Mathematics

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Chapter 1

Primitive Terms and Axioms

Let there be *sets*. We assume that everything is a set.

Let there be a binary relation of *membership*, $\in$. If $x \in A$ we say that x *belongs* to A, x is an *element* of A, or x is *contained* in A. If this does not hold we write $x \notin A$.

Definition 1.1 (Empty)**.** A set is *empty* iff it has no elements; otherwise it is *nonempty*.

Definition 1.2 (Disjoint)**.** Two sets A and B are *disjoint* iff there is no x such that $x \in A$ and $x \in B$.

Definition 1.3 (Pairwise Disjoint)**.** We say the elements of a set x are *pairwise disjoint* iff, for all $y, z \in x$, either y and z are disjoint or $y = z$.

Definition 1.4 (Subset)**.** Let A and B be sets. We say that A is a *subset* of B, or B *includes* A, and write $A \subseteq B$ or $B \supseteq A$, iff every element of A is an element of B.

Axiom 1.5 (Axiom of Extensionality)**.** *If two sets have the same elements then they are equal.*

Axiom 1.6 (Axiom of Union)**.** *For every set A, there exists a set that contains all the elements that belong to at least one element of A.*

Axiom 1.7 (Power Set Axiom)**.** *For any set A, there exists a set B such that every subset of A belongs to B.*

Axiom Schema 1.8 (Axiom Schema of Replacement)**.** *For any property $P(x, y)$, the following is an axiom:*

Let A be a set such that, for all $x \in A$, there exists at most one y such that $P(x, y)$. Then there exists a set B whose elements are exactly those sets y such that $\exists x \in A.P(x, y)$.

Axiom 1.9 (Axiom of Infinity)**.** *There exists a set I that has an empty element and such that, for all $x \in I$, there exists $y \in I$ such that the elements of y are exactly x and the elements of x.*

Axiom 1.10 (Axiom of Regularity)**.** *For any nonempty set A, there exists $m \in A$ such that m and A are disjoint.*

Axiom 1.11 (Axiom of Choice)**.** *Let A be a set of nonempty, pairwise disjoint sets. Then there exists a set C such that, for all $x \in A$, there is exactly one y such that $y \in C$ and $y \in x$.*

Chapter 2

Basic Properties and Operations on Sets

Theorem 2.1. *There exists a unique empty set.*

Proof: Existence follows from the Axiom of Infinity. Uniqueness follows from the Axiom of Extensionality. □

Definition 2.2 (Empty Set)**.** Let $\emptyset$ be the unique empty set.

Theorem Schema 2.3 (Comprehension, Aussonderungsaxiom)**.** *For any property $P(x)$, the following is a theorem:*

For any set A, there exists a set B whose elements are exactly those $x \in A$ such that $P(x)$.

Proof:
⟨1⟩1. Let: A be a set.
⟨1⟩2. For all $x \in A$, there exists at most one y such that $P(x)$ and $x = y$.
⟨1⟩3. Pick a set B whose elements are exactly those sets y such that $\exists x \in A(P(x) \wedge x = y)$.
Proof: Axiom Schema of Replacement.
⟨1⟩4. $\forall x(x \in B \Leftrightarrow x \in A \wedge P(x))$
□

Definition 2.4. Given a set A and a predicate $P(x)$, we write $\{x \in A : P(x)\}$ for the set whose elements are exactly those elements x of A for which $P(x)$ holds.

Definition 2.5 (Union)**.** For any set A, the *union* $\bigcup A$ is the set whose elements are exactly the elements of the elements of A.

Proof: This exists by the Axiom of Union, and is unique by the Axiom of Extensionality. □

Definition 2.6 (Power Set)**.** For any set A, the *power set* $\mathcal{P}A$ is the set whose elements are exactly the subsets of A.

PROOF: This exists by the Power Set Axiom, and is unique by the Axiom of Extensionality. □

Theorem 2.7. *For any sets a and b, there exists a set whose elements are just a and b.*

PROOF:
⟨1⟩1. For all $x \in \mathcal{P}\mathcal{P}\emptyset$, there exists at most one y such that $(x = \emptyset \wedge y = a) \vee (x = \mathcal{P}\emptyset \wedge y = b)$
⟨1⟩2. PICK a set B whose elements are the sets y such that $\exists x \in \mathcal{P}\mathcal{P}\emptyset((x = \emptyset \wedge y = a) \vee (x = \mathcal{P}\emptyset \wedge y = b))$
⟨1⟩3. The elements of B are exactly a and b.
□

Definition 2.8 ((Unordered) Pair)**.** For any sets a and b, the *(unordered) pair* $\{a, b\}$ is the set whose elements are just a and b.

Definition 2.9 (Singleton)**.** For any set a, the *singleton* $\{a\}$ is defined to be $\{a, a\}$.

Theorem 2.10.

$$\forall x . x \notin x$$

PROOF:
⟨1⟩1. LET: x be a set.
⟨1⟩2. PICK $m \in \{x\}$ such that m and $\{x\}$ are disjoint.
PROOF: Axiom of Regularity.
⟨1⟩3. $m = x$
PROOF: Since $m \in \{x\}$ (⟨1⟩2).
⟨1⟩4. $x \notin m$
PROOF: Since m and $\{x\}$ are disjoint (⟨1⟩2).
⟨1⟩5. $x \notin x$
PROOF: ⟨1⟩3, ⟨1⟩4
□

Corollary 2.10.1. *There is no set that contains every set.*

2.1 The Subset Relation

Theorem 2.11. *For any set A, we have $A \subseteq A$.*

PROOF: Every element of A is an element of A. □

Theorem 2.12. *For any sets A, B and C, if $A \subseteq B$ and $B \subseteq C$ then $A \subseteq C$.*

PROOF: If every element of A is an element of B, and every element of B is an element of C, then every element of A is an element of C. □

Theorem 2.13. *For any sets A and B, if $A \subseteq B$ and $B \subseteq A$ then $A = B$.*

PROOF: If every element of A is an element of B, and every element of B is an element of A, then A and B have the same elements, and therefore are equal by the Axiom of Extensionality. □

Definition 2.14 (Proper Subset)**.** Let A and B be sets. We say that A is a *proper* subset of B, or B *properly* includes A, and write $A \subsetneq B$ or $B \supsetneq A$, iff $A \subseteq B$ and $A \neq B$.

2.2 The Empty Set

Theorem 2.15. *There exists a set with no elements.*

PROOF: Immediate from the Axiom of Infinity. □

Definition 2.16 (Empty Set)**.** The *empty set* $\emptyset$ is the set with no elements.

Theorem 2.17. *For any set A we have $\emptyset \subset A$.*

PROOF: Vacuous. □

2.3 Unordered Pairs

Definition 2.18 (Singleton)**.** For any set a, the *singleton* $\{a\}$ is defined to be $\{a, a\}$.

2.4 Unions

Definition 2.19 (Union)**.** For any set $\mathcal{C}$, the *union* of $\mathcal{C}$, $\bigcup \mathcal{C}$, is the set whose elements are the elements of the elements of $\mathcal{C}$.

We write $\bigcup_{X \in \mathcal{A}} t[X]$ for $\bigcup \{t[X] \mid X \in \mathcal{A}\}$.

PROOF: This exists by the Union Axiom and Comprehension Axiom, and is unique by the Axiom of Extensionality. □

Proposition 2.20.

$$\bigcup \emptyset = \emptyset$$

PROOF: There is no set that is an element of an element of $\emptyset$. □

Proposition 2.21. *For any set A, we have $\bigcup \{A\} = A$.*

PROOF: For any x, we have x is an element of an element of $\{A\}$ if and only if x is an element of A. □

Definition 2.22. We write $A \cup B$ for $\bigcup \{A, B\}$.

Proposition 2.23. *For any set A, we have $A \cup \emptyset = A$.*

PROOF: $x \in A \cup \emptyset$ iff $x \in A$ or $x \in \emptyset$, iff $x \in A$. $\square$

Proposition 2.24 (Idempotence)**.** *For any set A, we have $A \cup A = A$.*

PROOF: $x \in A$ or $x \in A$ is equivalent to $x \in A$. $\square$

Proposition 2.25. *For any sets A and B, we have $A \subseteq B$ if and only if $A \cup B = B$.*

PROOF: For any x, the statement "if $x \in A$ then $x \in B$" is equivalent to "$x \in A$ or $x \in B$ if and only if $x \in B$". $\square$

Proposition 2.26. *For any sets a and b, we have $\{a\} \cup \{b\} = \{a, b\}$.*

PROOF: Immediate from definitions. $\square$

2.5 Intersections

Definition 2.27 (Intersection)**.** For any sets A and B, the *intersection* $A \cap B$ is defined to be $\{x \in A : x \in B\}$.

Proposition 2.28. *For any set A, we have $A \cap \emptyset = \emptyset$.*

PROOF: There is no x such that $x \in A$ and $x \in \emptyset$. $\square$

Proposition 2.29. *For any set A, we have*

$$A \cap A = A \ .$$

PROOF: We have $x \in A$ and $x \in A$ if and only if $x \in A$. $\square$

Proposition 2.30. *For any sets A and B, we have $A \subseteq B$ if and only if $A \cap B = A$.*

PROOF: For any x, the statement "if $x \in A$ then $x \in B$" is equivalent to "$x \in A$ and $x \in B$ if and only if $x \in A$". $\square$

Proposition 2.31. *For any sets A, B and C, we have $C \subseteq A$ if and only if $(A \cap B) \cup C = A \cap (B \cup C)$.*

PROOF: The statement "if $x \in C$ then $x \in A$" is equivalent to the statement "$((x \in A \wedge x \in B) \vee x \in C) \Leftrightarrow (x \in A \wedge (x \in B \vee x \in C))$". $\square$

Definition 2.32 (Disjoint)**.** Two sets A and B are *disjoint* if and only if $A \cap B = \emptyset$.

Definition 2.33 (Pairwise Disjoint)**.** Let A be a set. We say the elements of A are *pairwise disjoint* if and only if, for all $x, y \in A$, if $x \cap y \neq \emptyset$ then $x = y$.

Definition 2.34 (Intersection)**.** For any nonempty set $\mathcal{C}$, the *intersection* of $\mathcal{C}$, $\bigcap \mathcal{C}$, is the set that contains exactly those sets that belong to every element of $\mathcal{C}$.

We write $\bigcap_{X \in \mathcal{A}} t[X]$ for $\bigcap \{t[X] \mid X \in \mathcal{A}\}$.

PROOF:
⟨1⟩1. LET: $\mathcal{C}$ be a nonempty set.
⟨1⟩2. There exists a set I whose elements are exactly the sets that belong to every element of $\mathcal{C}$.
  PROOF: Pick $A \in \mathcal{C}$, and take $I = \{x \in A : \forall X \in \mathcal{C}. x \in X\}$.
⟨1⟩3. For any sets I, J, if the elements of I and J are exactly the sets that belong to every element of $\mathcal{C}$ then $I = J$.
  PROOF: Axiom of Extensionality.
□

2.6 Unordered Triples

Definition 2.35 ((Unordered) Triple)**.** Given sets $a_1, \ldots, a_n$, define the *(unordered) n-tuple* $\{a_1, \ldots, a_n\}$ to be

$$\{a_1, \ldots, a_n\} := \{a_1\} \cup \cdots \cup \{a_n\} \ .$$

2.7 Relative Complements

Definition 2.36 (Relative Complement)**.** For any sets A and B, the *difference* or *relative complement* $A - B$ is defined to be

$$A - B := \{x \in A : x \notin B\} \ .$$

Proposition 2.37. *For any sets A and E, we have $A \subseteq E$ if and only if*

$$E - (E - A) = A$$

PROOF:
⟨1⟩1. LET: A and E be sets.
⟨1⟩2. If $A \subseteq E$ then $E - (E - A) = A$
  ⟨2⟩1. ASSUME: $A \subseteq E$
  ⟨2⟩2. $E - (E - A) \subseteq A$
    PROOF: If $x \in E$ and $x \notin E - A$ then $x \in A$.
  ⟨2⟩3. $A \subseteq E - (E - A)$
    PROOF: If $x \in A$ then $x \in E$ and $x \notin E - A$.
⟨1⟩3. If $E - (E - A) = A$ then $A \subseteq E$.
  PROOF: Since $E - (E - A) \subseteq E$.
□

Proposition 2.38. *For any set E we have*

$$E - \emptyset = E$$

PROOF: $x \in E$ if and only if $x \in E$ and $x \notin \emptyset$. □

Proposition 2.39. *For any set E we have*

$$E - E = \emptyset \ .$$

Proof: There is no x such that $x \in E$ and $x \notin E$. ∎

Proposition 2.40. *For any sets A and E, we have*

$$A \cap (E - A) = \emptyset \ .$$

Proof: There is no x such that $x \in A$ and $x \in E - A$. ∎

Proposition 2.41. *Let A and E be sets. Then $A \subseteq E$ if and only if*

$$A \cup (E - A) = E \ .$$

Proof:
⟨1⟩1. Let: A and E be sets.
⟨1⟩2. If $A \subseteq E$ then $A \cup (E - A) = E$.
  ⟨2⟩1. Assume: $A \subseteq E$
  ⟨2⟩2. $A \cup (E - A) \subseteq E$
    Proof: If $x \in A$ or $x \in E - A$ then $x \in E$.
  ⟨2⟩3. $E \subseteq A \cup (E - A)$
    Proof: If $x \in E$ then either $x \in A$ or $x \notin A$. In the latter case, $x \in E - A$.
⟨1⟩3. If $A \cup (E - A) = E$ then $A \subseteq E$
  Proof: Since $A \subseteq A \cup (E - A)$.
∎

Proposition 2.42. *Let A, B and E be sets. Then:*

1. *If $A \subseteq B$ then $E - B \subseteq E - A$.*
2. *If $A \subseteq E$ and $E - B \subseteq E - A$ then $A \subseteq B$.*

Proof:
⟨1⟩1. Let: A, B and E be sets.
⟨1⟩2. If $A \subseteq B$ then $E - B \subseteq E - A$.
  Proof: If $A \subseteq B$, $x \in E$ and $x \notin B$, then we have $x \in E$ and $x \notin A$.
⟨1⟩3. If $A \subseteq E$ and $E - B \subseteq E - A$ then $A \subseteq B$.
  ⟨2⟩1. Assume: $A \subseteq E$
  ⟨2⟩2. Assume: $E - B \subseteq E - A$
  ⟨2⟩3. Let: $x \in A$
  ⟨2⟩4. $x \in E$
  ⟨2⟩5. $x \notin E - A$
  ⟨2⟩6. $x \notin E - B$
  ⟨2⟩7. $x \in B$
∎

Example 2.43. We cannot remove the hypothesis $A \subseteq E$ in item 2 above. Let $E = \emptyset$, $A = \{\emptyset\}$ and $B = \emptyset$. Then $E - B = E - A = \emptyset$ but $A \nsubseteq B$.

Proposition 2.44 (De Morgan's Law)**.** *For any sets A, B and E, we have $E - (A \cup B) = (E - A) \cap (E - B)$.*

PROOF: $(x \in E \wedge \neg(x \in A \vee x \in B)) \Leftrightarrow (x \in E \wedge x \notin A \wedge x \in E \wedge x \notin B)$. □

Proposition 2.45 (De Morgan's Law)**.** *For any sets A, B and E, we have $E - (A \cap B) = (E - A) \cup (E - B)$.*

PROOF: $(x \in E \vee \neg(x \in A \wedge x \in B)) \Leftrightarrow (x \in E \wedge x \notin A) \vee (x \in E \wedge x \notin B)$. □

Proposition 2.46. *For any sets A, B and E, if $A \subseteq E$ then*

$$A - B = A \cap (E - B) \ .$$

PROOF: If $A \subseteq E$ then we have $(x \in A \wedge x \notin B) \Leftrightarrow (x \in A \wedge x \in E \wedge x \notin B)$. □

Proposition 2.47. *For any sets A and B, we have $A \subseteq B$ if and only if $A - B = \emptyset$.*

PROOF: Both are equivalent to the statement that there is no x such that $x \in A$ and $x \notin B$. □

Proposition 2.48. *For any sets A and B, we have*

$$A - (A - B) = A \cap B \ .$$

PROOF: $(x \in A \wedge \neg(x \in A \wedge x \notin B)) \Leftrightarrow x \in A \wedge x \in B$. □

Proposition 2.49. *For any sets A, B and C, we have*

$$A \cap (B - C) = (A \cap B) - (A \cap C) \ .$$

PROOF: $(x \in A \wedge x \in B \wedge x \notin C) \Leftrightarrow (x \in A \wedge x \in B \wedge \neg(x \in A \wedge x \in C))$. □

Proposition 2.50. *For any sets A, B, C and E, if $(A \cap B) - C \subseteq E$ then we have*

$$A \cap B \subseteq (A \cap C) \cup (B \cap (E - C)) \ .$$

PROOF:
⟨1⟩1. LET: $x \in A \cap B$
PROVE: $x \in (A \cap C) \cup (B \cap (E - C))$
⟨1⟩2. CASE: $x \in C$
PROOF: Then $x \in A \cap C$.
⟨1⟩3. CASE: $x \notin C$
PROOF: Then $x \in E$ and so $x \in B \cap (E - C)$.
□

Proposition 2.51. *For any sets A, B, C and E, we have*

$$(A \cup C) \cap (B \cup (E - C)) \subseteq A \cup B \ .$$

Proof: The statement $(x \in A \vee x \in C) \wedge (x \in B \vee (x \in E \wedge x \notin C))$ implies $x \in A \vee x \in B$. □

Proposition 2.52 (De Morgan's Law)**.** *Let E be a set and $\mathcal{C}$ a nonempty set. Then*

$$E - \bigcup \mathcal{C} = \bigcap_{X \in \mathcal{C}} (E - X) \ .$$

Proof: Easy. □

Proposition 2.53 (De Morgan's Law)**.** *Let E be a set and $\mathcal{C}$ a nonempty set. Then*

$$E - \bigcap \mathcal{C} = \bigcup_{X \in \mathcal{C}} (E - X) \ .$$

Proof: Easy. □

2.8 Symmetric Difference

Definition 2.54 (Symmetric Difference)**.** For any sets A and B, the *symmetric difference* $A + B$ is defined to be

$$A + B := (A - B) \cup (B - A) \ .$$

Proposition 2.55. *For any sets A and B, we have*

$$A + B = B + A$$

Proof: From the commutativity of union. □

Proposition 2.56. *For any sets A, B and C, we have*

$$A + (B + C) = (A + B) + C \ .$$

Proof: Each is the set of all x that belong to either exactly one or all three of A, B and C. □

