1⟩2. LET: $f : Z \to B$ and $g : Z \to A$ satisfy $\mathrm{id}_B f = hg$
⟨1⟩3. $g : Z \to B$ is the unique morphism such that $\mathrm{id}_A g = g$ and $hg = f$.
□

Proposition 2.1.26. *The pullback of an isomorphism is an isomorphism.*

PROOF:
⟨1⟩1. LET:

$$\begin{tikzcd} W \arrow[r, "\xi"] \arrow[d, "\eta"'] & X \arrow[d, "\alpha"] \\ Y \arrow[r, "\beta"'] & M \end{tikzcd}$$

be a pullback diagram.
⟨1⟩2. ASSUME: β is an isomorphism.
⟨1⟩3. LET: ξ^{-1} be the unique morphism $X \to W$ such that $\xi\xi^{-1} = \mathrm{id}_X$ and $\eta\xi^{-1} = \beta^{-1}\alpha$.
PROOF: This exists since $\alpha \mathrm{id}_X = \beta\beta^{-1}\alpha = \alpha$.
⟨1⟩4. $\xi^{-1}\xi = \mathrm{id}_W$
PROOF: Each is the unique $x : W \to W$ such that $\xi x = \xi$ and $\eta x = \eta$.
□

Proposition 2.1.27. *Let $\beta : (Y, y) \to (M, m)$ and $\alpha : (X, x) \to (M, m)$ in $\mathcal{C}\backslash A$. Let*

$$\begin{tikzcd} W \arrow[r, "\xi"] \arrow[d, "\eta"'] & X \arrow[d, "\alpha"] \\ Y \arrow[r, "\beta"'] & M \end{tikzcd}$$

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

PROOF:
⟨1⟩1. LET: $(Z, z) \in \mathcal{C}\backslash A$
⟨1⟩2. LET: $f : (Z, z) \to (X, x)$ and $g : (Z, z) \to (Y, y)$ satisfy $\alpha f = \beta g$.
⟨1⟩3. LET: $h : Z \to W$ be the unique morphism such that $\xi h = f$ and $\eta h = g$.
⟨1⟩4. $hz = w$
⟨2⟩1. $\xi hz = \xi w$
PROOF:

$$\begin{aligned} \xi hz &= fz && (\langle 1\rangle 3) \\ &= x && (\langle 1\rangle 2) \\ &= \xi w \end{aligned}$$

⟨2⟩2. $\eta hz = \eta w$

PROOF: Similar.
⟨1⟩5. $h : (Z, z) \to (W, w)$
□

Proposition 2.1.28. *Let $\beta : (Y, y) \to (M, m)$ and $\alpha : (X, x) \to (M, m)$ in $\mathcal{C}/A$. Let*

$$\begin{tikzcd} W \arrow[r, "\xi"] \arrow[d, "\eta"'] & X \arrow[d, "\alpha"] \\ Y \arrow[r, "\beta"'] & M \end{tikzcd}$$

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

PROOF:
⟨1⟩1. $\eta : (W, w) \to (Y, y)$
PROOF:

$$\begin{aligned} y\eta &= m\beta\eta \\ &= m\alpha\xi \\ &= x\xi \\ &= w \end{aligned}$$

⟨1⟩2. LET: $(Z, z) \in \mathcal{C}/A$
⟨1⟩3. LET: $f : (Z, z) \to (X, x)$ and $g : (Z, z) \to (Y, y)$ satisfy $\alpha f = \beta g$.
⟨1⟩4. LET: $h : Z \to W$ be the unique morphism such that $\xi h = f$ and $\eta h = g$.
⟨1⟩5. $h : (Z, z) \to (W, w)$
PROOF:

$$\begin{aligned} wh &= x\xi h \\ &= xf && (\langle 1\rangle 4) \\ &= z && (\langle 1\rangle 3) \end{aligned}$$

□

Proposition 2.1.29. *In* **Set**, *let $\alpha : X \to M$ and $\beta : Y \to M$. Let $W = \{(x, y) \in X \times Y : \alpha(x) = \beta(y)\}$ with inclusion $i : W \to X \times Y$. Let $\xi = \pi_1 i : W \to X$ and $\eta : \pi_2 i : W \to Y$. Then ξ and η form the pullback of α and β.*

PROOF:
⟨1⟩1. $\alpha\xi = \beta\eta$
PROOF: For $w \in W$, if $i(w) = (x, y)$ then then $\alpha(\xi(w)) = \alpha(x) = \beta(y) = \beta(\eta(w))$.
⟨1⟩2. For every set Z and functions $f : Z \to X$, $g : Z \to Y$ such that $\alpha f = \beta g$, there exists a unique $h : Z \to W$ 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

2.1.9 Pushouts

Definition 2.1.30 (Pushout)**.** A diagram

$$\begin{tikzcd} W \arrow[r, "\xi"] \arrow[d, "\eta"'] & X \arrow[d, "\alpha"] \\ Y \arrow[r, "\beta"'] & M \end{tikzcd} \tag{2.1}$$

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

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

Proposition 2.1.31. *If $\alpha : X \to M$ and $\beta : Y \to M$ form a pushout of $\xi : W \to X$ and $\eta : W \to Y$, and $\alpha' : X \to M'$ and $\beta' : Y \to M'$ 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 2.1.24. □

Proposition 2.1.32. *For any morphism $h : A \to B$, the following diagram is a pushout diagram.*

$$\begin{tikzcd} A \arrow[r, "h"] \arrow[d, equal] & B \arrow[d, equal] \\ A \arrow[r, "h"'] & B \end{tikzcd}$$

Proof: Dual to Proposition 2.1.25.

Proposition 2.1.33. *The diagram (2.1) is a pushout in $\mathcal{C}$ iff it is a pullback in $\mathcal{C}^{\mathrm{op}}$.*

Proof: Immediate from definitions. □

Proposition 2.1.34. *The pushout of an isomorphism is an isomorphism.*

Proof: Dual to Proposition 2.1.26. □

Proposition 2.1.35. *Let $\xi : (W, w) \to (X, x)$ and $\eta : (W, w) \to (Y, y)$ in $\mathcal{C}\backslash A$. Let*

$$\begin{tikzcd} W \arrow[r, "\xi"] \arrow[d, "\eta"'] & X \arrow[d, "\alpha"] \\ Y \arrow[r, "\beta"'] & M \end{tikzcd}$$

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

PROOF: Dual to Proposition 2.1.28. □

Proposition 2.1.36. *Let $\xi : (W, w) \to (X, x)$ and $\eta : (W, w) \to (Y, y)$ in $\mathcal{C}/A$. Let*

$$\begin{tikzcd} W \arrow[r, "\xi"] \arrow[d, "\eta"'] & X \arrow[d, "\alpha"] \\ Y \arrow[r, "\beta"'] & M \end{tikzcd}$$

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

PROOF: Dual to Proposition 2.1.27. □

Proposition 2.1.37. Set *has pushouts.*

PROOF:
⟨1⟩1. LET: $\xi : W \to X$ and $\eta : W \to Y$.
⟨1⟩2. LET: $\sim$ be the equivalence relation on $X + Y$ generated by $\xi(w) \sim \eta(w)$ for all $w \in W$
⟨1⟩3. LET: $M = (X + Y)/\sim$ with canonical projection $\pi : X + Y \twoheadrightarrow M$.
⟨1⟩4. LET: $\alpha = \pi \circ \kappa_1 : X \to M$
⟨1⟩5. LET: $\beta = \pi \circ \kappa_2 : Y \to M$
⟨1⟩6. LET: Z be any set, $f : X \to Z$ and $g : Y \to Z$.
⟨1⟩7. ASSUME: $f\xi = g\eta$
⟨1⟩8. LET: $h : X + Y \to Z$ be the function defined by $h(x) = f(x)$ and $h(y) = g(y)$ for $x \in X$ and $y \in Y$
⟨1⟩9. h respects $\sim$
PROOF: For $w \in W$ we have

$$\begin{aligned} h(\xi(w)) &= f(\xi(w)) && (\langle 1\rangle 8) \\ &= g(\eta(w)) && (\langle 1\rangle 7) \\ &= h(\eta(w)) && (\langle 1\rangle 8) \end{aligned}$$

⟨1⟩10. LET: $\overline{h} : M \to Z$ be the induced function.
⟨1⟩11. $\overline{h}\alpha = f$
PROOF:

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

⟨1⟩12. $\overline{h}\beta = g$
PROOF: Similar.
⟨1⟩13. For all $k : M \to Z$, if $k\alpha = f$ and $k\beta = g$ then $k = \overline{h}$.

PROOF:

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

□

Definition 2.1.38. Let $u : A \rightarrowtail X$ be an injection. The *pointed set obtained from X by collapsing* (A, u), denoted $X/(A, u)$, is the pushout

$$\begin{tikzcd} A \arrow[r] \arrow[d, "u"] & 1 \arrow[d, "*"'] \\ X \arrow[r] & X/(A,u) \end{tikzcd}$$

Proposition 2.1.39. *In* $\mathbf{Set}_*$, *any two morphisms* $1 \to X$ *and* $1 \to Y$ *have a pushout.*

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

Definition 2.1.40 (Wedge)**.** The *wedge* of pointed sets X and Y, $X \vee Y$, is the pushout of the unique morphism $1 \to X$ and $1 \to Y$.

Definition 2.1.41 (Smash)**.** Let X and Y be pointed sets. Let $\xi : X \vee Y \to X$ be the unique morphism such that the following diagram commutes.

$$\begin{tikzcd} 1 \arrow[r] \arrow[d] & X \arrow[d] \arrow[ddr, equal, bend left] & \\ Y \arrow[r] \arrow[drr, bend right, "0"'] & X \vee Y \arrow[dr, "\xi"] & \\ & & X \end{tikzcd}$$

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

$$\begin{tikzcd} 1 \arrow[r] \arrow[d] & X \arrow[d] \arrow[ddr, bend left, "0"] & \\ Y \arrow[r] \arrow[drr, equal, bend right] & X \vee Y \arrow[dr, "\eta"] & \\ & & Y \end{tikzcd}$$

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

Pushout lemma

2.1.10 Subcategories

Definition 2.1.42 (Subcategory)**.** A *subcategory* $\mathcal{C}'$ of a category $\mathcal{C}$ consists of:

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

such that:

- for all $A \in \mathrm{Ob}(\mathcal{C}')$, we have $\mathrm{id}_A \in \mathcal{C}'[A,A]$
- 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 $A, B \in \mathrm{Ob}(\mathcal{C}')$, we have $\mathcal{C}'[A,B] = \mathcal{C}[A,B]$.

2.1.11 Opposite Category

Definition 2.1.43 (Opposite Category)**.** For any category $\mathcal{C}$, the *opposite* category $\mathcal{C}^{\mathrm{op}}$ is the category with

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

Proposition 2.1.44. *An object is initial in $\mathcal{C}$ iff it is terminal in $\mathcal{C}^{\mathrm{op}}$.*

Proof: Immediate from definitions. □

Proposition 2.1.45. *An object is terminal in $\mathcal{C}$ iff it is initial in $\mathcal{C}^{\mathrm{op}}$.*

Proof: Immediate from definitions. □

Corollary 2.1.45.1. *If T and T' are terminal objects in $\mathcal{C}$ then there exists a unique isomorphism $T \cong T'$.*

2.1.12 Groupoids

Definition 2.1.46 (Groupoid)**.** A *groupoid* is a category in which every morphism is an isomorphism.

2.1.13 Concrete Categories

Definition 2.1.47 (Concrete Category)**.** A *concrete category* $\mathcal{C}$ consists of:

- a set $\mathrm{Ob}(\mathcal{C})$ of *objects*
- for any object $A \in \mathrm{Ob}(\mathcal{C})$, a set $|A|$
- for any objects $A, B \in \mathrm{Ob}(\mathcal{C})$, 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 $\mathrm{id}_{|A|} \in \mathcal{C}[A, A]$.

2.1.14 Power of Categories

Definition 2.1.48. 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 $\{X_j\}_{j \in J} \to \{Y_j\}_{j \in J}$ all families $\{f_j\}_{j \in J}$ where $f_j : X_j \to Y_j$

2.1.15 Arrow Category

Definition 2.1.49 (Arrow Category)**.** Let $\mathcal{C}$ be a category. The *arrow category* $\mathcal{C}^{\to}$ is the category with:

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

2.1.16 Slice Category

Definition 2.1.50 (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 $f : A \to B$
- morphisms $(B, f) \to (C, g)$ are morphisms $u : B \to C$ such that $uf = g$.

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

Proposition 2.1.51. *If* $s : (B, f) \to (C, g)$ *in* $\mathcal{C}\backslash A$*, then any retraction of* s *in* $\mathcal{C}$ *is a retraction of* s *in* $\mathcal{C}\backslash A$*.*

Proof:
$\langle 1 \rangle 1$. Let: $r : C \to B$ be a retraction of s in $\mathcal{C}$.

$\langle 1 \rangle 2.$ $rg = f$
PROOF: $rg = rsf = f$.
$\langle 1 \rangle 3.$ $r : (C, g) \to (B, f)$ in $\mathcal{C} \backslash A$
$\langle 1 \rangle 4.$ $rs = \mathrm{id}_{(B,f)}$
PROOF: Because composition is inherited from $\mathcal{C}$.
$\square$

Proposition 2.1.52. id_A *is the initial object in* $\mathcal{C} \backslash A$.

PROOF: For any $(B, f) \in \mathcal{C} \backslash A$, we have f is the only morphism $A \to B$ such that $f \mathrm{id}_A = f$. $\square$

Proposition 2.1.53. *If A is terminal in $\mathcal{C}$ then* id_A *is the zero object in* $\mathcal{C} \backslash A$.

PROOF: For any $(B, f) \in \mathcal{C} \backslash A$, the unique morphism $! : B \to A$ is the unique morphism such that $!f = \mathrm{id}_A$. $\square$

Definition 2.1.54 (Pointed Sets)**.** The *category of pointed sets* is $\mathbf{Set} \backslash 1$.

Definition 2.1.55. 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 $f : B \to A$
- morphisms $u : (B, f) \to (C, g)$ all morphisms $u : B \to C$ such that $gu = f$.

Proposition 2.1.56. *Let* $u : (B, f) \to (C, g) : \mathcal{C}/A$. *Any section of u in $\mathcal{C}$ is a section of u in* $\mathcal{C}/A$.

PROOF: Dual to Proposition 2.1.51. $\square$

Proposition 2.1.57. id_A *is terminal in* $\mathcal{C}/A$.

PROOF: Dual to Proposition 2.1.52. $\square$

Proposition 2.1.58. *If A is initial in $\mathcal{C}$ then* id_A *is the zero object in* $\mathcal{C}/A$.

PROOF: Dual to Proposition 2.1.53. $\square$

Definition 2.1.59. 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 $u : A \to X$, $p : X \to A$ and $pu = \mathrm{id}_A$
- morphism $f : (X, u, p) \to (Y, v, q)$ all morphisms $f : X \to Y$ such that $fu = v$ and $qf = p$

Proposition 2.1.60. $(A, \mathrm{id}_A, \mathrm{id}_A)$ *is the zero object in* $\mathcal{C}_A^A$.