Proposition 2.57. *For any set A, we have*

$$A + \varnothing = A \ .$$

Proof:

$$\begin{aligned} A + \varnothing &= (A - \varnothing) \cup (\varnothing - A) \\ &= A \cup \varnothing \\ &= A \end{aligned}$$

□

Proposition 2.58. *For any set A we have*

$$A + A = \varnothing \ .$$

Proof:

$$\begin{aligned} A + A &= (A - A) \cup (A - A) \\ &= \varnothing \cup \varnothing \\ &= \varnothing \end{aligned}$$

□

2.9 Power Sets

Proposition 2.59.

$$\mathcal{P}\varnothing = \{\varnothing\}$$

Proof: The only subset of $\varnothing$ is $\varnothing$. □

Proposition 2.60. *For any set a, we have*

$$\mathcal{P}\{a\} = \{\varnothing, \{a\}\} \ .$$

Proof: The only subsets of $\{a\}$ are $\varnothing$ and $\{a\}$. □

Proposition 2.61. *For any sets a and b, we have*

$$\mathcal{P}\{a, b\} = \{\varnothing, \{a\}, \{b\}, \{a, b\}\} \ .$$

Proof: The only subsets of $\{a, b\}$ are $\varnothing$, $\{a\}$, $\{b\}$ and $\{a, b\}$. □

Proposition 2.62. *For any nonempty set $\mathcal{C}$ we have*

$$\bigcap_{X \in \mathcal{C}} \mathcal{P}X = \mathcal{P}\left(\bigcap \mathcal{C}\right) \ .$$

Proof:

$$\begin{aligned} x \in \bigcup_{X \in \mathcal{C}} \mathcal{P}X &\Leftrightarrow \forall X \in \mathcal{C}. x \subseteq X \\ &\Leftrightarrow \forall X \in \mathcal{C}. \forall y \in x. y \in X \\ &\Leftrightarrow \forall y \in x. \forall X \in mathcalC. y \in X \\ &\Leftrightarrow x \subseteq \bigcap \mathcal{C} \end{aligned}$$

□

Proposition 2.63. *For any set $\mathcal{C}$ we have*

$$\bigcup_{X \in \mathcal{C}} \mathcal{P}X \subseteq \mathcal{P} \bigcup \mathcal{C} \ .$$

Proof: If there exists $X \in \mathcal{C}$ such that $x \subseteq X$ then $x \subseteq \bigcup \mathcal{C}$. □

Proposition 2.64. *For any set E, we have*

$$\bigcap \mathcal{P}E = \varnothing \ .$$

Proof: Since $\varnothing \in \mathcal{P}E$. □

Proposition 2.65. *For any sets E and F, if $E \subseteq F$ then $\mathcal{P}E \subseteq \mathcal{P}F$.*

Proof: If $E \subseteq F$ and $X \subseteq E$ then $X \subseteq F$. □

Chapter 3

Relations and Functions

3.1 Ordered Pairs

Definition 3.1 (Ordered Pair)**.** For any sets a and b, the *ordered pair* (a, b) is defined by
$$(a, b) := \{\{a\}, \{a, b\}\} \ .$$

Proposition 3.2. *For any sets a, b, x and y, if $(a, b) = (x, y)$ then $a = x$ and $b = y$.*

Proof:
$\langle 1 \rangle 1$. Let: a, b, x and y be sets.
$\langle 1 \rangle 2$. Assume: $(a, b) = (x, y)$
$\langle 1 \rangle 3$. $a = x$
  Proof: $\{a\} = \bigcap(a, b) = \bigcap(x, y) = \{x\}$.
$\langle 1 \rangle 4$. $\{a, b\} = \{x, y\}$
$\langle 1 \rangle 5$. Case: $a = b$
  $\langle 2 \rangle 1$. $x = y$
    Proof: Since $\{x, y\} = \{a, b\}$ is a singleton.
  $\langle 2 \rangle 2$. $b = y$
    Proof: $b = a = x = y$
$\langle 1 \rangle 6$. Case: $a \neq b$
  $\langle 2 \rangle 1$. $x \neq y$
    Proof: Since $\{x, y\} = \{a, b\}$ is not a singleton.
  $\langle 2 \rangle 2$. $b = y$
    Proof: $\{b\} = \{a, b\} - \{a\} = \{x, y\} - \{x\} = \{y\}$.
□

Proposition 3.3. *For any sets A, B and X, we have*
$$(A - B) \times X = (A \times X) - (B \times X) \ .$$

Proof: Easy. □

Proposition 3.4. *For any sets A and B, we have $A \times B = \emptyset$ if and only if $A = \emptyset$ or $B = \emptyset$.*

PROOF: Easy. $\square$

Proposition 3.5. *For any sets A, B, X and Y, if $A \subseteq X$ and $B \subseteq Y$ then $A \times B \subseteq X \times Y$. The converse holds assuming $A \neq \emptyset$ and $B \neq \emptyset$.*

PROOF: Easy. $\square$

Definition 3.6 (Cartesian Product)**.** For any sets A and B, the *Cartesian product* $A \times B$ is

$$A \times B := \{p \in \mathcal{P}\mathcal{P}(A \cup B) : \exists a \in A . \exists b \in B . p = (a, b)\} \ .$$

3.2 Relations

Definition 3.7 (Relation)**.** A *relation* is a set of ordered pairs.

If R is a relation, we write xRy for $(x, y) \in R$.

Given sets X and Y, a relation *between X and Y* is a subset of $X \times Y$.

Given a set X, a relation *on* X is a relation between X and X.

Definition 3.8 (Domain)**.** The *domain* of a relation R is the set

$$\operatorname{dom} R := \left\{x \in \bigcup\bigcup R : \exists y . (x, y) \in R\right\} \ .$$

Definition 3.9 (Range)**.** The *range* of a relation R is the set

$$\operatorname{ran} R := \left\{y \in \bigcup\bigcup R : \exists x . (x, y) \in R\right\} \ .$$

Definition 3.10 (Reflexive)**.** Let R be a relation on X. Then R is *reflexive* iff, for all $x \in X$, we have xRx.

Definition 3.11 (Symmetric)**.** Let R be a relation on X. Then R is *symmetric* iff, whenever xRy, then yRx.

Definition 3.12 (Antisymmetric)**.** A relation R is *antisymmetric* iff, whenever xRy and yRx, then $x = y$.

Definition 3.13 (Transitive)**.** Let R be a relation on X. Then R is *transitive* iff, whenever xRy and yRz, then xRz.

Definition 3.14 (Identity Relation)**.** For any set X, the *identity relation* I_X on X is

$$I_X = \{(x, x) : x \in X\} \ .$$

3.3 Composition

Definition 3.15 (Composition)**.** Let R be a relation between X and Y, and S a relation between Y and Z. The *composite* or *relative product* $S \circ R = SR$ is the relation between X and Z defined by

$$x(S \circ R)z \Leftrightarrow \exists y \in Y(xRy \wedge ySz) \ .$$

Proposition 3.16. *Let R be a relation between X and Y, S a relation between Y and Z, and T a relation between Z and W. Then*

$$T(SR) = (TS)R \ .$$

PROOF: Easy. □

Example 3.17. Composition of relations is not commutative in general. Let $X = \{a, b\}$ where $a \neq b$. Let $R = \{(a, a), (b, a)\}$ and $S = \{(a, b), (b, b)\}$. Then $SR = S$ but $RS = R \neq S$.

Proposition 3.18. *A relation R is transitive if and only if $RR \subseteq R$.*

PROOF: Easy. □

3.4 Inverses

Definition 3.19 (Inverse)**.** Let R be a relation between X and Y. The *inverse* or *converse* R^{-1} is the relation between Y and X defined by

$$yR^{-1}x \Leftrightarrow xRy \ .$$

Proposition 3.20. *For any relation R, we have*

$$\operatorname{dom} R^{-1} = \operatorname{ran} R \ .$$

PROOF: Easy. □

Proposition 3.21. *For any relation R, we have*

$$\operatorname{ran} R^{-1} = \operatorname{dom} R \ .$$

PROOF: Easy. □

Proposition 3.22. *Let R be a relation between X and Y, and S a relation between Y and Z. Then*

$$(SR)^{-1} = R^{-1}S^{-1} \ .$$

PROOF: Easy. □

Proposition 3.23. *A relation R is symmetric if and only if $R \subseteq R^{-1}$.*

PROOF: Easy. □

Proposition 3.24. *Let R be a relation between X and Y. Then*

$$I_Y R = R I_X = R \ .$$

PROOF: Easy. □

Proposition 3.25. *A relation R on a set X is reflexive if and only if $I_X \subseteq R$.*

PROOF: Easy. □

Proposition 3.26. *Let R be a relation on a set X. Then R is antisymmetric iff $R \cap R^{-1} \subseteq I_X$.*

PROOF: Easy. □

3.5 Equivalence Relations

Definition 3.27 (Equivalence Relation)**.** Let R be a relation on X. Then R is an *equivalence relation* iff it is reflexive, symmetric and transitive.

Definition 3.28 (Partition)**.** Let X be a set. A *partition* of X is a pairwise disjoint set of nonempty subsets of X whose union is X.

Definition 3.29 (Equivalence Class)**.** Let R be an equivalence relation on X. Let $x \in X$. The *equivalence class* of x with respect to R is

$$x/R := \{y \in X : xRy\} \ .$$

We write X/R for the set of all equivalence classes with respect to R.

Definition 3.30 (Induced)**.** Let P be a partition of X. The relation *induced* by P is X/P where $x(X/P)y$ iff there exists $X \in P$ such that $x \in X$ and $y \in X$.

Theorem 3.31. *Let R be an equivalence relation on X. Then X/R is a partition of X that induces the relation R.*

PROOF: Easy. □

Theorem 3.32. *Let P be a partition of X. Then X/P is an equivalence relation on X, and $P = X/(X/P)$.*

PROOF: Easy. □

3.6 Functions

Definition 3.33 (Function)**.** Let X and Y be sets. A *function, map, mapping, transformation* or *operator f from X to Y*, $f : X \to Y$, is a relation f between X and Y such that, for all $x \in X$, there exists a unique $f(x) \in Y$, called the *value* of f at the *argument* x, such that $(x, f(x)) \in f$.

Definition 3.34 (Family)**.** Let I and X be sets. A *family* of elements of X *indexed* by I is a function $a : I \to X$. We write a_i for $a(i)$, and $\{a_i\}_{i \in I}$ for a.

Definition 3.35 (Cartesian Product of a Family of Sets)**.** Let $\{A_i\}_{i \in I}$ be a family of sets. The *Cartesian product* $\bigtimes_{i \in I} A_i$ is the set of all families $\{a_i\}_{i \in I}$ such that $\forall i \in I . a_i \in A_i$.

We write A^I for $\bigtimes_{i \in I} A$.

Definition 3.36 (Injective)**.** A function $f : X \to Y$ is *one-to-one* or *injective* or an *injection* iff, for all $x, y \in X$, if $f(x) = f(y)$ then $x = y$. In this case, we write $f : X \rightarrowtail Y$.

Definition 3.37 (Surjective)**.** Let $f : X \to Y$. We say f is *surjective*, or a *surjection*, or f maps X *onto* Y iff $\operatorname{ran} f = Y$. In this case, we write $f : X \twoheadrightarrow Y$.

Definition 3.38 (Bijective)**.** Let $f : X \to Y$. Then f is *bijective*, or a *bijection*, iff it is injective and surjective.

Definition 3.39 (Image)**.** Let $f : X \to Y$ and $A \subseteq X$. The *image* of A under f is

$$f(A) := \{f(x) : x \in A\} \ .$$

Proposition 3.40. *Let $f : X \to Y$ and $A \subseteq B \subseteq X$. Then $f(A) \subseteq f(B)$.*

PROOF:
⟨1⟩1. LET: X and Y be sets.
⟨1⟩2. LET: $f : X \to Y$
⟨1⟩3. LET: $A, B \in \mathcal{P}X$ with $A \subseteq B$.
⟨1⟩4. LET: $y \in f(A)$
⟨1⟩5. PICK $x \in A$ such that $f(x) = y$
  PROOF: ⟨1⟩4
⟨1⟩6. $x \in B$
  PROOF: ⟨1⟩3, ⟨1⟩5
⟨1⟩7. $y \in f(B)$
  PROOF: ⟨1⟩5, ⟨1⟩6
□

Proposition 3.41. *Let $f : X \to Y$. Let $\mathcal{A} \subseteq \mathcal{P}X$. Then $f\left(\bigcup \mathcal{A}\right) = \bigcup_{A \in \mathcal{A}} f(A)$.*

PROOF:

$$\begin{aligned} y \in f\left(\bigcup \mathcal{A}\right) &\Leftrightarrow \exists x \in \bigcup \mathcal{A} . y = f(x) \\ &\Leftrightarrow \exists x . \exists A \in \mathcal{A} (x \in A \wedge y = f(x)) \\ &\Leftrightarrow \exists A \in \mathcal{A} . \exists x \in A . y = f(x) \\ &\Leftrightarrow \exists A \in \mathcal{A} . y \in f(A) \\ &\Leftrightarrow y \in \bigcup_{A \in \mathcal{A}} f(A) \end{aligned}$$
□

Proposition 3.42. *Let $f : X \to Y$. Let $\mathcal{A}$ be a nonempty subset of $\mathcal{P}X$. Then $f\left(\bigcap \mathcal{A}\right) \subseteq \bigcap_{A \in \mathcal{A}} f(A)$. Equality holds if f is injective.*

PROOF:
$\langle 1 \rangle 1$. LET: X and Y be sets.
$\langle 1 \rangle 2$. LET: $f : X \to Y$
$\langle 1 \rangle 3$. LET: $\mathcal{A}$ be a nonempty subset of $\mathcal{P}X$.
$\langle 1 \rangle 4$. $f\left(\bigcap \mathcal{A}\right) \subseteq \bigcap_{A \in \mathcal{A}} f(A)$
  $\langle 2 \rangle 1$. LET: $y \in f\left(\bigcap \mathcal{A}\right)$
  $\langle 2 \rangle 2$. PICK $x \in \bigcap \mathcal{A}$ such that $y = f(x)$
    PROOF: $\langle 2 \rangle 1$
  $\langle 2 \rangle 3$. LET: $A \in \mathcal{A}$
  $\langle 2 \rangle 4$. $x \in A$
    PROOF: $\langle 2 \rangle 2$, $\langle 2 \rangle 3$
  $\langle 2 \rangle 5$. $y \in f(A)$
    PROOF: $\langle 2 \rangle 2$, $\langle 2 \rangle 4$
$\langle 1 \rangle 5$. If f is injective then $f\left(\bigcap \mathcal{A}\right) = \bigcap_{A \in \mathcal{A}} f(A)$
  $\langle 2 \rangle 1$. ASSUME: f is injective.
  $\langle 2 \rangle 2$. LET: $y \in \bigcap_{A \in \mathcal{A}} f(A)$
  $\langle 2 \rangle 3$. PICK $A \in \mathcal{A}$
    PROOF: $\mathcal{A}$ is nonempty by $\langle 1 \rangle 3$.
  $\langle 2 \rangle 4$. $y \in f(A)$
    PROOF: $\langle 2 \rangle 2$, $\langle 2 \rangle 3$
  $\langle 2 \rangle 5$. PICK $x \in A$ such that $y = f(x)$
    PROOF: $\langle 2 \rangle 4$
  $\langle 2 \rangle 6$. $x \in \bigcap \mathcal{A}$
    $\langle 3 \rangle 1$. LET: $A' \in \mathcal{A}$
    $\langle 3 \rangle 2$. $y \in f(A')$
      PROOF: $\langle 2 \rangle 2$, $\langle 3 \rangle 1$
    $\langle 3 \rangle 3$. PICK $x' \in A'$ such that $y = f(x')$
      PROOF: $\langle 3 \rangle 2$
    $\langle 3 \rangle 4$. $x = x'$
      PROOF: $\langle 2 \rangle 1$, $\langle 2 \rangle 5$, $\langle 3 \rangle 3$
    $\langle 3 \rangle 5$. $x \in A'$
      PROOF: $\langle 3 \rangle 3$, $\langle 3 \rangle 4$
  $\langle 2 \rangle 7$. $y \in f\left(\bigcap \mathcal{A}\right)$
    PROOF: $\langle 2 \rangle 5$, $\langle 2 \rangle 6$
$\square$

Proposition 3.43. *Let X and Y be sets. Let $f : X \to Y$. Let $A, B \in \mathcal{P}X$. Then $f(A) - f(B) \subseteq f(A - B)$. Equality holds if f is injective.*

PROOF:
$\langle 1 \rangle 1$. LET: X and Y be sets.
$\langle 1 \rangle 2$. LET: $f : X \to Y$
$\langle 1 \rangle 3$. LET: $A, B \in \mathcal{P}X$
$\langle 1 \rangle 4$. $f(A) - f(B) \subseteq f(A - B)$
  $\langle 2 \rangle 1$. LET: $y \in f(A) - f(B)$
  $\langle 2 \rangle 2$. $y \in f(A)$
    PROOF: $\langle 2 \rangle 1$

⟨2⟩3. PICK $x \in A$ such that $y = f(x)$.
PROOF: ⟨2⟩2
⟨2⟩4. $x \notin B$
⟨3⟩1. ASSUME: for a contradiction $x \in B$
⟨3⟩2. $y \in f(B)$
PROOF: ⟨2⟩3, ⟨3⟩1
⟨3⟩3. Q.E.D.
PROOF: ⟨2⟩1 and ⟨3⟩2 form a contradiction.
⟨2⟩5. $x \in A - B$
PROOF: ⟨2⟩3, ⟨2⟩4
⟨2⟩6. $y \in f(A - B)$
PROOF: ⟨2⟩3, ⟨2⟩5
⟨1⟩5. If f is injective then $f(A - B) = f(A) - f(B)$.
⟨2⟩1. ASSUME: f is injective.
⟨2⟩2. LET: $y \in f(A - B)$
⟨2⟩3. PICK $x \in A - B$ such that $y = f(x)$
PROOF: ⟨2⟩2
⟨2⟩4. $x \in A$
PROOF: ⟨2⟩3
⟨2⟩5. $y \in f(A)$
PROOF: ⟨2⟩3, ⟨2⟩4
⟨2⟩6. $y \notin f(B)$
⟨3⟩1. ASSUME: $y \in f(B)$
⟨3⟩2. PICK $x' \in B$ such that $y = f(x')$
PROOF: ⟨3⟩1
⟨3⟩3. $x = x'$
PROOF: ⟨2⟩1, ⟨2⟩3, ⟨3⟩2
⟨3⟩4. $x \in B$
PROOF: ⟨3⟩2, ⟨3⟩3
⟨3⟩5. Q.E.D.
PROOF: ⟨2⟩3 and ⟨3⟩4 form a contradiction.
⟨2⟩7. $y \in f(A) - f(B)$
PROOF: ⟨2⟩5, ⟨2⟩6
□

Definition 3.44 (Inclusion Map)**.** Let Y be a set and $X \subseteq Y$. Then the *inclusion map* $i : X \hookrightarrow Y$ is the function defined by $i(x) = x$ for all $x \in X$.