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

Definition 2.1.61 (Fibre Collapsing)**.** Let B be a set. Let $u : (A, a) \to (X, x)$ in $\mathbf{Set}/B$. Form the pushout

$$\begin{tikzcd}
A \arrow[r, "a"] \arrow[d, "u"] & B \arrow[d, "j"'] \\
X \arrow[r, "i"'] & C
\end{tikzcd}$$

Let $c : C \to B$ be the unique morphism such that $cj = \mathrm{id}_B$ 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 2.1.62 (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:

$$\begin{tikzcd}
B \arrow[r, "u_X"] \arrow[d, "u_Y"] & X \arrow[d] \\
Y \arrow[r] & X \vee_B Y
\end{tikzcd}$$

Definition 2.1.63 (Fibre Smash)**.** Let $X, Y \in \mathbf{Set}^B_B$. Let $\xi : X \vee_B Y \to X$ be the unique morphism such that the following diagram commutes.

$$\begin{tikzcd}
1 \arrow[r] \arrow[d] & X \arrow[d] \arrow[ddr, equal, bend left] & \\
Y \arrow[r] \arrow[drr, bend right, "0"'] & X \vee_B Y \arrow[dr, "\xi"] & \\
 & & X
\end{tikzcd}$$

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

$$\begin{tikzcd}
1 \arrow[r] \arrow[d] & X \arrow[d] \arrow[ddr, bend left, "0"] & \\
Y \arrow[r] \arrow[drr, equal, bend right] & X \vee_B Y \arrow[dr, "\eta"] & \\
 & & Y
\end{tikzcd}$$

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

Proposition 2.1.64. *A product in $\mathcal{C}$ constitutes a product in $\mathcal{C}\backslash A$.*

Proposition 2.1.65. *A coproduct in $\mathcal{C}$ constitutes a product in $\mathcal{C}/A$.*

2.2 Functors

Definition 2.2.1 (Functor)**.** Let $\mathcal{C}$ and $\mathcal{D}$ be categories. A *functor* $F : \mathcal{C} \to \mathcal{D}$ consists of:

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

such that:

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

Proposition 2.2.2. *Functors preserve isomorphisms.*

PROOF:
⟨1⟩1. LET: $F : \mathcal{C} \to \mathcal{D}$ be a functor.
⟨1⟩2. LET: $f : A \cong B$ in $\mathcal{C}$
⟨1⟩3. $Ff^{-1} \circ Ff = \mathrm{id}_{FA}$
PROOF:

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

⟨1⟩4. $Ff \circ Ff^{-1} = \mathrm{id}_{FB}$
PROOF:

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

□

Definition 2.2.3 (Identity Functor)**.** For any category $\mathcal{C}$, the *identity* functor on $\mathcal{C}$ is the functor $I_{\mathcal{C}} : \mathcal{C} \to \mathcal{C}$ defined by

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

Proposition 2.2.4. *Let $F : \mathcal{C} \to \mathcal{D}$. If $r : A \to B$ is a retraction of $s : B \to A$ in $\mathcal{C}$ then Fr is a retraction of Fs.*

PROOF:

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

□

Corollary 2.2.4.1. *Let $F : \mathcal{C} \to \mathcal{D}$. 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 2.2.5 (Composition of Functors)**.** Given functors $F : \mathcal{C} \to \mathcal{D}$ and $G : \mathcal{D} \to \mathcal{E}$, the *composite* functor $GF : \mathcal{C} \to \mathcal{E}$ is defined by

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

Definition 2.2.6 (Category of Categories)**.** Let **Cat** be the category of small categories and functors.

Definition 2.2.7 (Isomorphism of Categories)**.** Let $F : \mathcal{C} \to \mathcal{D}$ be a functor. Then F is an *isomorphism of categories* iff there exists a functor $F^{-1} : \mathcal{D} \to \mathcal{C}$, 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 2.2.8. *If A is initial in $\mathcal{C}$ then $\mathcal{C}\backslash A \cong \mathcal{C}$.*

Proof:
⟨1⟩1. Define $F : \mathcal{C}\backslash A \to \mathcal{C}$ by

$$\begin{aligned} F(B, f) &= B \\ F(u : (B, f) \to (C, g)) &= u \end{aligned}$$

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

$$GB = (B, !_B) \qquad \text{where } !_B \text{ is the unique morphism } A \to B$$

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

⟨1⟩3. $FG = \mathrm{id}_{\mathcal{C}}$
⟨1⟩4. $GF = \mathrm{id}_{\mathcal{C}\backslash A}$
Proof: Since $GF(B, f) = (B, !_B) = (B, f)$ because the morphism $A \to B$ is unique.
□

Proposition 2.2.9. *If A is terminal in $\mathcal{C}$ then $\mathcal{C}/A \cong \mathcal{C}$.*

Proof: Dual. □

Proposition 2.2.10.

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

Proof:
⟨1⟩1. Define a functor $F : \mathcal{C}^A_A \to (\mathcal{C}/A)\backslash(A, \mathrm{id}_A)$.
⟨2⟩1. Given $A \xrightarrow{u} X \xrightarrow{p} A$ in $\mathcal{C}^A_A$, let $F(X, u, p) = ((X, p), u)$
⟨2⟩2. Given $f : (A \xrightarrow{u} X \xrightarrow{p} A) \to (A \xrightarrow{v} Y \xrightarrow{q} A)$, let $Ff = f$.
⟨1⟩2. Define a functor $G : (\mathcal{C}/A)\backslash(A, \mathrm{id}_A) \to \mathcal{C}^A_A$.
⟨1⟩3. Define a functor $H : \mathcal{C}^A_A \to (\mathcal{C}\backslash A)/(A, \mathrm{id}_A)$.
⟨1⟩4. Define a functor $K : (\mathcal{C}\backslash A)/(A, \mathrm{id}_A) \to \mathcal{C}^A_A$.
□

Definition 2.2.11 (Forgetful Functor)**.** For any concrete category $\mathcal{C}$, define the *forgetful* functor $U : \mathcal{C} \to \mathbf{Set}$ by:

$$\begin{aligned} UA &= |A| \\ Uf &= f \end{aligned}$$

Definition 2.2.12 (Switching Functor)**.** For any category $\mathcal{C}$, define the *switching functor* $T : \mathcal{C} \times \mathcal{C} \to \mathcal{C} \times \mathcal{C}$ by

$$\begin{aligned} T(A, B) &= (B, A) \\ T(f, g) &= (g, f) \end{aligned}$$

Definition 2.2.13 (Reduction)**.** Let $\Phi : \mathbf{Set} \to \mathbf{Set}$ be a functor. The *reduction* of Φ is the functor $\Phi^* : \mathbf{Set}_* \to \mathbf{Set}_*$ defined by: $\Phi^*(X, a)$ is the collapse of $\Phi(X)$ with respect to $\Phi(a) : \Phi(1) \rightarrowtail \Phi(X)$.

Definition 2.2.14. Extend the wedge $\vee$ to a functor $\mathbf{Set}_* \times \mathbf{Set}_* \to \mathbf{Set}_*$ by defining, given $f : X \to X'$ and $g : Y \to Y'$, thene $f \vee g$ is the unique morphism that makes the following diagram commute.

$$\begin{tikzcd}
1 \arrow[r] \arrow[d] & X \arrow[d] \arrow[dr, "f"] & \\
Y \arrow[r] \arrow[dr, "g"'] & X \vee Y \arrow[dr, "f \vee g"] & X' \arrow[d] \\
& Y' \arrow[r] & X' \vee Y'
\end{tikzcd}$$

Definition 2.2.15. Extend smash to a functor $\wedge : \mathbf{Set}_* \times \mathbf{Set}_* \to \mathbf{Set}_*$ as follows. Given $f : X \to X'$ and $g : Y \to Y'$, let $f \wedge g : X \wedge Y \to X' \wedge Y'$ be the unique morphism such that the following diagram commutes.

$$\begin{tikzcd}
X \vee Y \arrow[r] \arrow[d] \arrow[ddr] & 1 \arrow[d] \arrow[ddr, equal] & \\
X \times Y \arrow[r] \arrow[ddr, "f \times g"'] & X \wedge Y \arrow[ddr] & \\
& X' \vee Y' \arrow[r] \arrow[d] & 1 \arrow[d] \\
& X' \times Y' \arrow[r] & X' \wedge Y'
\end{tikzcd}$$

Definition 2.2.16 (Reduction)**.** Let B be a small set. Let $\Phi_B : \mathbf{Set}/B \to \mathbf{Set}/B$ be a functor. The *reduction* of Φ_B is the functor $\Phi_B^B : \mathbf{Set}_B^B \to \mathbf{Set}_B^B$ defined as follows.

For $(X, u : B \to X, p : X \to B) \in \mathbf{Set}_B^B$, let $\Phi_B^B(X)$ be the set over and under B obtained from $\Phi_B(X)$ by collapsing with respect to $\Phi_B(u) : \Phi_B(B) \to \Phi_B(X)$.

Definition 2.2.17. Extend $\vee_B$ to a functor $\mathbf{Set}_B^B \times \mathbf{Set}_B^B \to \mathbf{Set}_B^B$.

Definition 2.2.18. Extend $\wedge_B$ to a functor $\mathbf{Set}_B^B \times \mathbf{Set}_B^B \to \mathbf{Set}_B^B$.

Definition 2.2.19 (Faithful)**.** A functor $F : \mathcal{C} \to \mathcal{D}$ is *faithful* iff, for any objects $A, B \in \mathcal{C}$ and morphisms $f, g : A \to B : \mathcal{C}$, if $Ff = Fg$ then $f = g$.

Definition 2.2.20 (Full)**.** A functor $F : \mathcal{C} \to \mathcal{D}$ is *full* iff, for any objects $A, B \in \mathcal{C}$ and morphism $g : FA \to FB : \mathcal{D}$, there exists $f : A \to B : \mathcal{C}$ such that $Ff = g$.

Definition 2.2.21 (Fully Faithful)**.** A functor $F : \mathcal{C} \to \mathcal{D}$ is *fully faithful* iff it is full and faithful.

Definition 2.2.22 (Full Embedding)**.** A functor $F : \mathcal{C} \to \mathcal{D}$ is a *full embedding* iff it is fully faithful and injective on objects.

2.3 Natural Transformations

Definition 2.3.1 (Natural Transformation)**.** Let $F, G : \mathcal{C} \to \mathcal{D}$. A *natural transformation* $\tau : F \Rightarrow G$ is a family of morphisms $\{\tau_X : FX \to GX\}_{X \in \mathcal{C}}$ such that, for every morphism $f : X \to Y : \mathcal{C}$, we have $Gf \circ \tau_X = \tau_Y \circ Ff$.

$$\begin{tikzcd}
FX \arrow[r, "Ff"] \arrow[d, "\tau_X"'] & FY \arrow[d, "\tau_Y"] \\
GX \arrow[r, "Gf"'] & GY
\end{tikzcd}$$

Definition 2.3.2 (Natural Isomorphism)**.** A natural transformation $\tau : F \Rightarrow G : \mathcal{C} \to \mathcal{D}$ 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 2.3.3 (Inverse)**.** Let $\tau : F \cong G$. The *inverse* natural isomorphism $\tau^{-1} : G \cong F$ is defined by $(\tau^{-1})_X = {\tau_X}^{-1}$.

2.4 Bifunctors

Definition 2.4.1 (Commutative)**.** A bifunctor $\square : \mathcal{C}^2 \to \mathcal{C}$ is *commutative* iff $\square \cong \square \circ T$, where $T : \mathcal{C}^2 \to \mathcal{C}^2$ is the swap functor.

Proposition 2.4.2. $\vee : \mathbf{Set}_* \times \mathbf{Set}_* \to \mathbf{Set}_*$ *is commutative.*

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

Proposition 2.4.3. $\wedge : \mathbf{Set}_* \times \mathbf{Set}_* \to \mathbf{Set}_*$ *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. □

Proposition 2.4.4. $\vee_B : \mathbf{Set}_B^B \times \mathbf{Set}_B^B \to \mathbf{Set}_B^B$ *is commutative.*

Proposition 2.4.5. $\wedge_B : \mathbf{Set}_B^B \times \mathbf{Set}_B^B \to \mathbf{Set}_B^B$ *is commutative.*

Definition 2.4.6 (Associative)**.** A bifunctor $\Box$ is *associative* iff $\Box \circ (\Box \times \mathrm{id}) \cong \Box \circ (\mathrm{id} \times \Box)$.

Proposition 2.4.7. $\vee : \mathbf{Set}_* \times \mathbf{Set}_* \to \mathbf{Set}_*$ *is associative.*

Proof: Since $X \vee (Y \vee Z)$ and $(X \vee Y) \vee Z$ are both the pushout of the unique morphisms $1 \to X$, $1 \to Y$ and $1 \to Z$. □

Proposition 2.4.8. $\wedge : \mathbf{Set}_* \times \mathbf{Set}_* \to \mathbf{Set}_*$ *is associative.*

Proof: Draw isomorphisms between the diagrams for $X \wedge (Y \wedge Z)$ and $(X \wedge Y) \wedge Z$. □

Product and coproduct are commutative and associative.

Proposition 2.4.9. $\vee_B : \mathbf{Set}_B^B \times \mathbf{Set}_B^B \to \mathbf{Set}_B^B$ *is associative.*

Proposition 2.4.10. $\wedge_B : \mathbf{Set}_B^B \times \mathbf{Set}_B^B \to \mathbf{Set}_B^B$ *is associative.*

Proposition 2.4.11. *Let $\mathcal{C}$ be a category with binary coproducts. Let $\Box : \mathcal{C} \times \mathcal{C} \to \mathcal{C}$ be a bifunctor. Then $\Box$* distributes *over $+$ iff the canonical morphism*

$$(X \Box Z) + (Y \Box Z) \to (X + Y) \Box Z$$

is an isomorphism for all X, Y, Z.

Proposition 2.4.12. *In a category with binary products and binary coproducts, then $\times$ distributes over $+$.*

Proposition 2.4.13. *In $\mathbf{Set}/*$, we have $\times$ does not distribute over $\vee$.*

Proposition 2.4.14. *In $\mathbf{Set}/*$, we have $\wedge$ distributes over $\vee$.*

Proposition 2.4.15. *In $\mathbf{Set}/B$, we have $\times_B$ distributes over $+_B$.*

Proposition 2.4.16. *In $\mathbf{Set}/B^B$, we have $\wedge_B$ distributes over $\vee_B$.*

2.5 Functor Categories

Definition 2.5.1 (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 2.5.2 (Yoneda Embedding)**.** Let $\mathcal{C}$ be a category. The *Yoneda embedding* $Y : \mathcal{C} \to \mathbf{Set}^{\mathcal{C}^{\mathrm{op}}}$ is the functor that maps an object A to $\mathcal{C}[-, A]$ and morphisms similarly.

Theorem 2.5.3 (Yoneda Lemma)**.** *Let $\mathcal{C}$ be a category. There exists a natural isomorphism*

$$\phi_{XF} : \mathbf{Set}^{\mathcal{C}^{\mathrm{op}}}[\mathcal{C}[-,X],F] \cong FX$$

that maps $\tau : \mathcal{C}[-,X] \Rightarrow F$ to $\tau_X(\mathrm{id}_X)$.