Proposition 3.45. *For any set X, the identity relation I_X is a function $X \to X$.*

PROOF: Easy. □

Definition 3.46 (Restriction)**.** Let $f : Y \to Z$ and $X \subseteq Y$. The *restriction* of f to X is the function $f \upharpoonright X : X \to Z$ defined by

$$(f \upharpoonright X)(x) = f(x) \qquad (x \in X) \ .$$

Given sets X, Y and Z with $X \subseteq Y$, if $f : X \to Z$ and $g : Y \to Z$, we say g is an *extension* of f to Y iff $f = g \restriction X$.

Definition 3.47 (Projection)**.** Given sets X and Y, the *projection* maps $\pi_1 : X \times Y \to X$ and $\pi_2 : X \times Y \to Y$ are defined by

$$\pi_1(x, y) = x, \qquad \pi_2(x, y) = y \qquad (x \in X, y \in Y) \ .$$

Definition 3.48 (Canonical Map)**.** Let X be a set and R an equivalence relation on X. The *canonical map* $\pi : X \to X/R$ is the map defined by $\pi(x) = x/R$.

Proposition 3.49. *Let $f : X \to Y$. Then the following are equivalent:*

1. *f is one-to-one.*
2. *For all $A, B \subseteq X$, we have $f(A \cap B) = f(A) \cap f(B)$.*
3. *For all $A \subseteq X$, we have $f(X - A) \subseteq Y - f(A)$.*

Proof: Easy. □

Proposition 3.50. *Let $f : X \to Y$. Then f maps X onto Y if and only if, for all $A \subseteq X$, we have $Y - f(A) \subseteq f(X - A)$.*

Proof: Easy. □

3.7 Families

Proposition 3.51 (Generalized Associative Law for Unions)**.** *Let $\{I_j\}_{j \in J}$ be a family of sets. Let $K = \bigcup_{j \in J} I_j$. Let $\{A_k\}_{k \in K}$ be a family of sets indexed by K. Then*

$$\bigcup_{k \in K} A_k = \bigcup_{j \in J} \bigcup_{i \in I_j} A_i \ .$$

Proof: Easy. □

Proposition 3.52 (Generalized Commutative Law for Unions)**.** *Let $\{I_j\}_{j \in J}$ be a family of sets. Let $f : J \to J$ be a one-to-one correspondence from J onto J. Then*

$$\bigcup_{j \in J} I_j = \bigcup_{j \in J} I_{f(j)} \ .$$

Proof: Easy. □

Proposition 3.53 (Generalized Associative Law for Intersections)**.** *Let $\{I_j\}_{j \in J}$ be a nonempty family of nonempty sets. Let $K = \bigcup_{j \in J} I_j$. Let $\{A_k\}_{k \in K}$ be a family of sets indexed by K. Then*

$$\bigcap_{k \in K} A_k = \bigcap_{j \in J} \bigcap_{i \in I_j} A_i \ .$$

PROOF: Easy. □

Proposition 3.54 (Generalized Commutative Law for Intersections)**.** *Let $\{I_j\}_{j\in J}$ be a nonempty family of sets. Let $f : J \to J$ be a one-to-one correspondence from J onto J. Then*

$$\bigcap_{j\in J} I_j = \bigcap_{j\in J} I_{f(j)} \ .$$

PROOF: Easy. □

Proposition 3.55. *Let B be a set and $\{A_i\}_{i\in I}$ a family of sets. Then*

$$B \cap \bigcup_{i\in I} A_i = \bigcup_{i\in I} (B \cap A_i)$$

PROOF: Easy. □

Proposition 3.56. *Let B be a set and $\{A_i\}_{i\in I}$ a nonempty family of sets. Then*

$$B \cup \bigcap_{i\in I} A_i = \bigcap_{i\in I} (B \cup A_i)$$

PROOF: Easy. □

Definition 3.57 (Projection)**.** Let $\{A_i\}_{i\in I}$ be a family of sets and $i \in I$. The *projection* function $\pi_i : \times_{i\in I} A_i \to A_i$ is defined by $\pi_i(a) = a_i$.

Proposition 3.58. *Let $\{A_i\}_{i\in I}$ and $\{B_j\}_{j\in J}$ be families of sets. Then*

$$\left(\bigcup_{i\in I} A_i\right) \times \left(\bigcup_{j\in J} B_j\right) = \bigcup_{i\in I} \bigcup_{j\in J} (A_i \times B_j) \ .$$

PROOF: Easy. □

Proposition 3.59. *Let $\{A_i\}_{i\in I}$ and $\{B_j\}_{j\in J}$ be nonempty families of sets. Then*

$$\left(\bigcap_{i\in I} A_i\right) \times \left(\bigcap_{j\in J} B_j\right) = \bigcap_{i\in I} \bigcap_{j\in J} (A_i \times B_j) \ .$$

PROOF: Easy. □

Proposition 3.60. *Let $f : X \to Y$. Let $\{A_i\}_{i\in I}$ be a family of subsets of X. Then*

$$f\left(\bigcup_{i\in I} A_i\right) = \bigcup_{i\in I} f(A_i) \ .$$

PROOF: Easy. □

Example 3.61. It is not true in general that, if $f : X \to Y$ and $\{A_i\}_{i\in I}$ is a nonempty family of subsets of X, then $f\left(\bigcap_{i\in I} A_i\right) = \bigcap_{i\in I} f(A_i)$.

Take $X = \{a, b\}$ and $Y = \{c\}$ where $a \neq b$. Take $I = \{i, j\}$ with $i \neq j$. Let $A_i = \{a\}$ and $A_j = \{b\}$. Let f be the unique function $X \to Y$. Then $f\left(\bigcap_{i\in I} A_i\right) = f(\varnothing) = \varnothing$ but $\bigcap_{i\in I} f(A_i) = \{c\}$.

3.8 Inverses and Composites of Functions

3.8.1 Inverse Image

Definition 3.62 (Inverse Image)**.** Let $f : X \to Y$. Let B be a subset of Y. Then the *inverse image* of B under f is

$$f^{-1}(B) = \{x \in X : f(x) \in B\} \ .$$

Proposition 3.63. *Let $f : X \to Y$. Let $B \subseteq Y$. Then*

$$f(f^{-1}(B)) \subseteq B \ .$$

Equality holds if f is surjective.

PROOF:
⟨1⟩1. LET: X and Y be sets.
⟨1⟩2. LET: $f : X \to Y$
⟨1⟩3. LET: $B \subseteq Y$
⟨1⟩4. $f(f^{-1}(B)) \subseteq B$
  ⟨2⟩1. LET: $y \in f(f^{-1}(B))$
  ⟨2⟩2. PICK $x \in f^{-1}(B)$ such that $f(x) = y$
  ⟨2⟩3. $f(x) \in B$
  ⟨2⟩4. $y \in B$
⟨1⟩5. If f is surjective then $f(f^{-1}(B)) = B$
  ⟨2⟩1. ASSUME: f is surjective.
  ⟨2⟩2. LET: $y \in B$
  ⟨2⟩3. PICK $x \in X$ such that $f(x) = y$
    PROOF: ⟨2⟩1, ⟨2⟩2
  ⟨2⟩4. $x \in f^{-1}(B)$
    PROOF: ⟨2⟩2, ⟨2⟩3
  ⟨2⟩5. $y \in f(f^{-1}(B))$
    PROOF: ⟨2⟩3, ⟨2⟩4
□

Proposition 3.64. *Let $f : X \to Y$. Let $A \subseteq X$. Then*

$$A \subseteq f^{-1}(f(A)) \ .$$

Equality holds if f is one-to-one.

PROOF:
⟨1⟩1. LET: X and Y be sets.
⟨1⟩2. LET: $f : X \to Y$
⟨1⟩3. LET: $A \subseteq X$
⟨1⟩4. $A \subseteq f^{-1}(f(A))$
  ⟨2⟩1. LET: $x \in A$
  ⟨2⟩2. $f(x) \in f(A)$
  ⟨2⟩3. $x \in f^{-1}(f(x))$

⟨1⟩5. If f is injective then $f^{-1}(f(A)) = A$

⟨2⟩1. ASSUME: f is injective.

⟨2⟩2. LET: $x \in f^{-1}(f(A))$

⟨2⟩3. $f(x) \in f(A)$

PROOF: ⟨2⟩2

⟨2⟩4. PICK $x' \in A$ such that $f(x') = f(x)$

PROOF: ⟨2⟩3

⟨2⟩5. $x' = x$

PROOF: ⟨2⟩1, ⟨2⟩4

⟨2⟩6. $x \in A$

PROOF: ⟨2⟩4, ⟨2⟩5

$\square$

Proposition 3.65. *Let $f : X \to Y$. Let $A \subseteq B \subseteq Y$. Then $f^{-1}(A) \subseteq f^{-1}(B)$.*

PROOF:

⟨1⟩1. LET: X and Y be sets.

⟨1⟩2. LET: $f : X \to Y$

⟨1⟩3. LET: $A \subseteq B \subseteq Y$

⟨1⟩4. LET: $x \in f^{-1}(A)$

⟨1⟩5. $f(x) \in A$

⟨1⟩6. $f(x) \in B$

⟨1⟩7. $x \in f^{-1}(B)$

$\square$

Proposition 3.66. *Let $f : X \to Y$. Let $\mathcal{B} \subseteq Y$. Then*

$$f^{-1}\left(\bigcup \mathcal{B}\right) = \bigcup_{B \in \mathcal{B}} f^{-1}(B) \ .$$

PROOF:

$$\begin{aligned} x \in f^{-1}\left(\bigcup \mathcal{B}\right) &\Leftrightarrow f(x) \in \bigcup \mathcal{B} \\ &\Leftrightarrow \exists B \in \mathcal{B}. f(x) \in B \\ &\Leftrightarrow \exists B \in \mathcal{B}. x \in f^{-1}(B) \\ &\Leftrightarrow x \in \bigcup_{B \in \mathcal{B}} f^{-1}(B) \end{aligned} \qquad \square$$

Proposition 3.67. *Let $f : X \to Y$. Let $\{B_i\}_{i \in I}$ be a nonempty family of subsets of Y. Then*

$$f^{-1}\left(\bigcap_{i \in I} B_i\right) = \bigcap_{i \in I} f^{-1}(B_i) \ .$$

PROOF: Easy. $\square$

Proposition 3.68. *Let $f : X \to Y$ and $B \subseteq Y$. Then $f^{-1}(Y - B) = X - f^{-1}(B)$.*

PROOF: Easy. $\square$

3.8.2 Inverse of a Function

Proposition 3.69. *Let $f : X \approx Y$. Then f^{-1} is a function, and is a bijection $f^{-1} : Y \approx X$.*

PROOF:
$\langle 1 \rangle 1$. LET: X and Y be sets.
$\langle 1 \rangle 2$. LET: $f : X \approx Y$
$\langle 1 \rangle 3$. f^{-1} is a function.
  $\langle 2 \rangle 1$. LET: $(x, y), (x, z) \in f^{-1}$
  $\langle 2 \rangle 2$. $(y, x), (z, x) \in f$
  $\langle 2 \rangle 3$. $y = z$
    PROOF: f is injective.
$\langle 1 \rangle 4$. $\mathrm{dom}\, f^{-1} = Y$
  PROOF: Proposition 3.20, $\langle 1 \rangle 2$
$\langle 1 \rangle 5$. $\mathrm{ran}\, f^{-1} = X$
  PROOF:

$$\begin{aligned} x \in \mathrm{ran}\, f^{-1} &\Leftrightarrow \exists y.(y, x) \in f^{-1} \\ &\Leftrightarrow \exists y.(x, y) \in f \\ &\Leftrightarrow x \in \mathrm{dom}\, f \\ &\Leftrightarrow x \in X \end{aligned}$$

$\langle 1 \rangle 6$. f^{-1} is injective.
  $\langle 2 \rangle 1$. LET: $y, y' \in Y$
  $\langle 2 \rangle 2$. ASSUME: $f^{-1}(y) = f^{-1}(y')$
  $\langle 2 \rangle 3$. $y = y'$
    PROOF: $y = f(f^{-1}(y)) = f(f^{-1}(y')) = y'$.
$\square$

Proposition 3.70. *Let $f : X \to Y$ and $g : Y \to Z$. Then $gf : X \to Z$ and, for all $x \in X$, we have*

$$(g \circ f)(x) = g(f(x)) \quad .$$

PROOF: Easy. $\square$

Example 3.71. Example 3.17 shows that function composition is not commutative in general.

Proposition 3.72. *The composite of two injective functions is injective.*

PROOF:
$\langle 1 \rangle 1$. LET: $f : X \rightarrowtail Y$ and $g : Y \rightarrowtail Z$
$\langle 1 \rangle 2$. LET: $x, y \in X$
$\langle 1 \rangle 3$. ASSUME: $(g \circ f)(x) = (g \circ f)(y)$
$\langle 1 \rangle 4$. $g(f(x)) = g(f(y))$
$\langle 1 \rangle 5$. $f(x) = f(y)$
  PROOF: g is injective.
$\langle 1 \rangle 6$. $x = y$
  PROOF: f is injective.

∎

Proposition 3.73. *Let $f : X \to Y$ and $g : Y \to Z$. If $g \circ f$ is injective then f is injective.*

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

Proposition 3.74. *The composite of two surjective functions is surjective.*

PROOF:
⟨1⟩1. LET: $f : X \twoheadrightarrow Y$ and $g : Y \twoheadrightarrow Z$
⟨1⟩2. LET: $z \in Z$
⟨1⟩3. PICK $y \in Y$ such that $g(y) = z$
  PROOF: Since g is surjective.
⟨1⟩4. PICK $x \in X$ such that $f(x) = y$
  PROOF: Since f is surjective.
⟨1⟩5. $(g \circ f)(x) = z$
∎

Proposition 3.75. *Let $f : X \to Y$ and $g : Y \to Z$. If $g \circ f$ is surjective then g is surjective.*

PROOF: Let $z \in Z$. Pick $x \in X$ such that $g(f(x)) = z$. Then there exists y such that $g(y) = z$, namely $y = f(x)$. ∎

Proposition 3.76. *The composite of two bijective functions is bijective.*

PROOF: Propositions 3.72 and 3.74. ∎

Proposition 3.77. *Let X, Y and Z be sets. Let $f : X \to Y$ and $g : Y \to Z$. Let $A \subseteq Z$. Then*

$$(g \circ f)^{-1}(A) = f^{-1}(g^{-1}(A)) \enspace .$$

PROOF:
⟨1⟩1. LET: X, Y and Z be sets.
⟨1⟩2. LET: $f : X \to Y$ and $g : Y \to Z$
⟨1⟩3. LET: $A \subseteq Z$
⟨1⟩4. $(g \circ f)^{-1}(A) = f^{-1}(g^{-1}(A))$
  PROOF:
  ⟨2⟩1. LET: $x \in X$
  ⟨2⟩2. $x \in (g \circ f)^{-1}(A) \Leftrightarrow x \in f^{-1}(g^{-1}(A))$
    PROOF:

$$\begin{aligned}
x \in (g \circ f)^{-1}(A) &\Leftrightarrow (g \circ f)(x) \in A \\
&\Leftrightarrow g(f(x)) \in A \qquad \text{(Proposition 3.70, ⟨1⟩2, ⟨2⟩1)} \\
&\Leftrightarrow f(x) \in g^{-1}(A) \\
&\Leftrightarrow x \in f^{-1}(g^{-1}(A))
\end{aligned}$$

∎

Proposition 3.78. *Let $f : X \approx Y$ and $g : Y \approx Z$. Then*

$$(gf)^{-1} = f^{-1}g^{-1} : Z \to X \ .$$

Proof: Easy. □

Definition 3.79 (Left Inverse, Right Inverse)**.** Let $f : X \to Y$ and $g : Y \to X$. Then g is a *left inverse* of f, and f is a *right inverse* of g, iff $g \circ f = I_X$.

Proposition 3.80. *Let $f : X \to Y$ and $g : Y \to X$. If $gf = I_X$ then f is one-to-one and g maps Y onto X.*

Proof: Easy. □

Lemma 3.81. *Let $f : A \to B$. If there are functions $g : B \to A$ and $h : B \to A$ such that $\forall a \in A.g(f(a)) = a$ and $\forall b \in B.f(h(b)) = b$, then f is bijective and $g = h = f^{-1}$.*

Proof:
⟨1⟩1. Let: A and B be sets.
⟨1⟩2. Let: $f : A \to B$ and $g, h : B \to A$
⟨1⟩3. Assume: $\forall a \in A.g(f(a)) = a$
⟨1⟩4. Assume: $\forall b \in B.f(h(b)) = b$
⟨1⟩5. f is injective.
  Proof: Proposition 3.80, ⟨1⟩2, ⟨1⟩3.
⟨1⟩6. f is surjective.
  Proof: Proposition 3.80, ⟨1⟩2, ⟨1⟩4.
⟨1⟩7. $g = h$
  ⟨2⟩1. Let: $b \in B$
  ⟨2⟩2. $g(b) = h(b)$
    Proof:

$$\begin{aligned} g(b) &= g(f(h(b))) && (\langle 1\rangle 4, \langle 2\rangle 1) \\ &= h(b) && (\langle 1\rangle 3, \langle 1\rangle 2, \langle 2\rangle 1) \end{aligned}$$

⟨1⟩8. $h = f^{-1}$
  ⟨2⟩1. Let: $b \in B$
  ⟨2⟩2. $f(h(b)) = b$
    Proof: ⟨1⟩4, ⟨2⟩1
  ⟨2⟩3. $h(b) = f^{-1}(b)$
□

3.9 Choice Functions

Definition 3.82 (Choice Function)**.** A *choice function* for a set X is a function $f : \mathcal{P}X - \{\emptyset\} \to X$ such that $f(S) \in S$ for all S.