PROOF:
⟨1⟩1. ϕ is natural in X.
  PROOF:
  ⟨2⟩1. LET: $f : X \to Y : \mathcal{C}$
  ⟨2⟩2. LET: $\tau : \mathcal{C}[-,X] \Rightarrow F$
  ⟨2⟩3. $Ff(\phi(\tau)) = \phi(\tau \circ \mathcal{C}[-,f])$
    PROOF:

$$\begin{aligned}
\phi(\tau \circ \mathcal{C}[-,f]) &= \tau_Y(\mathrm{id}_Y \circ f) \\
&= \tau_Y(f) \\
&= \tau_Y(f \circ \mathrm{id}_X) \\
&= Ff(\tau_X(\mathrm{id}_X)) && (\tau \text{ natural}) \\
&= Ff(\phi(\tau))
\end{aligned}$$

⟨1⟩2. ϕ is natural in F.
  ⟨2⟩1. LET: $\alpha : F \Rightarrow G : \mathcal{C}^{\mathrm{op}} \to \mathbf{Set}$
  ⟨2⟩2. LET: $\tau : \mathcal{C}[-,X] \Rightarrow F$
  ⟨2⟩3. $\alpha_X(\phi(\tau)) = \phi(\alpha \bullet \tau)$
    PROOF: $\phi(\alpha \bullet \tau) = \alpha_X(\tau_X(\mathrm{id}_X)) = \alpha_X(\phi(\tau))$
⟨1⟩3. Each ϕ_{XF} is injective.
  ⟨2⟩1. LET: $\sigma, \tau : \mathcal{C}[-,X] \Rightarrow F$
  ⟨2⟩2. ASSUME: $\phi(\sigma) = \phi(\tau)$
  ⟨2⟩3. LET: $f : Y \to X$
  ⟨2⟩4. $\sigma_Y(f) = \tau_Y(f)$
    PROOF:

$$\begin{aligned}
\sigma_Y(f) &= \sigma_Y(\mathrm{id}_X \circ f) \\
&= Ff(\sigma_X(\mathrm{id}_X)) && (\sigma \text{ is natural}) \\
&= Ff(\tau_X(\mathrm{id}_X)) && (\langle 2\rangle 2) \\
&= \tau_Y(\mathrm{id}_X \circ f) && (\tau \text{ is natural}) \\
&= \tau_Y(f)
\end{aligned}$$

⟨1⟩4. Each ϕ_{XF} is surjective.
  ⟨2⟩1. LET: $X \in \mathcal{C}$ and $F : \mathcal{C} \to \mathcal{D}$
  ⟨2⟩2. LET: $a \in FX$
  ⟨2⟩3. LET: $\tau : \mathcal{C}[-,X] \Rightarrow F$ be given by $\tau_Y(g) = Fg(a)$ for $g : Y \to X$
  ⟨2⟩4. τ is natural.
    ⟨3⟩1. LET: $h : Y \to Z : \mathcal{C}$
      PROVE: $Fh \circ \tau_Z = \tau_Y \circ \mathcal{C}[h, \mathrm{id}_X]$
    ⟨3⟩2. LET: $g : Z \to X$
    ⟨3⟩3. $Fh(\tau_Z(g)) = \tau_Y(g \circ h)$

PROOF:

$$\begin{aligned}\tau_Y(g \circ h) &= F(g \circ h)(a) \\ &= Fh(Fg(a)) \\ &= Fh(\tau_Z(g))\end{aligned}$$

⟨2⟩5. $\phi(\tau) = a$

PROOF:

$$\begin{aligned}\phi_X(\tau) &= \tau_X(\mathrm{id}_X) \\ &= F\mathrm{id}_X(a) \\ &= a\end{aligned}$$

□

Chapter 3

Monoid Theory

Definition 3.0.1 (Monoid)**.** A *monoid* is a category with one object.

Definition 3.0.2. Let $\mathcal{C}$ be a category and $X \in \mathcal{C}$. The monoid $\mathrm{End}_{\mathcal{C}}(X)$ is the set of all morphisms $X \to X$ under composition.

Proposition 3.0.3. *For any functor $F : \mathcal{C} \to \mathcal{D}$ and $X \in \mathcal{C}$, we have that $F : \mathrm{End}_{\mathcal{C}}(X) \to \mathrm{End}_{\mathcal{D}}(FX)$ is a monoid homomorphism.*

PROOF: Since $F\mathrm{id}_X = \mathrm{id}_{FX}$ and $F(g \circ f) = Fg \circ Ff$. □

Chapter 4

Group Theory

Definition 4.0.1. Let **Grp** be the category of small groups and group homomorphisms.

Definition 4.0.2. 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 4.0.3. *The trivial group is a zero object in* **Grp**.

PROOF: Easy. $\square$

The zero morphism $G \to H$ maps every element in G to e.

Definition 4.0.4. Let $\mathcal{C}$ be a category and $X \in \mathcal{C}$. We write $\mathrm{Aut}_{\mathcal{C}}(X)$ for the set of all isomorphisms $X \cong X$ under composition.

Proposition 4.0.5. *Let $F : \mathcal{C} \to \mathcal{D}$ be a functor and $X \in \mathcal{C}$. Then $F : \mathrm{Aut}_{\mathcal{C}}(X) \to \mathrm{Aut}_{\mathcal{D}}(FX)$ is a group homomorphism.*

PROOF: Since $F\mathrm{id}_X = \mathrm{id}_{FX}$, $F(g \circ f) = Fg \circ Ff$, and $Ff^{-1} = (Ff)^{-1}$. $\square$

Chapter 5

Ring Theory

Definition 5.0.1. Let **Ring** be the concrete category of rings and ring homomorphisms.

Definition 5.0.2. For any ring R, let $R - \mathbf{Mod}$ be the category of small R-modules and R-module homomorphisms.

Chapter 6

Linear Algebra

Definition 6.0.1. For any field K, let $\mathbf{Vect}_K$ be the concrete category of small vector spaces over K and linear transformations.

Dual space functor $\mathbf{Vect}_K^{\mathrm{op}} \to \mathbf{Vect}_K$.

Chapter 7

Topology

7.1 Topological Spaces

Definition 7.1.1 (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 toplogical space, and call its elements *open* sets. We shall often write X for the topological space $(X, \mathcal{O})$.

Definition 7.1.2 (Discrete Topology)**.** For any set X, the power set $\mathcal{P}X$ is called the *discrete* topology on X.

Proposition 7.1.3. *For any set X, the discrete topology on X is a topology on X.*

Definition 7.1.4 (Indiscrete Topology)**.** For any set X, the *indiscrete* or *trivial* topology on X is $\{\emptyset, X\}$.

Proposition 7.1.5. *For any set X, the indiscrete topology on X is a topology on X.*

Definition 7.1.6 (Closed Set)**.** Let X be a topological space and $A \subseteq X$. Then A is *closed* iff $X - A$ is open.

Proposition 7.1.7. *A set B is open if and only if $X - B$ is closed.*

Proposition 7.1.8. *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 $C \cup D \in \mathcal{C}$.*
- $\varnothing \in \mathcal{C}$

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

Definition 7.1.9 (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 7.1.10. *A set B is open if and only if it is a neighbourhood of each of its points.*

Proposition 7.1.11. *Let X be a set and $\mathcal{N} : X \to \mathcal{P}X$. 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 7.1.12 (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 7.1.13 (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 7.1.14 (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 7.1.15. *The interior of B is the union of all the open sets included in B.*

Definition 7.1.16 (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 7.1.17. *The closure of B is the intersection of all the closed sets that include B.*

Proposition 7.1.18. *A set B is open iff $X - B = \overline{X - B}$.*

Proposition 7.1.19 (Kuratowski Closure Axioms)**.** *Let X be a set and $\overline{} : \mathcal{P}X \to \mathcal{P}X$. 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:*

- $\overline{\varnothing} = \varnothing$
- *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 7.1.20 (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 *weaker* than $\mathcal{T}$, iff $\mathcal{T} \subseteq \mathcal{T}'$.

7.1.1 Subspaces

Definition 7.1.21 (Subspace)**.** Let X be a topological space and $X_0 \subseteq X$. The *subspace topology* on X_0 is $\{U \cap X_0 : U \text{ is open in } X\}$.

Example 7.1.22. The *unit sphere* S^2 is $\{x \in \mathbb{R}^3 : \|x\| = 1\}$ as a subspace of $\mathbb{R}^3$.

7.1.2 Topological Disjoint Union

Definition 7.1.23. Let X and Y be topological spaces. The *disjoint union* is $X + Y$ where $U \subseteq X + Y$ is open if and only if ${\kappa_1}^{-1}(U)$ is open in X and ${\kappa_2}^{-1}(U)$ is open in Y.