Proposition 3.83. *Every set has a choice function.*

Proof: Given a nonempty set X, apply the Axiom of Choice to the family $\{S\}_{S \in \mathcal{P}X - \{\emptyset\}}$. □

Proposition 3.84. *For any relation R, there exists a function $f \subseteq R$ such that* $\operatorname{dom} f = \operatorname{dom} R$.

PROOF:
$\langle 1\rangle 1$. LET: R be a relation.
$\langle 1\rangle 2$. PICK a choice function g for $\operatorname{ran} R$.
$\langle 1\rangle 3$. LET: $f : \operatorname{dom} R \to \operatorname{ran} R$ be the function $f(x) = g(\{y \in \operatorname{ran} R : xRy\})$
$\langle 1\rangle 4$. $f \subseteq R$ and $\operatorname{dom} f = \operatorname{dom} R$.
$\square$

Proposition 3.85. *If $\mathcal{C}$ is a set of pairwise disjoint nonempty sets , then there exists a set A such that, for all $C \in \mathcal{C}$, we have $A \cap C$ is a singleton.*

PROOF:
$\langle 1\rangle 1$. LET: f be a choice function for $\bigcup \mathcal{C}$
$\langle 1\rangle 2$. LET: $A = \{f(C) : C \in \mathcal{C}\}$
$\langle 1\rangle 3$. For all $C \in \mathcal{C}$ we have $A \cap C = \{f(C)\}$
$\square$

Chapter 4

Equivalence

Definition 4.1 (Equivalent)**.** Sets E and F are *equivalent*, $E \sim F$, iff there exists a one-to-one correspondence between them.

Proposition 4.2. *For any set X, equivalence is an equivalence relation on $\mathcal{P}X$.*

PROOF: Easy.

Theorem 4.3 (Schröder-Bernstein)**.** *Let X and Y be sets. If there exist injective functions $X \to Y$ and $Y \to X$, then $X \sim Y$.*

PROOF:
⟨1⟩1. LET: $f : X \to Y$ and $g : Y \to X$ be one-to-one.
⟨1⟩2. ASSUME: w.l.o.g. $X \cap Y = \emptyset$
⟨1⟩3. For $x \in X$, let us say that x is the *parent* of $f(x)$; and for $y \in Y$, let us say that y is the *parent* of $g(y)$.
⟨1⟩4. For $z \in X \cup Y$, let the set of *descendants* of z be the intersection of all the subsets S of $X \cup Y$ such that $z \in S$ and, if $t \in S$ and t is the parent of u then $u \in S$.
⟨1⟩5. LET: X_X be the set of all elements of X that are descendants of the elements of X that have no parent.
⟨1⟩6. LET: X_Y be the set of all elements of X that are descendants of the elements of Y that have no parent.
⟨1⟩7. LET: $X_\infty = X - X_X - X_Y$
⟨1⟩8. LET: Y_X be the set of all elements of Y that are descendants of the elements of X that have no parent.
⟨1⟩9. LET: Y_Y be the set of all elements of Y that are descendants of the elements of Y that have no parent.
⟨1⟩10. LET: $Y_\infty = Y - Y_X - Y_Y$
⟨1⟩11. $f \restriction X_X : X_X \sim Y_X$
⟨1⟩12. $g \restriction Y_Y : Y_Y \sim X_Y$
⟨1⟩13. $f \restriction X_\infty : X_\infty \sim Y_\infty$
⟨1⟩14. Define $h : X \to Y$ by $h(x) = g^{-1}(x)$ if $x \in X_Y$, and $f(x)$ if not.

$\langle 1 \rangle 15.$ $h : X \sim Y$
$\square$

Theorem 4.4 (Cantor)**.** *For any set X we have $X \nsim \mathcal{P}X$.*

Proof: If $f : X \to \mathcal{P}X$ then $\{x \in X : x \notin f(x)\}$ is a subset of X not in $\operatorname{ran} f$. $\square$

Chapter 5

Order

5.1 Partial Orders

Definition 5.1 (Partial Order)**.** A *partial order* on a set X is a relation on X that is reflexive, antisymmetric and transitive.

A *partially ordered set* or *poset* is a pair $(X, \leqslant)$ such that $\leqslant$ is a partial order on X. We write X for the poset $(X, \leqslant)$.

Given a partial order $\leqslant$, we write $\geqslant$ for the inverse of $\leqslant$.

We write $x < y$ or $y > x$ for $x \leqslant y \wedge x \neq y$. When this holds, we say x is *less than* y or *smaller* than y; and y is *greater than* x, *larger* than x.

Proposition 5.2. *For any set X, the relation $\subseteq$ is a partial order on $\mathcal{P}X$.*

Proof: From Theorems 2.11, 2.12 and 2.13. □

Proposition 5.3. *Let X be a set. Let $<$ be a relation on X. Then there exists a partial order $\leqslant$ on X such that*

$$\forall x, y \in X(x < y \Leftrightarrow x \leqslant y \wedge x \neq y)$$

if and only if $<$ is irreflexive and transitive. In this case, $\leqslant$ is unique and is defined by

$$\forall x, y \in X(x \leqslant y \Leftrightarrow x < y \vee x = y) \ .$$

Proof:
⟨1⟩1. Let: X be a set.
⟨1⟩2. Let: $<$ be a relation on X.
⟨1⟩3. If there exists a partial order $\leqslant$ on X such that $\forall x, y \in X(x < y \Leftrightarrow x \leqslant y \wedge x \neq y)$, then $<$ is irreflexive.
Proof: Trivial.
⟨1⟩4. If there exists a partial order $\leqslant$ on X such that $\forall x, y \in X(x < y \Leftrightarrow x \leqslant y \wedge x \neq y)$, then $<$ is transitive.
⟨2⟩1. Let: $\leqslant$ be a partial order on X.
⟨2⟩2. Assume: $\forall x, y \in X(x < y \Leftrightarrow x \leqslant y \wedge x \neq y)$

$\langle 2\rangle 3$. LET: $x < y$ and $y < z$

$\langle 2\rangle 4$. $x \leqslant y$

PROOF: $\langle 2\rangle 3$

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

PROOF: $\langle 2\rangle 3$

$\langle 2\rangle 6$. $y \leqslant z$

PROOF: $\langle 2\rangle 3$

$\langle 2\rangle 7$. $y \neq z$

PROOF: $\langle 2\rangle 3$

$\langle 2\rangle 8$. $x \leqslant z$

PROOF: From $\langle 2\rangle 4$ and $\langle 2\rangle 6$ since $\leqslant$ is transitive by $\langle 2\rangle 1$.

$\langle 2\rangle 9$. $x \neq z$

$\langle 3\rangle 1$. ASSUME: for a contradiction $x = z$

$\langle 3\rangle 2$. $y \leqslant x$

PROOF: $\langle 2\rangle 6$, $\langle 3\rangle 1$

$\langle 3\rangle 3$. $x = y$

PROOF: From $\langle 2\rangle 4$ and $\langle 3\rangle 2$ since $\leqslant$ is antisymmetric by $\langle 2\rangle 1$.

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

PROOF: $\langle 2\rangle 5$ and $\langle 3\rangle 3$ form a contradiction.

$\langle 2\rangle 10$. $x < z$

PROOF: $\langle 2\rangle 8$, $\langle 2\rangle 9$

$\langle 1\rangle 5$. If there exists a partial order $\leqslant$ on X such that $\forall x, y \in X(x < y \Leftrightarrow x \leqslant y \wedge x \neq y)$, then $\forall x, y \in X(x \leqslant y \Leftrightarrow x < y \vee x = y)$.

PROOF: Trivial.

$\langle 1\rangle 6$. If $<$ is irreflexive and transitive, then the relation $\leqslant$ defined by $\forall x, y \in X(x \leqslant y \Leftrightarrow x < y \vee x = y)$ is a partial order on X.

$\langle 2\rangle 1$. ASSUME: $<$ is irreflexive.

$\langle 2\rangle 2$. ASSUME: $<$ is transitive.

$\langle 2\rangle 3$. LET: $\leqslant$ be the relation defined by $\forall x, y \in X(x \leqslant y \Leftrightarrow x < y \vee x = y)$

$\langle 2\rangle 4$. $\leqslant$ is reflexive.

PROOF: Immediate from $\langle 2\rangle 3$.

$\langle 2\rangle 5$. $\leqslant$ is transitive.

$\langle 3\rangle 1$. LET: $x, y, z \in X$

$\langle 3\rangle 2$. ASSUME: $x \leqslant y$ and $y \leqslant z$

$\langle 3\rangle 3$. $x < y$ or $x = y$

PROOF: $\langle 2\rangle 4$, $\langle 3\rangle 2$

$\langle 3\rangle 4$. $y < z$ or $y = z$

PROOF: $\langle 2\rangle 4$, $\langle 3\rangle 2$

$\langle 3\rangle 5$. CASE: $x < y$ and $y < z$

$\langle 4\rangle 1$. $x < z$

PROOF: $\langle 2\rangle 2$

$\langle 4\rangle 2$. $x \leqslant z$

PROOF: $\langle 2\rangle 4$, $\langle 4\rangle 1$

$\langle 3\rangle 6$. CASE: $x = y$

PROOF: Then $x \leqslant z$ from $\langle 3\rangle 2$

$\langle 3\rangle 7$. CASE: $y = z$

PROOF: Then $x \leqslant z$ from $\langle 3 \rangle 2$

$\langle 2 \rangle 6$. $\leqslant$ is antisymmetric.

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

$\langle 3 \rangle 2$. ASSUME: $x \leqslant y$

$\langle 3 \rangle 3$. ASSUME: $y \leqslant x$

$\langle 3 \rangle 4$. $x < y$ or $x = y$

PROOF: $\langle 2 \rangle 4$, $\langle 3 \rangle 2$

$\langle 3 \rangle 5$. $y < x$ or $y = x$

PROOF: $\langle 2 \rangle 4$, $\langle 3 \rangle 2$

$\langle 3 \rangle 6$. $\neg(x < y \wedge y < x)$

$\langle 4 \rangle 1$. ASSUME: for a contradiction $x < y$ and $y < x$

$\langle 4 \rangle 2$. $x < x$

PROOF: $\langle 2 \rangle 2$, $\langle 4 \rangle 1$

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

PROOF: $\langle 2 \rangle 1$ and $\langle 4 \rangle 2$ form a contradiction.

$\langle 3 \rangle 7$. $x = y$

PROOF: $\langle 3 \rangle 4$, $\langle 3 \rangle 5$, $\langle 3 \rangle 6$

$\langle 1 \rangle 7$. If $<$ is irreflexive, then the relation $\leqslant$ defined by $\forall x, y \in X(x \leqslant y \Leftrightarrow x < y \vee x = y)$ satisfies $\forall x, y \in X(x < y \Leftrightarrow x \leqslant y \wedge x \neq y)$.

PROOF: Trivial.

□

Proposition 5.4. *In a poset, we never have $x < y$ and $y < x$.*

PROOF: We would then have $x < x$ by transitivity, contradicting the irreflexivity of $<$. □

Definition 5.5 ((Strict) Initial Segment)**.** Let X be a poset and $a \in X$. The *(strict) initial segment* determined by a is

$$s(a) := \{x \in X : x < a\} \ .$$

Definition 5.6 (Weak Initial Segment)**.** Let X be a poset and $a \in X$. The *weak initial segment* determined by a is

$$\overline{s}(a) := \{x \in X : x \leqslant a\} \ .$$

Definition 5.7 (Immediate Successor)**.** Let X be a poset and $x, y \in X$. Then y is the *(immediate) successor* of x, and x is the *(immediate) predecessor* of y, iff $x < y$ and there is no z such that $x < z < y$.

Definition 5.8 (Least)**.** Let X be a partial order and $a \in X$. Then a is *least* in X iff $\forall x \in X. a \leqslant x$.

Proposition 5.9. *A poset has at most one least element.*

PROOF: If a and b are least then $a \leqslant b$ and $b \leqslant a$, hence $a = b$. □

Definition 5.10 (Greatest)**.** Let X be a partial order and $a \in X$. Then a is *greatest* in X iff $\forall x \in X. x \leqslant a$.

Proposition 5.11. *A poset has at most one greatest element.*

PROOF: If a and b are greatest then $a \leqslant b$ and $b \leqslant a$, hence $a = b$. □

Definition 5.12 (Minimal)**.** Let X be a poset and $a \in X$. Then a is *minimal* iff there is no $x \in X$ such that $x < a$.

Definition 5.13 (Maximal)**.** Let X be a poset and $a \in X$. Then a is *maximal* iff there is no $x \in X$ such that $a < x$.

Definition 5.14 (Lower Bound)**.** Let X be a poset. Let $E \subseteq X$ and $a \in X$. Then a is a *lower bound* for E iff $\forall x \in E.a \leqslant x$.

Definition 5.15 (Upper Bound)**.** Let X be a poset. Let $E \subseteq X$ and $a \in X$. Then a is an *upper bound* for E iff $\forall x \in E.x \leqslant a$.

Definition 5.16 (Greatest Lower Bound, Infimum)**.** Let X be a poset. Let $E \subseteq X$ and $a \in X$. Then a is the *greatest lower bound* or *infimum* for E iff a is the greatest element in the set of lower bounds for E.

Definition 5.17 (Least Upper Bound, Supremum)**.** Let X be a poset. Let $E \subseteq X$ and $a \in X$. Then a is the *least upper bound* or *supremum* for E iff a is the least element in the set of upper bounds for E.

5.2 Linear Orders

Definition 5.18 (Linear Order)**.** A partial order $\leqslant$ on a set X is a *linear order*, *total order* or *simple order* iff, for all $x, y \in X$, either $x \leqslant y$ or $y \leqslant x$. We then call the poset $(X, \leqslant)$ a *linearly ordered set* or a *chain*.

Proposition 5.19. *Let R be a partial order on X. Then R is total if and only if $X^2 \subseteq R \cup R^{-1}$.*

PROOF: Easy. □

Proposition 5.20. *Let X be a set and $<$ a relation on X. Then there exists a linear order $\leqslant$ on X such that*

$$\forall x, y \in X.(x < y \Leftrightarrow x \leqslant y \wedge x \neq y)$$

if and only if $<$ is irreflexive, transitive, and:

$$\forall x, y \in X.(x < y \vee x = y \vee y < x) \ .$$

In this case, $\leqslant$ is unique and is defined by

$$\forall x, y \in X.(x \leqslant y \Leftrightarrow x < y \vee x = y)$$

PROOF:
⟨1⟩1. LET: X be a set.

$\langle 1\rangle 2$. LET: $<$ be a relation on X

$\langle 1\rangle 3$. If there exists a linear order $\leqslant$ on X such that $\forall x, y \in X(x < y \Leftrightarrow x \leqslant y \wedge x \neq y)$, then $<$ is irreflexive.

PROOF: Trivial.

$\langle 1\rangle 4$. If there exists a linear order $\leqslant$ on X such that $\forall x, y \in X(x < y \Leftrightarrow x \leqslant y \wedge x \neq y)$, then $<$ is transitive.

$\langle 2\rangle 1$. LET: $\leqslant$ be a linear order on X.

$\langle 2\rangle 2$. ASSUME: $\forall x, y \in X(x < y \Leftrightarrow x \leqslant y \wedge x \neq y)$

$\langle 2\rangle 3$. LET: $x < y$ and $y < z$

$\langle 2\rangle 4$. $x \leqslant y$

PROOF: $\langle 2\rangle 3$

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

PROOF: $\langle 2\rangle 3$

$\langle 2\rangle 6$. $y \leqslant z$

PROOF: $\langle 2\rangle 3$

$\langle 2\rangle 7$. $y \neq z$

PROOF: $\langle 2\rangle 3$

$\langle 2\rangle 8$. $x \leqslant z$

PROOF: From $\langle 2\rangle 4$ and $\langle 2\rangle 6$ since $\leqslant$ is transitive.

$\langle 2\rangle 9$. $x \neq z$

$\langle 3\rangle 1$. ASSUME: for a contradiction $x = z$

$\langle 3\rangle 2$. $y \leqslant x$

PROOF: $\langle 2\rangle 6$, $\langle 3\rangle 1$

$\langle 3\rangle 3$. $x = y$

PROOF: From $\langle 2\rangle 4$ and $\langle 3\rangle 2$ since $\leqslant$ is antisymmetric.

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

PROOF: $\langle 2\rangle 5$ and $\langle 3\rangle 3$ form a contradiction.

$\langle 2\rangle 10$. $x < z$

PROOF: $\langle 2\rangle 8$, $\langle 2\rangle 9$

$\langle 1\rangle 5$. If there exists a linear order $\leqslant$ on X such that $\forall x, y \in X(x < y \Leftrightarrow x \leqslant y \wedge x \neq y)$, then $\forall x, y \in X(x < y \vee x = y \vee y < x)$.

$\langle 2\rangle 1$. LET: $\leqslant$ be a linear order on X.

$\langle 2\rangle 2$. ASSUME: $\forall x, y \in X(x < y \Leftrightarrow x \leqslant y \wedge x \neq y)$

$\langle 2\rangle 3$. LET: $x, y \in X$

$\langle 2\rangle 4$. $x \leqslant y$ or $y \leqslant x$

$\langle 2\rangle 5$. CASE: $x \leqslant y$

PROOF: Then $x < y$ or $x = y$ using $\langle 2\rangle 2$.

$\langle 2\rangle 6$. CASE: $y \leqslant x$

PROOF: Then $y < x$ or $x = y$ using $\langle 2\rangle 2$.

$\langle 1\rangle 6$. If there exists a linear order $\leqslant$ on X such that $\forall x, y \in X(x < y \Leftrightarrow x \leqslant y \wedge x \neq y)$, then $\forall x, y \in X(x \leqslant y \Leftrightarrow x < y \vee x = y)$.