7.1.3 Product Topology

Definition 7.1.24 (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.

7.1.4 Bases

Definition 7.1.25 (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 7.1.26. *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* $\mathcal{B}$.

7.1.5 Subbases

Definition 7.1.27 (Subbasis)**.** Let X be a topological space. A *subbasis* for the topology on X is a subset $\mathcal{S} \subseteq \mathcal{P}X$ such that every open set is a union of finite intersections of $\mathcal{S}$.

Definition 7.1.28 (Space with Basepoint)**.** A *space with basepoint* is a pair (X, x) where X is a topological space and $x : \mathrm{El}\,(X)$.

7.1.6 Countability Axioms

Definition 7.1.29 (Neighbourhood Basis)**.** Let X be a topological space and $x_0 : \mathrm{El}\,(X)$. 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 7.1.30 (First Countable)**.** A topological space is *first countable* iff every point has a countable neighbourhood basis.

Definition 7.1.31 (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 7.1.32. *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 $\lambda : \mathrm{El}\,(\Lambda)$, PICK U_λ open in X_λ such that $\emptyset \neq U_\lambda \neq X_\lambda$.
⟨1⟩2. For all $\lambda : \mathrm{El}\,(\lambda)$, 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.
□

7.2 Continuous Functions

Definition 7.2.1 (Continuous)**.** Let X and Y be topological spaces. A function $f : X \to Y$ is *continuous* iff, for every open set V in Y, the inverse image $f^{-1}(V)$ is open in X.

Proposition 7.2.2. *1.* id_X *is continuous*

2. *The composite of two continuous functions is continuous.*

3. *If* $f : X \to Y$ *is continuous and* $X_0 \subseteq X$ *then* $f \restriction X_0 : X_0 \to Y$ *is continuous.*

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

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

Definition 7.2.3 (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 7.2.4 (Retraction)**.** Let X be a topological space and A a subspace of X. A continuous function $\rho : X \to A$ is a *retraction* iff $\rho \restriction A = \mathrm{id}_A$. We say A is a *retract* of X iff there exists a retraction.

Definition 7.2.5. Let **Top** be the category of small topological spaces and continuous functions.

Forgetful functor **Top** $\to$ **Set**.
Basepoint preserving continuous functor.

7.3 Convergence

Definition 7.3.1 (Convergence)**.** Let X be a topological space. Let (x_n) be a sequence in X. A point $a : \mathrm{El}\,(X)$ is a *limit* of the sequence iff, for every neighbourhood U of a, there exists n_0 such that $\forall n \geqslant n_0 . x_n \in U$.

Convergence in a product space is pointwise convergence.
If $f : X \to Y$ is continuous and $x_n \to l$ in X then $f(x_n) \to f(l)$ in Y.

Example 7.3.2. The converse does not hold.

Let X be the set of all continuous functions $[0, 1] \to [-1, 1]$ under the product topology. Let $i : X \to L^2([0, 1])$ be the inclusion.

If $f_n \to f$ then $i(f_n) \to i(f)$ — 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 $\forall \phi \in K_\epsilon . \int \phi^2 < 1/2$. Let $K = \prod_{\lambda \in [0,1]} U_\lambda$ where $U_\lambda = [-1, 1]$ except for $\lambda = \lambda_1, \ldots, \lambda_n$. Let ϕ be the function that is 0 at $\lambda_1, \ldots, \lambda_n$ and 1 everywhere else. Then $\phi \in K$ but $\int \phi^2 = 1$.

Proposition 7.3.3. *The converse does hold for first countable spaces. If* $f : X \to Y$ *where* X *is first countable, and* Y *is a topological space, and whenever* $x_n \to x$ *then* $f(x_n) \to f(x)$*, then* f *is continuous.*

7.4 Connected Spaces

Definition 7.4.1 (Connected)**.** A topological space is *connected* iff it is not the union of two nonempty open disjoint subsets.

Proposition 7.4.2. *The continuous image of a connected space is connected.*

Proposition 7.4.3. *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 7.4.4. *If X and Y are nonempty topological spaces, then $X \times Y$ is connected if and only if X and Y are connected.*

Definition 7.4.5 (Path-connected)**.** A topological space X is *path-connected* iff, for any points $a, b \in X$, there exists a continuous function $\alpha : [0, 1] \to X$, called a *path*, such that $\alpha(0) = a$ and $\alpha(1) = b$.

Proposition 7.4.6. *The continuous image of a path connected space is path connected.*

Proposition 7.4.7. *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 7.4.8. *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.*

7.5 Hausdorff Spaces

Definition 7.5.1 (Hausdorff)**.** A topological space is a *Hausdorff* space or a T_2 space iff any two distinct points have disjoint neighbourhoods.

Proposition 7.5.2. *In a Hausdorff space, a sequence has at most one limit.*

Proposition 7.5.3.

1. *Every subspace of a Hausdorff space is Hausdorff.*
2. *The disjoint union of two Hausdorff spaces is Hausdorff.*
3. *The product of two Hausdorff spaces is Hausdorff.*

Proposition 7.5.4. *Let A be a topological space and B a Hausdorff space. Let $f, g : A \to B$ 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 7.5.5. *Let X and Y be metric spaces. Let $f : X \to Y$ be uniformly continuous. Let $\hat{X}$ and $\hat{Y}$ be the completions of X and Y. Then f extends uniquely to a continuous map $\hat{X} \to \hat{Y}$.*

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

7.6 Separable Spaces

Definition 7.6.1 (Separable)**.** A topological space is *separable* iff it has a countable dense subset.

Every second countable space is separable.

7.7 Sequential Compactness

Definition 7.7.1 (Sequentially Compact)**.** A topological space is *sequentially compact* iff every sequence has a convergent subsequence.

7.8 Compactness

Definition 7.8.1 (Compact)**.** A topological space is *compact* iff every open cover has a finite subcover.

Proposition 7.8.2. *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 $U_1, \ldots, U_n \in P$
$\langle 1\rangle 3.$ $X = U_1 \cup \cdots \cup U_n \in P$
∎

Corollary 7.8.2.1. *Let f be a compact space and $f : X \to \mathbb{R}$ be locally bounded. Then f is bounded.*

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

Proposition 7.8.3. *The continuous image of a compact space is compact.*

Proposition 7.8.4. *A closed subspace of a compact space is compact.*

Proposition 7.8.5. *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 7.8.6. *A compact subspace of a Hausdorff space is closed.*

Proposition 7.8.7. *A continuous bijection from a compact space to a Hausdorff space is a homeomorphism.*

Proposition 7.8.8. *A first countable compact space is sequentially compact.*

7.9 Quotient Spaces

Definition 7.9.1 (Quotient Space)**.** Let X be a topological space and $\sim$ an equivalence relation on X. The *quotient topology* on $X/\sim$ is defined by: $U : \mathrm{El}\,(\mathcal{P}X)$ is open in $X/\sim$ if and only if $\pi^{-1}(U)$ is open in X.

Proposition 7.9.2. *Let X and Y be topological spaces. Let $\sim$ be an equivalence relation on X. Let $f : X/\sim \to Y$. Then f is continuous if and only if $f \circ \pi$ is continuous.*

Proposition 7.9.3. *Let X and Y be topological spaces. Let $\sim$ be an equivalence relation on X. Let $\phi : Y \to X/\sim$.*

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

Proposition 7.9.4. *A quotient of a connected space is connected.*

Proposition 7.9.5. *A quotient of a path connected space is path connected.*

Proposition 7.9.6. *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 7.9.7. Let X be a topological space and $A_1, \ldots, A_r \subseteq X$. Then $X/A_1, \ldots, A_r$ 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 7.9.8 (Cone)**.** Let X be a topological space. The *cone over* X is the space $(X \times [0,1])/(X \times \{1\})$.