PROOF: Trivial.

$\langle 1\rangle 7$. If $<$ is irreflexive, transitive and satisfies $\forall x, y \in X.(x < y \vee x = y \vee y < x)$, then the relation $\leqslant$ defined by $\forall x, y(x \leqslant y \Leftrightarrow x < y \vee x = y)$ is a linear order on X.

$\langle 2\rangle 1$. ASSUME: $<$ is irreflexive.

$\langle 2\rangle 2$. ASSUME: $<$ is transitive.
$\langle 2\rangle 3$. ASSUME: $\forall x, y \in X(x < y \vee x = y \vee y < x)$
$\langle 2\rangle 4$. LET: $\leqslant$ be the relation defined by $\forall x, y(x \leqslant y \Leftrightarrow x < y \vee x = y)$
$\langle 2\rangle 5$. $\leqslant$ is reflexive.
PROOF: Immediate from $\langle 2\rangle 4$.
$\langle 2\rangle 6$. $\leqslant$ is transitive.
$\langle 3\rangle 1$. LET: $x, y, z \in X$
$\langle 3\rangle 2$. ASSUME: $x \leqslant y$ and $y \leqslant z$
$\langle 3\rangle 3$. $x < y$ or $x = y$
PROOF: $\langle 2\rangle 4$, $\langle 3\rangle 2$
$\langle 3\rangle 4$. $y < z$ or $y = z$
PROOF: $\langle 2\rangle 4$, $\langle 3\rangle 2$
$\langle 3\rangle 5$. CASE: $x < y$ and $y < z$
$\langle 4\rangle 1$. $x < z$
PROOF: $\langle 2\rangle 2$
$\langle 4\rangle 2$. $x \leqslant z$
PROOF: $\langle 2\rangle 4$, $\langle 4\rangle 1$
$\langle 3\rangle 6$. CASE: $x = y$
PROOF: Then $x \leqslant z$ from $\langle 3\rangle 2$
$\langle 3\rangle 7$. CASE: $y = z$
PROOF: Then $x \leqslant z$ from $\langle 3\rangle 2$
$\langle 2\rangle 7$. $\leqslant$ is antisymmetric.
$\langle 3\rangle 1$. LET: $x, y \in X$
$\langle 3\rangle 2$. ASSUME: $x \leqslant y$
$\langle 3\rangle 3$. ASSUME: $y \leqslant x$
$\langle 3\rangle 4$. $x < y$ or $x = y$
PROOF: $\langle 2\rangle 4$, $\langle 3\rangle 2$
$\langle 3\rangle 5$. $y < x$ or $y = x$
PROOF: $\langle 2\rangle 4$, $\langle 3\rangle 2$
$\langle 3\rangle 6$. $\neg(x < y \wedge y < x)$
$\langle 4\rangle 1$. ASSUME: for a contradiction $x < y$ and $y < x$
$\langle 4\rangle 2$. $x < x$
PROOF: $\langle 2\rangle 2$, $\langle 4\rangle 1$
$\langle 4\rangle 3$. Q.E.D.
PROOF: $\langle 2\rangle 1$ and $\langle 4\rangle 2$ form a contradiction.
$\langle 3\rangle 7$. $x = y$
PROOF: $\langle 3\rangle 4$, $\langle 3\rangle 5$, $\langle 3\rangle 6$
$\langle 2\rangle 8$. $\forall x, y \in X(x \leqslant y \vee y \leqslant x)$
$\langle 3\rangle 1$. LET: $x, y \in X$
$\langle 3\rangle 2$. $x < y$ or $x = y$ or $y < x$
PROOF: $\langle 2\rangle 3$, $\langle 3\rangle 1$
$\langle 3\rangle 3$. $x \leqslant y$ or $y \leqslant x$
PROOF: $\langle 2\rangle 4$, $\langle 3\rangle 2$

□

Theorem 5.21 (Zorn's Lemma)**.** *Let X be a poset such that every chain in X*

has an upper bound. Then X has a maximal element.

PROOF:

$\langle 1\rangle 1$. PICK a choice function f for X.

$\langle 1\rangle 2$. LET: $\mathcal{X}$ be the set of chains in X.

$\langle 1\rangle 3$. For all $A \in \mathcal{X}$,
LET: $\hat{A} = \{x \in X : A \cup \{x\} \in \mathcal{X}\}$

$\langle 1\rangle 4$. LET: $g : \mathcal{X} \to \mathcal{X}$ be the function

$$g(A) = \begin{cases} A \cup \{f(\hat{A} - A)\} & \text{if } \hat{A} - A \neq \emptyset \\ A & \text{if } \hat{A} - A = \emptyset \end{cases}$$

$\langle 1\rangle 5$. For $\mathcal{T} \subseteq \mathcal{X}$, let us say $\mathcal{T}$ is a *tower* iff:

- $\emptyset \in \mathcal{T}$
- $\forall A \in \mathcal{T}.g(A) \in \mathcal{T}$
- For every chain $\mathcal{C}$ in $\mathcal{T}$, we have $\bigcup \mathcal{C} \in \mathcal{T}$

$\langle 1\rangle 6$. LET: $\mathcal{T}_0$ be the intersection of the set of all towers.
PROOF: The set of all towers is nonempty since $\mathcal{X}$ is a tower.

$\langle 1\rangle 7$. LET: $A = \bigcup \mathcal{T}_0$

$\langle 1\rangle 8$. A is a chain in X.

$\langle 2\rangle 1$. $\mathcal{T}_0$ is a chain under $\subseteq$

$\langle 3\rangle 1$. Given $C \in \mathcal{T}_0$, let us say that C is *comparable* iff, for all $A \in \mathcal{T}_0$, either $A \subseteq C$ or $C \subseteq A$.

$\langle 3\rangle 2$. For all $A, C \in \mathcal{T}_0$, if C is comparable and $A \subsetneq C$ then $g(A) \subseteq C$.
PROOF: Since $g(A) - A$ has at most one element, so if $A \subsetneq C \subseteq g(A)$ then $C = g(A)$.

$\langle 3\rangle 3$. For $C \in \mathcal{T}_0$ comparable,
LET: $\mathcal{U}_C = \{A \in \mathcal{T}_0 : A \subseteq C \vee g(C) \subseteq A\}$

$\langle 3\rangle 4$. For $C \in \mathcal{T}_0$ comparable, $\mathcal{U}_C$ is a tower.

$\langle 4\rangle 1$. LET: $C \in \mathcal{T}_0$ be comparable

$\langle 4\rangle 2$. $\emptyset \in \mathcal{U}_C$
PROOF: Since $\emptyset \subseteq C$.

$\langle 4\rangle 3$. $\forall A \in \mathcal{U}_C.g(A) \in \mathcal{U}_C$
PROOF: By $\langle 1\rangle 8$.

$\langle 4\rangle 4$. For every chain $\mathcal{C} \subseteq \mathcal{U}_C$ we have $\bigcup \mathcal{C} \in \mathcal{U}_C$

$\langle 5\rangle 1$. LET: $\mathcal{C} \subseteq \mathcal{U}_C$ be a chain.

$\langle 5\rangle 2$. CASE: $\exists A \in \mathcal{C}.g(C) \subseteq A$
PROOF: Then $g(C) \subseteq \bigcup \mathcal{C}$

$\langle 5\rangle 3$. CASE: $\forall A \in \mathcal{C}.A \subseteq C$
PROOF: Then $\bigcup \mathcal{C} \subseteq C$.

$\langle 3\rangle 5$. For $C \in \mathcal{T}_0$ comparable, $\mathcal{U}_C = \mathcal{T}_0$.

$\langle 3\rangle 6$. For $C \in \mathcal{T}_0$ comparable we have $g(C)$ is comparable.
PROOF: Since for all $A \in \mathcal{T}_0$ either $A \subseteq C \subseteq g(C)$ or $g(C) \subseteq A$.

$\langle 3\rangle 7$. The set of comparable sets in $\mathcal{T}_0$ is a tower.

$\langle 4\rangle 1$. $\emptyset$ is comparable.
PROOF: $\forall A \in \mathcal{T}_0.\emptyset \subseteq A$

⟨4⟩2. For all $C \in \mathcal{T}_0$, if A is comparable then $g(C)$ is comparable.
PROOF: ⟨3⟩6

⟨4⟩3. For every chain $\mathcal{C} \subseteq \mathcal{T}_0$ of comparable sets, we have $\bigcup \mathcal{C}$ is comparable.

⟨5⟩1. LET: $\mathcal{C} \subseteq \mathcal{T}_0$ be a chain of comparable sets.

⟨5⟩2. LET: $A \in \mathcal{T}_0$

⟨5⟩3. CASE: there exists $C \in \mathcal{C}$ such that $A \subseteq C$
PROOF: Then $A \subseteq \bigcup \mathcal{C}$.

⟨5⟩4. CASE: for all $C \in \mathcal{C}$ we have $C \subseteq A$
PROOF: Then $\bigcup \mathcal{C} \subseteq A$.

⟨3⟩8. Every set in $\mathcal{T}_0$ is comparable.

⟨2⟩2. LET: $x, y \in A$

⟨2⟩3. PICK $A, C \in \mathcal{T}_0$ such that $x \in A$ and $y \in C$

⟨2⟩4. ASSUME: w.l.o.g. $A \subseteq C$

⟨2⟩5. $x, y \in C$

⟨2⟩6. $x \leqslant y$ or $y \leqslant x$
PROOF: Since $C \in \mathcal{X}$ so C is a chain.

⟨1⟩9. PICK an upper bound u for A.

⟨1⟩10. $A \in \mathcal{T}_0$
PROOF: Since $\mathcal{T}_0$ is a chain in $\mathcal{T}_0$ so $\bigcup \mathcal{T}_0 \in \mathcal{T}_0$.

⟨1⟩11. $g(A) \in \mathcal{T}_0$

⟨1⟩12. $g(A) \subseteq A$

⟨1⟩13. $g(A) = A$

⟨1⟩14. $\hat{A} - A = \emptyset$

⟨1⟩15. $u \in A$
PROOF: Since $A \cup \{u\}$ is a chain so $u \in \hat{A}$ and therefore $u \in A$.

⟨1⟩16. u is maximal in X.

⟨2⟩1. LET: $x \in X$

⟨2⟩2. ASSUME: $u \leqslant x$

⟨2⟩3. $A \cup \{x\}$ is a chain.

⟨2⟩4. $x \in A$

⟨2⟩5. $x \leqslant u$

⟨2⟩6. $x = u$

□

Definition 5.22 (Cofinal)**.** Let X be a poset and $A \subseteq X$. Then A is *cofinal* iff, for all $x \in X$, there exists $a \in A$ such that $x \leqslant a$.

Definition 5.23 (Order Isomorphism)**.** Two posets X and Y are *(order) isomorphic*, $X \cong Y$ iff there exists an order preserving one-to-one correspondence f between them. We write $f : X \cong Y$ and call f a *(order) isomorphism*.

Proposition 5.24. *Let X and Y be posets. Let f be a one-to-one correspondence between X and Y. Then f is a similarity if and only if, for all $x, y \in X$, we have $x < y$ iff $f(x) < f(y)$.*

PROOF: Easy. □

Proposition 5.25. *For any poset X we have $I_X : X \cong X$.*

PROOF: Easy. □

Proposition 5.26. *If $f : X \cong Y$ then $f^{-1} : Y \cong X$.*

PROOF: Easy. □

Proposition 5.27. *If $f : X \cong Y$ and $g : Y \cong Z$ then $g \circ f : X \cong Z$.*

PROOF: Easy. □

Corollary 5.27.1. *For any set E, similarity is an equivalence relation on the set of all posets that are subsets of E.*

Definition 5.28 (Open Interval)**.** Let X be a linearly ordered set. Let $a, b \in X$ with $a < b$. The *open interval* (a, b) is

$$(a,b) := \{x \in X : a < x < b\} \ .$$

Definition 5.29 (Lexicographical Order)**.** Let A and B be linearly ordered sets. The *lexicographical* order on $A \times B$ is the relation $\leqslant$ defined by $(a, b) \leqslant (x, y)$ iff $a < x$ or ($a = x$ and $b \leqslant y$).

Definition 5.30 (Least Upper Bound Property)**.** A linearly ordered set A has the *least upper bound property* iff every nonempty subset of A bounded above has a least upper bound.

Proposition 5.31. *Let A be a linearly ordered set. Then A has the least upper bound property if and only if every nonempty subset of A bounded below has a greatest lower bound.*

PROOF:

⟨1⟩1. For any linearly ordered set A, if A has the least upper bound property then every nonempty subset of A bounded below has a greatest lower bound.

⟨2⟩1. LET: A be a linearly ordered set.

⟨2⟩2. ASSUME: A has the least upper bound property.

⟨2⟩3. LET: S be a nonempty subset of A bounded below.

⟨2⟩4. LET: $S\downarrow$ be the set of all lower bounds for S.

⟨2⟩5. $S\downarrow \neq \emptyset$

PROOF: Since S is bounded below by ⟨2⟩3.

⟨2⟩6. $S\downarrow$ is bounded above.

⟨3⟩1. PICK $s \in S$

PROOF: S is nonempty by ⟨2⟩3.

⟨3⟩2. s is an upper bound for $S\downarrow$.

⟨2⟩7. LET: l be the supremum of $S\downarrow$.

PROOF: ⟨2⟩2, ⟨2⟩5, ⟨2⟩6

⟨2⟩8. l is a lower bound for S.

⟨3⟩1. LET: $s \in S$

⟨3⟩2. s is an upper bound for $S\downarrow$

⟨3⟩3. $l \leqslant s$

PROOF: ⟨2⟩7, ⟨3⟩2

⟨2⟩9. For any lower bound l' for S we have $l' \leqslant l$.

PROOF: Since l is an upper bound for $S\downarrow$ by ⟨2⟩7.

⟨1⟩2. For any linearly ordered set A, if every nonempty subset of A bounded below has a greatest lower bound then A has the least upper bound property.

⟨2⟩1. LET: $(A, \leqslant)$ be a linearly ordered set.

⟨2⟩2. ASSUME: Every nonempty subset of A bounded below has a greatest lower bound.

⟨2⟩3. $(A, \geqslant)$ has the least upper bound property.

⟨2⟩4. Every nonempty subset of A bounded below with respect to $\geqslant$ has ¡a greatest lower bound with respect to $\geqslant$.

⟨2⟩5. Every nonempty subset of A bounded above with respect to $\leqslant$ has a least upper bound with respect to $\leqslant$.

□

5.3 Linear Continua

Definition 5.32 (Linear Continuum)**.** A *linear continuum* is a linearly ordered set X with the least upper bound property such that, for all $x, y \in X$, if $x < y$ then there exists $z \in X$ such that $x < z < y$.

5.4 Well Orderings

Definition 5.33 (Well Ordered Set)**.** A poset X is *well ordered*, and its ordering is a *well ordering*, iff every nonempty subset of X has a least element.

Proposition 5.34. *Every well ordered set is totally ordered.*

PROOF: For all x and y we have $\{x, y\}$ has a least element, so $x \leqslant y$ or $y \leqslant x$. □

Theorem 5.35 (Transfinite Induction)**.** *Let X be a well ordered set. Let $S \subseteq X$ satisfy:*

$$\forall x \in X (\forall y < x . y \in S) \Rightarrow x \in S \ .$$

Then $S = X$.

PROOF: We have $X - S$ has no least element, so $X - S = \emptyset$. □

Definition 5.36 (Continuation)**.** Let A and B be well ordered sets. Then B is a *continuation* of A iff there exists $b \in B$ such that $A = s(b)$ and the order on A is the restriction of the order on B to A.