Definition 7.9.9 (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 7.9.10 (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 7.9.11 (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 7.9.12. $D^n/S^{n-1} \cong S^n$

PROOF:
⟨1⟩1. LET: $\phi : D^n/S^{n-1} \to S^n$ be the function induced by the map $D^n \to S^n$ that maps the radii of D^n onto the meridians of S^n from the north to the south pole.
⟨1⟩2. ϕ is a bijection.
⟨1⟩3. ϕ is a homeomorphism.
PROOF: Since D^n/S^{n-1} is compact and S^n is Hausdorff.
□

7.10 Gluing

Definition 7.10.1 (Gluing)**.** Let X and Y be topological spaces, $X_0 \subseteq X$ and $\phi : X_0 \to Y$ 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 $x : \mathrm{El}\,(X)$.

Proposition 7.10.2. *Y is a subspace of $Y \cup_\phi X$.*

Definition 7.10.3. 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 $x : \mathrm{El}\,(X)$.

Definition 7.10.4 (Möbius Strip)**.** The *Möbius strip* is $([-1,1] \times [0,1])/\alpha$ where $\alpha(x) = -x$.

Definition 7.10.5 (Klein Bottle)**.** The *Klein bottle* is $(S^1 \times [0,1])/\alpha$ where $\alpha(z) = \overline{z}$.

Proposition 7.10.6. *Let M be the Möbius strip and K the Klein bottle. Then $M \cup_{\mathrm{id}_{\partial M}} M \cong K$.*

PROOF:
⟨1⟩1. LET: $f : ([-1,1] \times [0,1]) + ([-1,1] \times [0,1]) \to S^1 \times [0,1]$ be the function that maps $\kappa_1(\theta, t)$ to $(e^{\pi i\theta/2}, t)$ and $\kappa_2(\theta, t)$ to $(-e^{-\pi i\theta/2}, t)$.
⟨1⟩2. f induces a bijection $M \cup_{\mathrm{id}_{\partial M}} M \approx K$
⟨1⟩3. f is a homeomorphism.
□

7.11 Metric Spaces

Definition 7.11.1 (Metric Space)**.** Let X be a set and $d : X^2 \to \mathbb{R}$. We say (X, d) is a *metric space* iff:

- For all $x, y \in X$ we have $d(x, y) \geqslant 0$
- 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 $d(x, z) \leqslant d(x, y) + d(y, z)$

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

Definition 7.11.2 (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 7.11.3 (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 7.11.4 (Metrizable)**.** A topological space is *metrizable* iff there exists a metric that induces its topology.

Proposition 7.11.5. *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.

7.12 Complete Metric Spaces

Definition 7.12.1 (Complete)**.** A metric space is *complete* iff every Cauchy sequence converges.

Example 7.12.2. $\mathbb{R}$ is complete.

Proposition 7.12.3. *The product of two complete metric spaces is complete.*

Proposition 7.12.4. *Every compact metric space is complete.*

Proposition 7.12.5. *Let X be a complete metric space and $A \subseteq X$. Then A is complete if and only if A is closed.*

Definition 7.12.6 (Completion)**.** Let X be a metric space. A *completion* of X is a complete metric space $\hat{X}$ and injection $i : X \rightarrowtail \hat{X}$ such that:

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

Proposition 7.12.7. *Let $i_1 : X \to Y_1$ and $i_2 : X \to Y_2$ 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 $\phi(\lim_{n\to\infty} i_1(x_n)) = \lim_{n\to\infty} i_2(x_n)$. $\square$

Theorem 7.12.8. *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 $d(x_n, y_n) \to 0$. $\square$

7.13 Manifolds

Definition 7.13.1 (Manifold)**.** An *n-dimensional manifold* is a second countable Hausdorff space locally homeomorphic to $\mathbb{R}^n$.

Chapter 8

Homotopy Theory

8.1 Homotopies

Definition 8.1.1 (Homotopy)**.** Let X and Y be topological spaces. Let $f, g : X \to Y$ be continuous. A *homotopy* between f and g is a continuous function $h : X \times [0, 1] \to Y$ such that

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

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

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

Proposition 8.1.2. *Let $f, f' : X \to Y$ and $g, g' : Y \to Z$ be continuous. If $f \simeq f'$ and $g \simeq g'$ then $g \circ f \simeq g' \circ f'$.*

Definition 8.1.3. Let **HTop** be the category whose objects are the small topological spaces and whose morphisms are the homotopy classes of continuous functions.

Definition 8.1.4. A functor $F : \mathbf{Top} \to \mathcal{C}$ is *homotopy invariant* iff, for any topological spaces X, Y and continuous functions $f, g : X \to Y$, if $f \simeq g$ then $Hf = Hg$.

Basepoint-preserving homotopy.

8.2 Homotopy Equivalence

Definition 8.2.1 (Homotopy Equivalence)**.** Let X and Y be topological spaces. A *homotopy equivalence* between X and Y, $f : X \simeq Y$, is a continuous function $f : X \to Y$ such that there exists a continuous function $g : Y \to X$, the *homotopy inverse* to f, such that $g \circ f \simeq \mathrm{id}_X$ and $f \circ g \simeq \mathrm{id}_Y$.

Definition 8.2.2 (Contractible)**.** A topological space X is *contractible* iff $X \simeq 1$.

Example 8.2.3. $\mathbb{R}^n$ is contractible.

Example 8.2.4. D^n is contractible.

Definition 8.2.5 (Deformation Retract)**.** Let X be a topological space and A a subspace of X. A retraction $\rho : X \to A$ is a *deformation retraction* iff $i \circ \rho \simeq \mathrm{id}_X$, where i is the inclusion $A \rightarrowtail X$. We say A is a *deformation retract* of X iff there exists a deformation retraction.

Definition 8.2.6 (Strong Deformation Retract)**.** Let X be a topological space and A a subspace of X. A *strong deformation retraction* $\rho : X \to A$ is a continuous function such that there exists a homotopy $h : X \times [0,1] \to X$ between $i \circ \rho$ and id_X such that, for all $a : \mathrm{El}(X)$ and $t : \mathrm{El}([0,1])$, we have $h(a,t) = a$.

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

Example 8.2.7. $\{0\}$ is a strong deformation retract of $\mathbb{R}^n$ and of D^n.

Example 8.2.8. S^1 is a strong deformation retract of the torus $S^1 \times D^2$.

Example 8.2.9. S^{n-1} is a strong deformation retract of $D^n - \{0\}$.

Example 8.2.10. For any topological space X, the singleton consisting of the vertex is a strong deformation retract of the cone over X.

Chapter 9

Simplicial Complexes

Definition 9.0.1 (Simplex)**.** A *k-dimensional simplex* or *k-simplex* in $\mathbb{R}^n$ is the convex hull $s(x_0, \ldots, x_k)$ of $k+1$ points in general position.

Definition 9.0.2 (Face)**.** A *sub-simplex* or *face* of $s(x_0, \ldots, x_k)$ is the convex hull of a subset of $\{x_0, \ldots, x_k\}$.

Definition 9.0.3 (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 $\mathbb{R}^n$.

9.1 Cell Decompositions

Definition 9.1.1 (n-cell)**.** An *n-cell* is a topological space homeomorphic to $\mathbb{R}^n$.

Definition 9.1.2 (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 9.1.3 (n-skeleton)**.** Given a cell decomposition of X, the *n-skeleton* X^n is the union of all the cells of dimension $\leqslant n$.

9.2 CW-complexes

Definition 9.2.1 (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 $\Phi_e : D^n \to X$ such that $\Phi((D^n)^\circ) = e$, 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 $\overline{e}$ intersects only finitely many other cells in $\mathcal{E}$.

3. *Weak Topology* Given $A \subseteq X$, we have A is closed iff for all $e \in \mathcal{E}$, $A \cap \overline{e}$ is closed.

Proposition 9.2.2. *If a cell decomposition $\mathcal{E}$ satisfies the Characteristic Maps axiom, then for every n-cell $e \in \mathcal{E}$ we have $\overline{e} = \Phi_e(D^n)$. Therefore $\overline{e}$ is compact and $\overline{e} - e = \Phi_e(S^{n-1}) \subseteq X^{n-1}$.*

PROOF:
⟨1⟩1. $e \subseteq \Phi_e(D^n) \subseteq \overline{e}$
PROOF:

$$\begin{aligned} e &= \Phi_e((D^n)^\circ) \\ &\subseteq \Phi_e(D^n) \\ &= \Phi_e(\overline{(D^n)^\circ}) \\ &\subseteq \overline{\Phi_e((D^n)^\circ)} \\ &= \overline{e} \end{aligned}$$

⟨1⟩2. $\Phi_e(D^n)$ is compact.
PROOF: Because D^n is compact.
⟨1⟩3. $\Phi_e(D^n)$ is closed.
⟨1⟩4. $\Phi_e(D^n) = \overline{e}$
□

Chapter 10

Topological Groups

Definition 10.0.1 (Topological Group)**.** A *topological group* is a group G with a topology such that the function $G^2 \to G$ that maps (x, y) to xy^{-1} is continuous.

Example 10.0.2. $GL(n, \mathbb{R})$ and $GL(n, \mathbb{C})$ are topological groups.

Proposition 10.0.3. *Any subgroup of a topological group is a topological group under the subspace topology.*

Definition 10.0.4 (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 10.0.5. *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 □

10.1 Continuous Actions

Definition 10.1.1 (Continuous Action)**.** Let G be a topological group and X a topological space. A *continuous action* of G on X is a continuous function $\cdot : G \times X \to X$ such that:

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

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

Definition 10.1.2 (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 10.1.3. *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:
⟨1⟩1. LET: $f_3 : S^2/SO(2) \to [-1, 1]$ be the function induced by $\pi_3 : S^2 \to [-1, 1]$
⟨1⟩2. f_3 is bijective.
⟨1⟩3. $S^2/SO(2)$ is compact.
PROOF: It is the continuous image of S^2 which is compact.
⟨1⟩4. $[-1, 1]$ is Hausdorff.
⟨1⟩5. f_3 is a homeomorphism.
□

Definition 10.1.4 (Stabilizer)**.** Let X be a G-space and $x \in X$. The *stabilizer* of x is $G_x := \{g : \mathrm{El}\,(G) \mid gx = x\}$.

Proposition 10.1.5. *The function that maps gG_x to gx is a continuous bijection from G/G_x to Gx.*

PROOF:
⟨1⟩1. If $gG_x = hG_x$ then $gx = hx$.
⟨2⟩1. ASSUME: $gG_x = hG_x$
⟨2⟩2. $g^{-1}h \in G_x$
⟨2⟩3. $g^{-1}hx = x$
⟨2⟩4. $gx = hx$
⟨1⟩2. If $gx = hx$ then $gG_x = hG_x$.
PROOF: Similar.
⟨1⟩3. The function is continuous.
PROOF: Proposition 7.9.2.
□

Chapter 11

Topological Vector Spaces

Definition 11.0.1 (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:

- Substraction is a continuous function $E^2 \to E$
- Multiplication is a continuous function $K \times E \to E$

Proposition 11.0.2. *Every topological vector space is a topological group under addition.*

Proof: Immediate from the definition. □

Theorem 11.0.3. *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 □

Proposition 11.0.4. *Let E be a topological vector space and E_0 a subspace of E. Then $\overline{E_0}$ is a subspace of E.*

Definition 11.0.5. Let E be a topological vector space. The topological space *associated* with E is $E/\overline{\{0\}}$.

11.1 Cauchy Sequences

Definition 11.1.1 (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 $\forall m, n \geqslant n_0 . x_n - x_m \in U$.

Definition 11.1.2 (Complete Topological Vector Space)**.** A topological vector space is *complete* iff every Cauchy sequence converges.

11.2 Seminorms

Definition 11.2.1 (Seminorm)**.** Let E be a vector space over K. A *seminorm* on E is a function $\| \, \| : E \to \mathbb{R}$ such that:

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

Example 11.2.2. The function that maps $(x_1, \ldots, x_n)$ to $|x_i|$ is a seminorm on $\mathbb{R}^n$.

Definition 11.2.3. 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 $B^\lambda_\epsilon(x) = \{y \in E : \lambda(y - x) < \epsilon\}$ for $\epsilon > 0$, $\lambda \in \Lambda$ and $x : \mathrm{El}\,(E)$.

Proposition 11.2.4. *E is a topological vector space under this topology. It is Hausdorff iff, for all $x : \mathrm{El}\,(E)$, if $\forall \lambda \in \Lambda . \lambda(x) = 0$ then $x = 0$.*

11.3 Fréchet Spaces

Definition 11.3.1 (Pre-Fréchet Space)**.** A *pre-Fréchet space* is a Hausdorff topological vector space whose topology is generated by a countable set of seminorms.

Proposition 11.3.2. *Let E be a pre-Fréchet space whose topology is generated by the family of seminorms $\{\| \, \|_n : n \in \mathbb{Z}^+\}$. 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 11.3.3 (Fréchet Space)**.** A *Fréchet space* is a complete pre-Fréchet space.

11.4 Normed Spaces

Definition 11.4.1 (Normed Space)**.** Let E be a vector space over K. A *norm* on E is a function $\| \, \| : E \to \mathbb{R}$ 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 11.4.2. *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.*

Proposition 11.4.3. *Let $\| \ \|$ be a seminorm on the vector space E. Then $\| \ \|$ defines a norm on $E/\overline{\{0\}}$.*

Proposition 11.4.4. *Let E and F be normed spaces. Any continuous linear map $E \to F$ is uniformly continuous.*

Definition 11.4.5. For $p \geqslant 1$. let $\mathcal{L}^p(\mathbb{R}^n)$ be the vector space of all Lebesgue-measurable functions $f : \mathbb{R}^n \to \mathbb{R}$ 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

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

11.5 Inner Product Spaces

Proposition 11.5.1. *If E is an inner product space then $\|x\| = \sqrt{\langle x, x \rangle}$ is a norm on E.*

11.6 Banach Spaces

Definition 11.6.1 (Banach Space)**.** A *Banach space* is a complete normed space.

Example 11.6.2. For any topological space X, the set $C(X)$ of bounded continuous functions $X \to \mathbb{R}$ is a Banach space under $\|f\| = \sup_{x\in X} |f(x)|$.

Proposition 11.6.3. *The completion of a normed space is a Banach space.*

Proposition 11.6.4. *Let E and F be normed spaces. Let $f : E \to F$ be a continuous linear map. Then the extension to the completions $\hat{E} \to \hat{F}$ is linear.*

Proposition 11.6.5. *$L^p(\mathbb{R}^n)$ is a Banach space.*

Proposition 11.6.6. *$C(\mathbb{R})$ 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. $\square$

11.7 Hilbert Spaces

Definition 11.7.1 (Hilbert Space)**.** A *Hilbert space* is a complete inner product space.

Example 11.7.2. The set of *square-integrable functions* is the set of Lebesgue integrable functions $[-\pi,\pi] \to \mathbb{R}$ 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 11.7.3. *The completion of an inner product space is a Hilbert space.*

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

11.8 Locally Convex Spaces

Definition 11.8.1 (Locally Convex Space)**.** A topological vector space is *locally convex* iff every neighbourhood of 0 includes a convex neighbourhood of 0.

Proposition 11.8.2. *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. □

Proposition 11.8.3. *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. □

Example 11.8.4. 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 $E \to \mathbb{R}$ is continuous as a map $E' \to \mathbb{R}$. 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 11.8.5 (Thom Space)**.** Let E be a vector bundle with a Riemannian metric, $DE = \{x : \mathrm{El}\,(E) \mid \|x\| \leqslant 1\}$ its disc bundle and $SE := \{v : \mathrm{El}\,(E) \mid \|v\| = 1\}$ its sphere bundle. The *Thom space* of E is the quotient space DE/SE.