Proposition 5.37. *Let $\mathcal{C}$ be a set of well ordered sets that is totally ordered under continuation. Then there exists a unique well ordering on $\bigcup \mathcal{C}$ such that $\bigcup \mathcal{C}$ is a continuation of every element of $\mathcal{C}$.*

PROOF: Define $\leqslant$ on $\bigcup \mathcal{C}$ by: $x \leqslant y$ iff there exists $C \in \mathcal{C}$ such that $x, y \in C$ and $x \leqslant y$ in C. ∎

Proposition 5.38. *Every totally ordered set has a cofinal well ordered subset.*

PROOF:
⟨1⟩1. LET: X be a totally ordered set.
⟨1⟩2. LET: $\mathcal{C}$ be the poset of all well ordered subsets of X under continuation.
⟨1⟩3. Every chain in $\mathcal{C}$ has an upper bound.
PROOF: Proposition 5.37.
⟨1⟩4. PICK a maximal element C of $\mathcal{C}$
PROVE: C is cofinal
PROOF: Zorn's Lemma
⟨1⟩5. LET: $x \in X$
⟨1⟩6. We cannot have $\forall c \in C.c < x$
PROOF: Then $C \cup \{x\}$ would be a larger chain.
⟨1⟩7. $\exists c \in C.x \leqslant c$
∎

Theorem 5.39 (Well Ordering Theorem)**.** *Every set can be well ordered.*

PROOF:
⟨1⟩1. LET: X be a set.
⟨1⟩2. LET: $\mathcal{W}$ be the poset of all well ordered subsets of X under continuation.
⟨1⟩3. Every chain in $\mathcal{W}$ has an upper bound.
PROOF: Proposition 5.37.
⟨1⟩4. PICK a maximal $M \in \mathcal{W}$
PROOF: Zorn's Lemma
⟨1⟩5. $M = X$
PROOF: If $x \in X - M$ then $M \cup \{x\}$ with x as the greatest element is a continuation of M.
∎

Theorem 5.40 (Transfinite Recursion)**.** *Let W be a well ordered set and X a set. Let S be the set of all functions f such that* $\operatorname{ran} f \subseteq X$*, and there exists $a \in W$ such that* $\operatorname{dom} f = s(a)$*. Then there exists a unique function $U : W \to X$ such that*

$$\forall a \in W.U(a) = f(U \restriction s(a)) \ .$$

PROOF:
⟨1⟩1. Let us say that a subset $A \subseteq W \times X$ is *f-closed* iff, whenever $a \in W$ and $t : s(a) \to X$ satisfies $\forall c < a.(c, t(c)) \in A$, then $(a, f(t)) \in A$.
⟨1⟩2. LET: U be the intersection of the set of f-closed subsets of $W \times X$
PROOF: This set is nonempty since $W \times X$ is f-closed.
⟨1⟩3. U is f-closed.
⟨1⟩4. U is a function.
⟨2⟩1. LET: $P(a)$ be the property: there is at most one $x \in X$ such that $(a, x) \in U$

$\langle 2\rangle 2.$ Let: $a \in W$
$\langle 2\rangle 3.$ Assume: as transfinite induction hypothesis $\forall c < a.P(c)$
$\langle 2\rangle 4.$ Let: $(a, x), (a, y) \in U$
$\langle 2\rangle 5.$ $x = f(U \upharpoonright c)$
Proof: If not then $U - \{(a, x)\}$ would be f-closed.
$\langle 2\rangle 6.$ $y = f(U \upharpoonright c)$
$\langle 2\rangle 7.$ $x = y$
$\langle 1\rangle 5.$ $\mathrm{dom}\, U = W$
$\langle 2\rangle 1.$ Let: $a \in W$
$\langle 2\rangle 2.$ Assume: as transfinite induction hypothesis $\forall c < a.c \in \mathrm{dom}\, U$
$\langle 2\rangle 3.$ $(a, f(U \upharpoonright s(a))) \in U$
$\langle 1\rangle 6.$ If $U' : W \to X$ and $\forall a \in W.U'(a) = f(U' \upharpoonright s(a))$, then $U' = U$.
Proof: Prove $U'(a) = U(a)$ by transfinite induction on a.
□

Proposition 5.41. *Let X be a well ordered set and f a similarity between X and a subset of X. Then, for all $a \in X$, we have $a \leqslant f(a)$.*

Proof:
$\langle 1\rangle 1.$ Let: $a \in X$
$\langle 1\rangle 2.$ Assume: as transfinite induction hypothesis $\forall c < a.c \leqslant f(c)$
$\langle 1\rangle 3.$ Assume: for a contradiction $f(a) < a$
$\langle 1\rangle 4.$ $f(a) \leqslant f(f(a))$
Proof: $\langle 1\rangle 2$
$\langle 1\rangle 5.$ $f(f(a)) < f(a)$
Proof: From $\langle 1\rangle 3$ since f is a similarity.
$\langle 1\rangle 6.$ Q.E.D.
Proof: This is a contradiction.
□

Proposition 5.42. *Let X and Y be well ordered sets. Then there is at most one similarity between them.*

Proof:
$\langle 1\rangle 1.$ Let: $f, g : X \cong Y$
Prove: $\forall a \in X.f(a) = g(a)$
$\langle 1\rangle 2.$ Let: $a \in X$
$\langle 1\rangle 3.$ Assume: as transfinite induction hypothesis $\forall c < a.f(c) = g(c)$
$\langle 1\rangle 4.$ $f(a)$ is the least element of $Y - \{f(c) : c < a\}$
$\langle 1\rangle 5.$ $g(a)$ is the least element of $Y - \{g(c) : c < a\}$
$\langle 1\rangle 6.$ $f(a) = g(a)$
□

Proposition 5.43. *A well ordered set is not similar to any of its initial segments.*

Proof:
$\langle 1\rangle 1.$ Let: X be a well ordered set.

$\langle 1\rangle 2.$ ASSUME: for a contradiction $f : X \cong s(a)$ for some $a \in X$
$\langle 1\rangle 3.$ $f(a) < a$
$\langle 1\rangle 4.$ Q.E.D.
  PROOF: This contradicts Proposition 5.41.
□

Theorem 5.44 (Comparability Theorem)**.** *Given well ordered sets X and Y, either $X \cong Y$, or X is similar to an initial segment of Y, or Y is similar to an initial segment of X.*

PROOF:
$\langle 1\rangle 1.$ LET: $X_0 = \{a \in X : \exists b \in Y . s(a) \cong s(b)\}$
$\langle 1\rangle 2.$ LET: $U : X_0 \to Y$ be the function: for $a \in X_0$, we have $U(a)$ is the unique element in Y such that $s(a) \cong s(U(a))$
$\langle 1\rangle 3.$ LET: $Y_0 = \operatorname{ran} U$
$\langle 1\rangle 4.$ Either $X_0 = X$ or there exists $a \in X$ such that $X_0 = s(a)$
  $\langle 2\rangle 1.$ ASSUME: $X_0 \neq X$
  $\langle 2\rangle 2.$ LET: a be the least element of $X - X_0$
  $\langle 2\rangle 3.$ LET: $x \in X_0$
    PROVE: $x < a$
  $\langle 2\rangle 4.$ PICK $f : s(x) \cong s(U(x))$
  $\langle 2\rangle 5.$ ASSUME: for a contradiction $a < x$
  $\langle 2\rangle 6.$ $f \restriction s(a) : s(a) \cong s(f(a))$
  $\langle 2\rangle 7.$ $a \in X_0$
  $\langle 2\rangle 8.$ Q.E.D.
    PROOF: This is a contradiction.
$\langle 1\rangle 5.$ Either $Y_0 = Y$ or there exists $b \in Y$ such that $Y_0 = s(b)$
  PROOF: Similar.
$\langle 1\rangle 6.$ CASE: $X_0 = X$ and $Y_0 = Y$
  PROOF: Then $U : X \cong Y$.
$\langle 1\rangle 7.$ CASE: $X_0 = X$ and $Y_0 \neq Y$
  PROOF: Then $U : X \cong s(b)$ where $Y_0 = s(b)$.
$\langle 1\rangle 8.$ CASE: $X_0 \neq X$ and $Y_0 = Y$
  PROOF: Then $U : s(a) \cong Y$ where $X_0 = s(a)$.
$\langle 1\rangle 9.$ CASE: $X_0 \neq X$ and $Y_0 \neq Y$
  $\langle 2\rangle 1.$ LET: $X_0 = s(a)$ and $Y_0 = s(b)$
  $\langle 2\rangle 2.$ $U : s(a) \cong s(b)$
  $\langle 2\rangle 3.$ $a \in X_0$
  $\langle 2\rangle 4.$ Q.E.D.
    PROOF: This is a contradiction.
□

Corollary 5.44.1. *Let X be a well ordered set. Then any subset A of X is either similar to X or to an initial segment of X.*

PROOF: We cannot have X is similar to an initial segment of A, say $f : X \cong \{x \in A : x < a\}$, because then we would have $f(a) < a$ contradicting Proposition 5.41. □

Corollary 5.44.2. *For any sets X and Y, either there exists an injective function $X \to Y$, or there exists an injective function $Y \to X$.*

Proof: Using the Well Ordering Theorem. $\square$

Chapter 6

Natural Numbers

6.1 Natural Numbers

Definition 6.1 (Successor)**.** The *successor* of a set x, x^+, is defined by

$$x^+ := x \cup \{x\} \ .$$

Definition 6.2. We define

$$\begin{aligned} 0 &= \varnothing \\ 1 &= 0^+ \\ 2 &= 1^+ \end{aligned}$$

etc.

Definition 6.3 (Characteristic Function)**.** Let X be a set and $A \subseteq X$. The *characteristic function* of A is the function $\chi_A : X \to 2$ defined by

$$\chi_A(x) = \begin{cases} 1 & \text{if } x \in A \\ 0 & \text{if } x \notin A \end{cases}$$

Theorem 6.4. *Let X be a set. The function $\chi : \mathcal{P}X \to 2^X$ that maps a subset A of X to χ_A is a one-to-one correspondence.*

PROOF: Easy. □

Definition 6.5. The set ω of *natural numbers* is the set such that:

- $0 \in \omega$
- For all $n \in \omega$ we have $n^+ \in \omega$
- For any set X, if $0 \in X$ and $\forall n \in X . n^+ \in X$ then $\omega \subseteq X$

PROOF: To show this exists, pick a set A such that $0 \in A$ and $\forall n \in A.n^+ \in A$ (by the Axiom of Infinity), and let $\omega = \bigcap\{X \in \mathcal{P}A : 0 \in X \wedge \forall n \in X.n^+ \in X\}$. ∎

Definition 6.6 (Sequence)**.** A *finite sequence* is a family whose index set is a natural number. An *infinite sequence* is a family whose index set is ω.

Given a finite sequence of sets $\{A_i\}_{i \in n^+}$, we write $\bigcup_{i=0}^n A_i$ for $\bigcup_{i \in n^+} A_i$. Given an infinite sequence of sets $\{A_i\}_{i \in \omega}$, we write $\bigcup_{i=0}^\infty A_i$ for $\bigcup_{i \in \omega} A_i$.

We make similar definitions for $\bigcap$ and $\times$.

Proposition 6.7. *For any natural numbers m and n, if $m \in n$ then $m^+ \in n^+$.*

PROOF:
⟨1⟩1. LET: $P(n)$ be the property $\forall m \in n.m^+ \in n^+$
⟨1⟩2. $P(0)$
  PROOF: Vacuous.
⟨1⟩3. For any natural number n, if $P(n)$ then $P(n^+)$.
  ⟨2⟩1. LET: n be a natural number.
  ⟨2⟩2. ASSUME: $P(n)$
  ⟨2⟩3. LET: $m \in n^+$
  ⟨2⟩4. $m \in n$ or $m = n$
  ⟨2⟩5. $m^+ \in n^+$ or $m^+ = n^+$
    PROOF: ⟨2⟩2
  ⟨2⟩6. CASE: $m^+ \in n^{++}$
∎

Theorem 6.8 (Principle of Mathematical Induction)**.** *For any subset S of ω, if $0 \in S$ and $\forall n \in S.n^+ \in S$, then $S = \omega$.*

PROOF: From the definition of ω. ∎

Proposition 6.9.

$$\forall n \in \omega.\forall x \in n.n \nsubseteq x$$

PROOF:
⟨1⟩1. $\forall x \in 0.0 \nsubseteq x$
  PROOF: Vacuous.
⟨1⟩2. For any natural number n, if $\forall x \in n.n \nsubseteq x$ then $\forall x \in n^+.n^+ \nsubseteq x$.
  ⟨2⟩1. LET: n be a natural number.
  ⟨2⟩2. ASSUME: $\forall x \in n.n \nsubseteq x$
  ⟨2⟩3. LET: $x \in n^+$
  ⟨2⟩4. ASSUME: for a contradiction $n^+ \subseteq x$
  ⟨2⟩5. $x \in n$ or $x = n$
  ⟨2⟩6. CASE: $x \in n$
    PROOF: Then we have $n \subseteq n^+ \subseteq x$ contradicting ⟨2⟩2.
  ⟨2⟩7. CASE: $x = n$
    PROOF: Then we have $n \in n^+ \subseteq x = n$ and $n \subseteq n$ contradicting ⟨2⟩2.
∎

Corollary 6.9.1. *For any natural number n we have $n \notin n$.*

Corollary 6.9.2. *For any natural number n we have $n \neq n^+$.*

Definition 6.10 (Transitive Set)**.** A set E is a *transitive* set iff, whenever $x \in y \in E$, then $x \in E$.

Proposition 6.11. *Every natural number is a transitive set.*

PROOF:
⟨1⟩1. 0 is a transitive set.
  PROOF: Vacuously, if $x \in y \in 0$ then $x \in 0$.
⟨1⟩2. For any natural number n, if n is a transitive set, then n^+ is a transitive set.
  ⟨2⟩1. LET: n be a natural number.
  ⟨2⟩2. ASSUME: n is a transitive set.
  ⟨2⟩3. LET: $x \in y \in n^+$
  ⟨2⟩4. $y \in n$ or $y = n$
  ⟨2⟩5. CASE: $y \in n$
    ⟨3⟩1. $x \in n$
      PROOF: ⟨2⟩2, ⟨2⟩3, ⟨2⟩5.
    ⟨3⟩2. $x \in n^+$
  ⟨2⟩6. CASE: $y = n$
    ⟨3⟩1. $x \in n$
      PROOF: ⟨2⟩3, ⟨2⟩6
    ⟨3⟩2. $x \in n^+$
□

Proposition 6.12. *For any natural numbers m and n, if $m^+ = n^+$ then $m = n$.*

PROOF:
⟨1⟩1. LET: m and n be natural numbers.
⟨1⟩2. ASSUME: $m^+ = n^+$
⟨1⟩3. $m \in m^+ = n^+$
⟨1⟩4. $m \in n$ or $m = n$
⟨1⟩5. $n \in n^+ = m^+$
⟨1⟩6. $n \in m$ or $n = m$
⟨1⟩7. We cannot have $m \in n$ and $n \in m$
  ⟨2⟩1. ASSUME: for a contradiction $m \in n$ and $n \in m$
  ⟨2⟩2. $m \in m$
    PROOF: Since m is a transitive set (Proposition 6.11).
  ⟨2⟩3. Q.E.D.
    PROOF: This contradicts Proposition 6.9.
⟨1⟩8. $m = n$
□

Theorem 6.13 (Recursion Theorem)**.** *Let X be a set. Let $a \in X$. Let $f : X \to X$. There exists a function $u : \omega \to X$ such that $u(0) = a$ and, for all $n \in \omega$, we have $u(n^+) = f(u(n))$.*

PROOF:
$\langle 1\rangle 1$. LET: $\mathcal{C} = \{A \in \mathcal{P}(\omega \times X) : (0, a) \in A \wedge \forall n \in \omega.\forall x \in X.(n, x) \in A \Rightarrow (n^+, f(x)) \in A\}$
$\langle 1\rangle 2$. $\mathcal{C} \neq \emptyset$
PROOF: $\omega \times X \in \mathcal{C}$
$\langle 1\rangle 3$. LET: $u = \bigcap \mathcal{C}$
$\langle 1\rangle 4$. $u \in \mathcal{C}$
$\langle 1\rangle 5$. u is a function.
$\langle 2\rangle 1$. LET: $P(n)$ be the property: $\forall x, y \in X.(n, x) \in u \wedge (n, y) \in u \Rightarrow x = y$
$\langle 2\rangle 2$. $P(0)$
$\langle 3\rangle 1$. $\forall x \in X.(0, x) \in u \Rightarrow x = a$
PROOF: If $(0, x) \in u$ and $x \neq a$ then $u - \{(0, x)\} \in \mathcal{C}$ and so $u - \{(0, x)\} \subseteq u$, which is impossible.
$\langle 2\rangle 3$. For every natural number n, if $P(n)$ then $P(n^+)$.
$\langle 3\rangle 1$. LET: n be a natural number.
$\langle 3\rangle 2$. ASSUME: $P(n)$
$\langle 3\rangle 3$. LET: $x, y \in X$
$\langle 3\rangle 4$. ASSUME: $(n^+, x), (n^+, y) \in u$
$\langle 3\rangle 5$. PICK $x', y' \in X$ such that $(n, x') \in u$, $(n, y') \in u$ and $f(x') = x$ and $f(y') = y$
PROOF: If no such x' exists then $u - \{(n^+, x)\} \in \mathcal{C}$ and so $u - \{(n^+, x)\} \subseteq u$ which is impossible. Similarly for y'.
$\langle 3\rangle 6$. $x' = y'$
PROOF: $\langle 3\rangle 2$
$\langle 3\rangle 7$. $x = y$
$\square$

Proposition 6.14. *For any natural number n, either $n = 0$ or there exists a natural number m such that $n = m^+$.*

PROOF: Easy induction on n. $\square$

Proposition 6.15. *ω is a transitive set.*

PROOF:
$\langle 1\rangle 1$. LET: $P(n)$ be the property $\forall x \in n.x \in \omega$
$\langle 1\rangle 2$. $P(0)$
PROOF: Vacuous.
$\langle 1\rangle 3$. For any natural number n, if $P(n)$ then $P(n^+)$.
$\langle 2\rangle 1$. LET: n be a natural number.
$\langle 2\rangle 2$. ASSUME: $P(n)$
$\langle 2\rangle 3$. LET: $x \in n^+$
$\langle 2\rangle 4$. $x \in n$ or $x = n$
$\langle 2\rangle 5$. CASE: $x \in n$
PROOF: Then $x \in \omega$ by $\langle 2\rangle 2$.
$\langle 2\rangle 6$. CASE: $x = n$
PROOF: Then $x \in \omega$ by $\langle 2\rangle 1$.

∎

Proposition 6.16. *For any natural number n and any nonempty subset $E \subseteq n$, there exists $k \in E$ such that $\forall m \in E.k = m \vee k \in m$.*

PROOF:
⟨1⟩1. LET: $P(n)$ be the property: for any nonempty subset $E \subseteq n$, there exists $k \in E$ such that $\forall m \in E.k = m \vee k \in m$
⟨1⟩2. $P(0)$
PROOF: Vacuous as there is no nonempty subset of 0.
⟨1⟩3. For any natural number n, if $P(n)$ then $P(n^+)$.
⟨2⟩1. LET: n be a natural number.
⟨2⟩2. ASSUME: $P(n)$
⟨2⟩3. LET: E be a nonempty subset of n^+
⟨2⟩4. CASE: $E - \{n\} = \emptyset$
PROOF: Then $E = \{n\}$ so take $k = n$.
⟨2⟩5. CASE: $E - \{n\} \neq \emptyset$
⟨3⟩1. PICK $k \in E - \{n\}$ such that $\forall m \in E - \{n\}.k = m \vee k \in m$
PROOF: By ⟨2⟩2.
⟨3⟩2. $\forall m \in E.k = m \vee k \in m$
PROOF: Since $k \in n$.

∎

Chapter 7

Ordinal Numbers

Definition 7.1 (Ordinal (Number))**.** An *ordinal (number)* is a well ordered set α such that $\forall \xi \in \alpha . s(\xi) = \xi$.

Given ordinals α, β, we write $\alpha < \beta$ iff $\alpha \in \beta$.

Proposition 7.2. *Every natural number is an ordinal.*

PROOF: Easy. □

Proposition 7.3. *ω is an ordinal.*

PROOF: Easy. □

Proposition 7.4. *If α is an ordinal number then so is α^+.*

PROOF: Easy. □

Proposition 7.5. *Let α be an ordinal and $\eta, \xi \in \alpha$. Then $\eta < \xi$ if and only if $\eta \in \xi$.*

PROOF: Easy. □

Proposition 7.6. *Every ordinal is a transitive set.*

PROOF: Easy. □

Proposition 7.7. *Every element of an ordinal is an ordinal.*

PROOF: Easy. □

Proposition 7.8. *Similar ordinals are equal.*

PROOF:
$\langle 1 \rangle 1$. LET: α, β be ordinals.
$\langle 1 \rangle 2$. LET: $f : \alpha \cong \beta$ be a similarity.
PROVE: $\forall \xi \in \alpha . f(\xi) = \xi$
$\langle 1 \rangle 3$. LET: $\xi \in \alpha$

$\langle 1\rangle 4.$ ASSUME: as transfinite induction hypothesis $\forall \eta < \xi . f(\eta) = \eta$
$\langle 1\rangle 5.$ $f(\xi) \subseteq \xi$
  $\langle 2\rangle 1.$ LET: $\eta \in f(\xi)$
  $\langle 2\rangle 2.$ PICK $\zeta \in \alpha$ such that $f(\zeta) = \eta$
  $\langle 2\rangle 3.$ $\zeta \in \xi$
    PROOF: Since $f(\zeta) \in f(\xi)$ and f is a similarity.
  $\langle 2\rangle 4.$ $f(\zeta) = \zeta$
    PROOF: $\langle 1\rangle 4$
  $\langle 2\rangle 5.$ $\eta = \zeta$
    PROOF: $\langle 2\rangle 2$, $\langle 2\rangle 4$
  $\langle 2\rangle 6.$ $\eta \in \xi$
    PROOF: $\langle 2\rangle 3$, $\langle 2\rangle 5$
$\langle 1\rangle 6.$ $\xi \subseteq f(\xi)$
  $\langle 2\rangle 1.$ LET: $\eta \in \xi$
  $\langle 2\rangle 2.$ $\eta = f(\eta) \in f(\xi)$
$\langle 1\rangle 7.$ $f(\xi) = \xi$
□

Proposition 7.9. *Let α and β be ordinals. Then the following are equivalent.*

1. $\alpha \in \beta$
2. $\alpha \subsetneq \beta$
3. *β is a continuation of α.*

PROOF:
$\langle 1\rangle 1.$ $1 \Rightarrow 3$
  PROOF: If $\alpha \in \beta$ then $\alpha = s(\alpha)$.
$\langle 1\rangle 2.$ $3 \Rightarrow 2$
  PROOF: Immediate from definitions.
$\langle 1\rangle 3.$ $2 \Rightarrow 1$
  $\langle 2\rangle 1.$ LET: γ be the least element of β such that $\gamma \notin \alpha$
  $\langle 2\rangle 2.$ $\alpha \subseteq \gamma$
    $\langle 3\rangle 1.$ LET: $\eta \in \alpha$
    $\langle 3\rangle 2.$ $\eta \subseteq \alpha$
    $\langle 3\rangle 3.$ $\gamma \notin \eta$
    $\langle 3\rangle 4.$ $\eta \in \gamma$ or $\eta = \gamma$
    $\langle 3\rangle 5.$ $\eta \neq \gamma$
      PROOF: Since $\eta \in \alpha$ and $\gamma \notin \alpha$.
    $\langle 3\rangle 6.$ $\eta \in \gamma$
  $\langle 2\rangle 3.$ $\gamma \subseteq \alpha$
    PROOF: For all $\eta \in \gamma$ we have $\eta \in \alpha$ by leastness of γ.
  $\langle 2\rangle 4.$ $\gamma = \alpha$
  $\langle 2\rangle 5.$ $\alpha \in \beta$
□

Proposition 7.10. *For any ordinal numbers α and β, either $\alpha = \beta$, or $\alpha < \beta$, or $\beta < \alpha$.*

PROOF:
$\langle 1 \rangle 1$. Either $\alpha = \beta$, or α is similar to an initial segment of β, or β is similar to an initial segment of α.
$\langle 1 \rangle 2$. CASE: α is similar to an initial segment of β.
$\langle 2 \rangle 1$. PICK $\eta \in \beta$ such that $\alpha \sim s(\eta)$
$\langle 2 \rangle 2$. $\alpha \sim \eta$
$\langle 2 \rangle 3$. $\alpha = \eta$
PROOF: Proposition 7.8.
$\langle 2 \rangle 4$. $\alpha \in \beta$
$\langle 1 \rangle 3$. CASE: β is similar to an initial segment of α.
PROOF: Then $\beta \in \alpha$ similarly.
□

Proposition 7.11. *Every set of ordinals is well ordered by $<$.*

PROOF:
$\langle 1 \rangle 1$. LET: E be a set of ordinals.
$\langle 1 \rangle 2$. LET: A be a nonempty subset of E.
$\langle 1 \rangle 3$. PICK $\alpha \in A$
$\langle 1 \rangle 4$. CASE: $\alpha \cap A = \emptyset$
PROOF: Then α is least in A.
$\langle 1 \rangle 5$. CASE: $\alpha \cap A \neq \emptyset$
PROOF: Then $\alpha \cap A$ has a least element, which is least in A.
□

Definition 7.12 (Limit Ordinal)**.** A *limit ordinal* is an ordinal number that is not 0 and not α^+ for any ordinal α.

Proposition 7.13. *For any set E of ordinal numbers, $\bigcup E$ is an ordinal and is the supremum of E.*

PROOF: Proposition 5.37. □

Theorem 7.14 (Burali-Forti Paradox)**.** *There is no set whose members are exactly the ordinal numbers.*

PROOF: For any set of ordinals E, we have $(\bigcup E)^+$ is an ordinal that is not in E. □

Theorem 7.15 (Counting Theorem)**.** *Every well ordered set is similar to a unique ordinal.*

PROOF:
$\langle 1 \rangle 1$. LET: X be a well ordered set.
$\langle 1 \rangle 2$. There exists an ordinal α such that $X \cong \alpha$.
$\langle 2 \rangle 1$. For all $a \in X$, there exists a unique ordinal α such that $s(a) \cong \alpha$
$\langle 3 \rangle 1$. LET: $a \in X$
$\langle 3 \rangle 2$. ASSUME: as transfinite induction hypothesis that, for all $b < a$, there exists a unique ordinal β such that $s(b) \cong \beta$

⟨3⟩3. LET: $\alpha = \{\beta : \beta \text{ is an ordinal } \wedge \exists b < a. s(b) \cong \beta\}$
PROOF: This is a set by the Axiom of Substitution.
⟨3⟩4. α is an ordinal
⟨4⟩1. LET: $\gamma \in \beta \in \alpha$
⟨4⟩2. PICK $b < a$ and $f : s(b) \cong \beta$
⟨4⟩3. PICK $c < b$ such that $f(c) = \gamma$
⟨4⟩4. $f \upharpoonright s(c) : s(c) \cong \gamma$
⟨3⟩5. $s(a) \cong \alpha$
PROOF: The function $f : s(a) \to \alpha$ defined by $f(b)$ is the ordinal such that $s(b) \cong f(b)$ is a similarity.
⟨3⟩6. α is unique.
PROOF: Proposition 7.8.
⟨2⟩2. LET: $\alpha = \{\beta : \beta \text{ is an ordinal } \wedge \exists a \in X. s(a) \cong \beta\}$
PROOF: This is a set by the Axiom of Substitution.
⟨2⟩3. α is an ordinal.
PROOF: Similar.
⟨2⟩4. $X \cong \alpha$
PROOF: Similar.
⟨1⟩3. For any ordinals α and β, if $X \cong \alpha$ and $X \cong \beta$ then $\alpha = \beta$.
PROOF: Proposition 7.8.
□

7.1 Order on the Natural Numbers

Proposition 7.16. *For natural numbers m, n and k, if $m < n$ then $m + k < n + k$.*

PROOF:
⟨1⟩1. LET: $m, n \in \omega$
⟨1⟩2. ASSUME: $m < n$
⟨1⟩3. $m + 0 < n + 0$
⟨1⟩4. $\forall k \in \omega. m + k < n + k \Rightarrow m + k^+ < n + k^+$
PROOF: By Proposition 6.7.
□

Proposition 7.17. *For natural numbers m, n and k, if $m < n$ and $k \neq 0$ then $mk < nk$.*

PROOF:
⟨1⟩1. LET: $m, n \in \omega$
⟨1⟩2. ASSUME: $m < n$
⟨1⟩3. $m1 < n1$
⟨1⟩4. For all $k \in \omega$, if $k \neq 0$ and $mk < nk$ then $m(k + 1) < n(k + 1)$

PROOF:

$$\begin{aligned} m(k+1) &= mk + m \\ &< mk + n && \text{(Proposition 7.16)} \\ &< nk + n && \text{(Proposition 7.16)} \\ &= n(k+1) \end{aligned}$$

∎

Proposition 7.18. *Let n be a natural number. Let X be a proper subset of n. Then there exists $m < n$ such that $X \sim m$.*

PROOF:
⟨1⟩1. LET: $P(n)$ be the property: for every proper subset $X \subsetneq n$, there exists $m < n$ such that $X \sim m$.
⟨1⟩2. $P(0)$
PROOF: Vacuous.
⟨1⟩3. $\forall n \in \omega . P(n) \Rightarrow P(n+1)$
⟨2⟩1. LET: $n \in \omega$
⟨2⟩2. ASSUME: $P(n)$
⟨2⟩3. LET: X be a proper subset of $n+1$
⟨2⟩4. CASE: $X - \{n\} = n$
PROOF: Then $X = n$ so $X \sim n < n + 1$.
⟨2⟩5. CASE: $X - \{n\} \subsetneq n$
⟨3⟩1. PICK $m < n$ such that $X - \{n\} \sim m$
⟨3⟩2. $X \sim m$ or $X \sim m + 1$
PROOF: If $n \in X$ then $X \sim m + 1$. If $n \notin X$ then $X \sim m$.

∎

Proposition 7.19. *For every natural number n, we have n is not equivalent to a proper subset of n.*

PROOF:
⟨1⟩1. LET: $P(n)$ be the property: every one-to-one function $n \to n$ is onto.
⟨1⟩2. $P(0)$
PROOF: The only function $0 \to 0$ is $\emptyset$.
⟨1⟩3. $\forall n \in \omega . P(n) \Rightarrow P(n+1)$
⟨2⟩1. LET: $n \in \omega$
⟨2⟩2. ASSUME: $P(n)$
⟨2⟩3. ASSUME: $f : n+1 \to n+1$ is one-to-one.
⟨2⟩4. LET: $g : n \to n$ be the function

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

PROOF: If $k < n$ and $f(k) = n$ then $f(n) < n$ since f is one-to-one.
⟨2⟩5. g is one-to-one.
⟨3⟩1. LET: $k, l < n$
⟨3⟩2. ASSUME: $g(k) = g(l)$
⟨3⟩3. CASE: $f(k) < n$ and $f(l) < n$

PROOF: Then $f(k) = g(k) = g(l) = f(l)$ so $k = l$ since f is one-to-one.

⟨3⟩4. CASE: $f(k) < n$ and $f(l) = n$

PROOF: Then $f(k) = g(k) = g(l) = f(n)$ contradicting the fact that f is one-to-one.

⟨3⟩5. CASE: $f(k) = n$ and $f(l) < n$

PROOF: Similar.

⟨3⟩6. CASE: $f(k) = n$ and $f(l) = n$

PROOF: Then $k = l$ since f is one-to-one.

⟨2⟩6. g maps n onto n.

PROOF: ⟨2⟩2

⟨2⟩7. f maps $n + 1$ onto $n + 1$.

⟨3⟩1. LET: $l < n + 1$

⟨3⟩2. CASE: $l < n$

⟨4⟩1. PICK $k < n$ such that $g(k) = l$

⟨4⟩2. $f(k) = l$ or $f(n) = l$

⟨3⟩3. CASE: $l = n$

⟨4⟩1. CASE: $f(n) = n$

PROOF: Then $l \in \operatorname{ran} f$ as required.

⟨4⟩2. CASE: $f(n) < n$

⟨5⟩1. PICK $k < n$ such that $g(k) = f(n)$

⟨5⟩2. $f(k) = n$

□

Corollary 7.19.1. *Equivalent natural numbers are equal.*

Proposition 7.20. *The lexicographical order is a well ordering on $\omega \times \omega$.*

PROOF: Easy. □

7.2 Finite Sets

Definition 7.21 (Finite)**.** A set is *finite* iff it is equivalent to a natural number; otherwise, it is *infinite*.

Proposition 7.22. *No finite set is equivalent to one of its proper subsets.*

PROOF: From Proposition 7.19. □

Proposition 7.23. *ω is infinite.*

PROOF: Since the function that maps n to $n + 1$ is a one-to-one correspondence between ω and $\omega - \{0\}$. □

Proposition 7.24. *Every subset of a finite set is finite.*

PROOF: Proposition 7.18. □

Definition 7.25 (Number of Elements)**.** For any finite set E, the *number of elements* in E, $\sharp(E)$, is the unique natural number such that $E \sim \sharp(E)$.

Proposition 7.26. *Let E and F be finite sets. If $E \subseteq F$ then $\sharp(E) \leqslant \sharp(F)$.*

PROOF: Proposition 7.18. ∎

Proposition 7.27. *Let E and F be disjoint finite sets. Then $E \cup F$ is finite and $\sharp(E \cup F) = \sharp(E) \cup \sharp(F)$.*

PROOF:
⟨1⟩1. LET: $P(n)$ be the statement: $n \in \omega$ and for any $m \in \omega$, if $E \sim m$, $F \sim n$ and $E \cap F = \emptyset$, then $E \cup F \sim m + n$
⟨1⟩2. $P(0)$
⟨2⟩1. LET: $m \in \omega$
⟨2⟩2. LET: $E \sim m$ and $F \sim 0$
⟨2⟩3. $F = \emptyset$
⟨2⟩4. $E \cup F = E \sim m = m + 0$
⟨1⟩3. $\forall n \in \omega . P(n) \Rightarrow P(n+1)$
⟨2⟩1. LET: $n \in \omega$
⟨2⟩2. ASSUME: $P(n)$
⟨2⟩3. LET: $m \in \omega$
⟨2⟩4. LET: $E \sim m$ and $F \sim n + 1$
⟨2⟩5. ASSUME: $E \cap F = \emptyset$
⟨2⟩6. PICK $f \in F$
⟨2⟩7. $F - \{f\} \sim n$
⟨2⟩8. $E \cap (F - \{f\}) = \emptyset$
⟨2⟩9. $E \cup (F - \{f\}) \sim m + n$
PROOF: ⟨2⟩2
⟨2⟩10. $E \cup F \sim m + n + 1$
∎

Corollary 7.27.1. *The union of two finite sets is finite.*

PROOF: Since, if E and F are finite, then $E \cup F = (E - F) \cup (E \cap F) \cup (F - E)$ and these are finite and disjoint. ∎

Proposition 7.28. *If E and F are finite sets then $E \times F$ is finite and $\sharp(E \times F) = \sharp(E)\sharp(F)$.*

PROOF:
⟨1⟩1. LET: $P(n)$ be the statement: $n \in \omega$ and for all $m \in \omega$, if $E \sim m$ and $F \sim n$ then $E \times F \sim mn$
⟨1⟩2. $P(0)$
PROOF: If $F \sim 0$ then $F = \emptyset$ so $E \times F = \emptyset \sim 0$.
⟨1⟩3. $\forall n \in \omega . P(n) \Rightarrow P(n+1)$
⟨2⟩1. LET: $n \in \omega$
⟨2⟩2. ASSUME: $P(n)$
⟨2⟩3. LET: $m \in \omega$
⟨2⟩4. ASSUME: $E \sim m$ and $F \sim n + 1$
⟨2⟩5. PICK $f \in F$

⟨2⟩6. $F - \{f\} \sim n$
⟨2⟩7. $E \times (F - \{f\}) \sim mn$
⟨2⟩8. $E \times F = (E \times (F - \{f\})) \cup (E \times \{f\})$
⟨2⟩9. $E \times \{f\} \sim m$
⟨2⟩10. $E \times F \sim mn + m$
Proof: Proposition 7.27.
□

Proposition 7.29. *For any finite sets E and F, we have E^F is finite and $\sharp(E^F) = \sharp(E)^{\sharp(F)}$.*

Proof:
⟨1⟩1. Let: $P(n)$ be the property: $n \in \omega$ and for all $m \in \omega$, if $E \sim m$ and $F \sim n$ then $E^F \sim m^n$
⟨1⟩2. $P(0)$
Proof: Since $E^\varnothing = \{\varnothing\} \sim 1$
⟨1⟩3. $\forall n \in \omega . P(n) \Rightarrow P(n+1)$
⟨2⟩1. Let: $n \in \omega$
⟨2⟩2. Assume: $P(n)$
⟨2⟩3. Let: $m \in \omega$
⟨2⟩4. Let: $E \sim m$ and $F \sim n + 1$
⟨2⟩5. Pick $f \in F$
⟨2⟩6. $F - \{f\} \sim n$
⟨2⟩7. Let: $\phi : E^F \to E^{F-\{f\}} \times E$ be the function $\phi(g) = (g \restriction (F - \{f\}), g(f))$
⟨2⟩8. ϕ is a one-to-one correspondence
⟨2⟩9. $\sharp(E^F) = m^{n+1}$
Proof:

$$\begin{aligned} \sharp(E^F) &= \sharp(E^{F-\{f\}} \times E) & \\ &= \sharp(E^{F-\{f\}})\sharp(E) & \text{(Proposition 7.28)} \\ &= m^n m & (\langle 2\rangle 2, \langle 2\rangle 4) \\ &= m^{n+1} & \end{aligned}$$

□

Corollary 7.29.1. *If E is finite then $\mathcal{P}E$ is finite and $\sharp(\mathcal{P}E) = 2^{\sharp(E)}$.*

Proposition 7.30. *The union of a finite set of finite sets is finite.*

Proof:
⟨1⟩1. Let: $P(n)$ be the property: for any set E, if $E \sim n$ and every element of E is finite, then $\bigcup E$ is finite.
⟨1⟩2. $P(0)$
Proof: Since $\bigcup \varnothing = \varnothing$ is finite.
⟨1⟩3. $\forall n \in \omega . P(n) \Rightarrow P(n+1)$
⟨2⟩1. Let: n be a natural number.
⟨2⟩2. Assume: $P(n)$
⟨2⟩3. Let: $E \sim n + 1$

$\langle 2\rangle 4.$ Pick $X \in E$
$\langle 2\rangle 5.$ $E - \{X\} \sim n$
$\langle 2\rangle 6.$ $\bigcup(E - \{X\})$ is finite.
Proof: $\langle 2\rangle 2$
$\langle 2\rangle 7.$ $\bigcup E = \bigcup(E - \{X\}) \cup X$
$\langle 2\rangle 8.$ $\bigcup E$ is finite.
Proof: Corollary 7.27.1.
□

Proposition 7.31. *Every nonempty finite set of natural numbers has a greatest element.*

Proof:
$\langle 1\rangle 1.$ Let: $P(n)$ be the property: for every $E \subseteq \mathbb{N}$, if $E \sim n$ then E has a greatest element.
$\langle 1\rangle 2.$ $P(1)$
Proof: Since k is the greatest element of $\{k\}$.
$\langle 1\rangle 3.$ $\forall n \geqslant 1.P(n) \Rightarrow P(n+1)$
$\langle 2\rangle 1.$ Let: $n \geqslant 1$
$\langle 2\rangle 2.$ Assume: $P(n)$
$\langle 2\rangle 3.$ Assume: $E \subseteq \omega$ and $E \sim n+1$
$\langle 2\rangle 4.$ Pick $k \in E$
$\langle 2\rangle 5.$ Let: l be the greatest element of $E - \{k\}$
$\langle 2\rangle 6.$ Either k or l is greatest in E.
□

Proposition 7.32. *Every infinite set has a subset equivalent to ω.*

Proof:
$\langle 1\rangle 1.$ Let: X be an infinite set.
$\langle 1\rangle 2.$ Pick a choice function f for X.
$\langle 1\rangle 3.$ Let: $\mathcal{C}$ be the set of all finite subsets of X.
$\langle 1\rangle 4.$ For all $A \in \mathcal{C}$ we have $X - A \in \operatorname{dom} f$.
Proof: For all $A \in \mathcal{C}$ we have $X - A \neq \emptyset$.
$\langle 1\rangle 5.$ Let: $U : \omega \to \mathcal{C}$ be the function defined recursively by $U(0) = \emptyset$ and $U(n+1) = U(n) \cup \{f(X - U(n))\}$ for all $n \in \omega$.
$\langle 1\rangle 6.$ Let: $v : \omega \to X$ be the function $v(n) = f(X - U(n))$
Prove: v is one-to-one.
$\langle 1\rangle 7.$ $\forall n \in \omega.v(n) \notin U(n)$
Proof: Since $v(n) = f(X - U(n)) \in X - U(n)$.
$\langle 1\rangle 8.$ $\forall n \in \omega.v(n) \in U(n+1)$
$\langle 1\rangle 9.$ $\forall m, n \in \omega.n \leqslant m \Rightarrow U(n) \subseteq U(m)$
Proof: Since $U(n) \subseteq U(n+1)$ for all n.
$\langle 1\rangle 10.$ $\forall m, n \in \omega.n < m \Rightarrow v(n) \neq v(m)$
Proof: Since $v(n) \in U(m)$ and $v(m) \notin U(m)$.
□

Corollary 7.32.1. *A set is infinite if and only if it is equivalent to a proper subset.*

7.3 Ordinal Arithmetic

Definition 7.33 (Addition)**.** Let I be a well ordered set and $(\alpha_i)_{i \in I}$ be a sequence of ordinals. Choose a well ordered set A_i such that $A_i \cong \alpha_i$ for each $i \in I$, and assume the sets A_i are pairwise disjoint. The *sum* $\sum_{i \in I} \alpha_i$ is the ordinal of the well ordered set $\bigcup_{i \in I} A_i$, where:

- for $x, y \in A_i$, we have $x <_{\bigcup_{i \in I} A_i} y$ if and only if $x <_{A_i} y$
- for $x \in A_i$ and $y \in A_j$ with $i \neq j$, we have $x <_{\bigcup_{i \in I} A_i} y$ iff $i <_I j$

We write $\alpha + \beta$ for $\sum_{i \in 2} \gamma_i$ where $\gamma_0 = \alpha$ and $\gamma_1 = \beta$.

Proposition 7.34.

$$\begin{aligned} \alpha + 0 &= \alpha \\ 0 + \alpha &= \alpha \\ \alpha + 1 &= \alpha^+ \\ \alpha + (\beta + \gamma) &= (\alpha + \beta) + \gamma \end{aligned}$$

Proof: Easy. $\square$

Proposition 7.35. *For any ordinals α and β, we have $\alpha < \beta$ if and only if there exists $\gamma \neq 0$ such that $\beta = \alpha + \gamma$.*

Proof: Easy. $\square$

Proposition 7.36.

$$1 + \omega = \omega$$

Proof: Easy. $\square$

Definition 7.37 (Multiplication)**.** Given ordinals α and β, the *product* $\alpha\beta$ is the ordinal of $\alpha \times \beta$ under the *reverse lexicographic order*: $(a, b) < (c, d)$ iff $b < d$ or ($b = d$ and $a < c$).

Proposition 7.38.

$$\begin{aligned} \alpha 0 &= 0 \\ 0 \alpha &= 0 \\ \alpha 1 &= \alpha \\ 1 \alpha &= \alpha \\ \alpha(\beta\gamma) &= (\alpha\beta)\gamma \\ \alpha(\beta + \gamma) &= \alpha\beta + \alpha\gamma \end{aligned}$$

Proof: Easy. $\square$

Proposition 7.39. *For ordinals α and β, if $\alpha\beta = 0$ then $\alpha = 0$ or $\beta = 0$.*

PROOF: Easy. □

Example 7.40. The commutative law fails:

$$2\omega = \omega \neq \omega 2$$

PROOF: Easy. □

Example 7.41. The right distributive law fails:

$$(1+1)\omega = \omega \neq 1\omega + 1\omega = \omega 2$$

Definition 7.42 (Exponentiation)**.** Given ordinals α and β, define the ordinal α^β by

$$\begin{aligned} \alpha^0 &= 1 \\ \alpha^{\beta+1} &= \alpha^\beta \alpha \\ \alpha^\lambda &= \bigcup_{\beta<\lambda} \alpha^\beta && (\lambda \text{ a limit ordinal}) \end{aligned}$$

Proposition 7.43.

$$\begin{aligned} 0^\alpha &= 0 && (\alpha \geqslant 1) \\ 1^\gamma &= 1 \\ \alpha^{\beta+\gamma} &= \alpha^\beta \alpha^\gamma \\ \alpha^{\beta\gamma} &= (\alpha^\beta)^\gamma \end{aligned}$$

PROOF: Easy. □

Example 7.44. $(\alpha\beta)^\gamma$ is different from $\alpha^\gamma\beta^\gamma$ in general:

$$(2 \cdot 2)^\omega = \omega \neq 2^\omega 2^\omega = \omega^2 \ .$$

7.4 Arithmetic on the Natural Numbers

Proposition 7.45. *For all $m, n \in \omega$, we have*

$$m + n = n + m \ .$$

PROOF:
⟨1⟩1. LET: $P(m)$ be the property $\forall n \in \omega . m + n = n + m$
⟨1⟩2. $P(0)$
  ⟨2⟩1. LET: $Q(n)$ be the property $0 + n = n + 0$
  ⟨2⟩2. $Q(0)$
    PROOF: Trivial.
  ⟨2⟩3. $\forall n \in \omega . Q(n) \Rightarrow Q(n^+)$
    ⟨3⟩1. LET: $n \in \omega$

⟨3⟩2. Assume: $Q(n)$
⟨3⟩3. $0 + n^+ = n^+ + 0$
Proof:

$$\begin{aligned} 0 + n^+ &= (0 + n)^+ \\ &= (n + 0)^+ && (\langle 3\rangle 2) \\ &= n^+ \\ &= n^+ + 0 \end{aligned}$$

⟨1⟩3. $\forall m \in \omega . P(m) \Rightarrow P(m^+)$
⟨2⟩1. Let: $m \in \omega$
⟨2⟩2. Assume: $P(m)$
⟨2⟩3. Let: $Q(n)$ be the property $m^+ + n = n + m^+$
⟨2⟩4. $Q(0)$
Proof: ⟨1⟩2
⟨2⟩5. $\forall n \in \omega . Q(n) \Rightarrow Q(n^+)$
⟨3⟩1. Let: $n \in \omega$
⟨3⟩2. Assume: $Q(n)$
⟨3⟩3. $Q(n^+)$
Proof:

$$\begin{aligned} m^+ + n^+ &= (m^+ + n)^+ \\ &= (n + m^+)^+ && (\langle 3\rangle 2) \\ &= (n + m)^{++} \\ &= (m + n)^{++} && (\langle 2\rangle 2) \\ &= (m + n^+)^+ \\ &= (n^+ + m)^+ && (\langle 2\rangle 2) \\ &= n^+ + m^+ \end{aligned}$$

□

Proposition 7.46. *For all $m, n \in \omega$, we have*

$$mn = nm \ .$$

Proof:
⟨1⟩1. Let: $P(m)$ be the statement $\forall n \in \omega . mn = nm$
⟨1⟩2. $P(0)$
⟨2⟩1. Let: $Q(n)$ be the statement $0n = n0$
⟨2⟩2. $Q(0)$
Proof: Trivial.
⟨2⟩3. $\forall n \in \omega . Q(n) \Rightarrow Q(n^+)$
⟨3⟩1. Let: $n \in \omega$
⟨3⟩2. Assume: $Q(n)$
⟨3⟩3. $Q(n^+)$

PROOF:

$$\begin{aligned} 0n^+ &= 0n + 0 \\ &= 0n \\ &= n0 && (\langle 3\rangle 2) \\ &= 0 \\ &= n^+0 \end{aligned}$$

$\langle 1\rangle 3.$ $\forall m \in \omega . P(m) \Rightarrow P(m^+)$

$\langle 2\rangle 1.$ LET: $m \in \omega$

$\langle 2\rangle 2.$ ASSUME: $P(m)$

$\langle 2\rangle 3.$ LET: $Q(n)$ be the statement $m^+n = nm^+$

$\langle 2\rangle 4.$ $Q(0)$

PROOF: $\langle 1\rangle 2$

$\langle 2\rangle 5.$ $\forall n \in \omega . Q(n) \Rightarrow Q(n^+)$

$\langle 3\rangle 1.$ LET: $n \in \omega$

$\langle 3\rangle 2.$ ASSUME: $Q(n)$

$\langle 3\rangle 3.$ $Q(n^+)$

PROOF:

$$\begin{aligned} m^+n^+ &= m^+n + m^+ \\ &= (m^+n + m)^+ \\ &= (nm^+ + m)^+ && (\langle 3\rangle 2) \\ &= (nm + n + m)^+ \\ &= (mn + m + n)^+ && (\langle 2\rangle 2, \text{Proposition 7.45}) \\ &= (mn^+ + n)^+ \\ &= (n^+m + n)^+ && (\langle 2\rangle 2) \\ &= n^+m + n^+ \\ &= n^+m^+ \end{aligned}$$

∎

Chapter 8

Countable Sets

Definition 8.1 (Countable)**.** A set A is *countable* or *denumerable* iff there exists an injective function $A \to \omega$.

Definition 8.2 (Countably Infinite)**.** A set is *countably infinite* iff it is similar to ω.

Proposition 8.3. *Every subset of a countable set is countable.*

Proof: Easy. □

Proposition 8.4. *Let X be a set. If there exists a function from ω onto X, then X is countable.*

Proof:
$\langle 1\rangle 1.$ Let: f be a function from ω onto X.
$\langle 1\rangle 2.$ Choose a function $g : X \to \omega$ such that, for all $x \in X$, we have $f(g(x)) = x$.
$\langle 1\rangle 3.$ g is one-to-one.
□

Proposition 8.5. *$\omega \times \omega$ is countable.*

Proof: The sequence

$$(0, 0), (0, 1), (1, 0), (0, 2), (1, 1), (2, 0), \ldots$$

is an enumeration of $\omega \times \omega$. □

Corollary 8.5.1. *A countable union of countable sets is countable.*

Proof:
$\langle 1\rangle 1.$ Let: A be a countable set of countable sets.
$\langle 1\rangle 2.$ Pick a surjection $f : \omega \to A$
$\langle 1\rangle 3.$ For $n \in \omega$, Pick a surjection $g_n : \omega \to f(n)$
$\langle 1\rangle 4.$ Pick a surjection $h : \omega \to \omega \times \omega$
$\langle 1\rangle 5.$ $\lambda n \in \omega . g_{\pi_1(h(n))}(\pi_2(h(n)))$ is a surjection $\omega \to \bigcup A$
□

Corollary 8.5.2. *The Cartesian product of two countable sets is countable.*

Corollary 8.5.3. *For any countable set A, the set of all finite subsets of A is countable.*

PROOF: Prove by induction on n that the set of all subsets of size n is countable. The set of all finite subsets is then the union of these. $\square$

Proposition 8.6. *$\mathcal{P}\omega$ is uncountable.*

PROOF: Cantor's Theorem. $\square$

Chapter 9

Cardinal Numbers

Definition 9.1 (Cardinal Number)**.** A *cardinal number* or *initial ordinal* is an ordinal α such that, for all $\beta < \alpha$, we have $\beta \not\sim \alpha$.

Definition 9.2 (Cardinality)**.** For any set X, the *cardinality* of X, $\operatorname{card} X$, is the least ordinal that is equivalent to X.

Proposition 9.3. *Given sets X and Y, we have $X \sim Y$ if and only if* $\operatorname{card} X = \operatorname{card} Y$*.*

Proof: Easy. □

Proposition 9.4. *For sets X and Y, we have* $\operatorname{card} X \leqslant \operatorname{card} Y$ *if and only if there exists an injective function $X \to Y$.*

Proof: Easy. □

Proposition 9.5. *Every natural number is a cardinal. ω is a cardinal.*

Proof: Easy. □

Proposition 9.6. *Every inifinite cardinal is a limit ordinal.*

Proof: For α infinite we have $f : \alpha^+ \sim \alpha$ where $f(\alpha) = 0$ and $f(\beta) = \beta^+$ for all other β. □

9.1 Cardinal Arithmetic

Definition 9.7 (Addition)**.** Given a family of cardinal numbers $\{\kappa_i\}_{i \in I}$, let $\sum_{i \in I} \kappa_i$ be $\operatorname{card} \bigcup_{i \in I} A_i$, where $\{A_i\}_{i \in I}$ is a pairwise disjoint family of sets with $\operatorname{card} A_i = \kappa_i$ for all i.

We write $\kappa + \lambda$ for $\sum_{i \in 2} \kappa_i$ where $\kappa_0 = \kappa$ and $\kappa_1 = \lambda$.

Proposition 9.8.

$$\kappa + \lambda = \lambda + \kappa$$
$$\kappa + (\lambda + \mu) = (\kappa + \lambda) + \mu$$

PROOF: Easy. □

Proposition 9.9. *Cardinal addition agrees with ordinal addition on the natural numbers.*

PROOF: Easy induction. □

Proposition 9.10. *If $\kappa \leqslant \kappa'$ then $\kappa + \lambda \leqslant \kappa' + \lambda$.*

PROOF: Easy. □

Proposition 9.11. *If κ is an infinite cardinal number then $\kappa + \kappa = \kappa$.*

PROOF:
⟨1⟩1. LET: A be an infinite set.
  PROVE: $A \times 2 \sim A$
⟨1⟩2. LET: $\mathcal{F}$ be the set of all functions f such that there exists $X \subseteq A$ such that $f : X \times 2 \sim X$.
⟨1⟩3. $\mathcal{F}$ is non-empty.
  PROOF: Pick a subset $X \subseteq A$ such that $X \sim \omega$, and a bijection $X \times 2 \sim X$.
⟨1⟩4. $\mathcal{F}$ is partially ordered by extension.
⟨1⟩5. Every chain in $\mathcal{F}$ has an upper bound.
  PROOF: If $\mathcal{C} \subseteq \mathcal{F}$ is a chain then $\bigcup \mathcal{C} \in \mathcal{F}$.
⟨1⟩6. PICK $f \in \mathcal{F}$ maximal.
⟨1⟩7. PICK $X \subseteq A$ such that $f : X \times 2 \sim X$
⟨1⟩8. $X - A$ is finite.
  ⟨2⟩1. ASSUME: for a contradiction $X - A$ is infinite.
  ⟨2⟩2. PICK $Y \subseteq X - A$ such that $Y \sim \omega$.
  ⟨2⟩3. PICK $g : Y \times 2 \sim Y$
  ⟨2⟩4. $f \cup g : (X \cup Y) \times 2 \sim X \cup Y$
  ⟨2⟩5. Q.E.D.
    PROOF: This contradicts the maximality of f.
⟨1⟩9. $\operatorname{card} A + \operatorname{card} A = \operatorname{card} A$
  PROOF:

$$\begin{aligned}
2 \operatorname{card} A &= 2(\operatorname{card} X + \operatorname{card}(A - X)) \\
&= 2 \operatorname{card} X + 2 \operatorname{card}(A - X) \\
&= \operatorname{card} X + 2 \operatorname{card}(A - X) && (\langle 1\rangle 7) \\
&= \operatorname{card} X && (\langle 1\rangle 8) \\
&= \operatorname{card} X + \operatorname{card}(A - X) && (\langle 1\rangle 8) \\
&= \operatorname{card} A
\end{aligned}$$

□

Corollary 9.11.1. *For any cardinals κ and λ that are not both finite, we have*

$$\kappa + \lambda = \max(\kappa, \lambda) \ .$$

Definition 9.12 (Multiplication)**.** Given a family of cardinal numbers $\{\kappa_i\}_{i \in I}$, let $\prod_{i \in I} \kappa_i = \operatorname{card} \bigtimes_{i \in I} \kappa_i$.

We write $\kappa\lambda$ for $\prod_{i \in 2} \kappa_i$ where $\kappa_0 = \kappa$ and $\kappa_1 = \lambda$.

Proposition 9.13.

$$\kappa\lambda = \lambda\kappa$$
$$\kappa(\lambda\mu) = (\kappa\lambda)\mu$$
$$\kappa(\lambda + \mu) = \kappa\lambda + \kappa\mu$$

Proposition 9.14. *Cardinal multiplication agrees with ordinal multiplication on the natural numbers.*

PROOF: Easy induction. □

Proposition 9.15. *If $\kappa \leqslant \kappa'$ then $\kappa\lambda \leqslant \kappa'\lambda$.*

PROOF: Easy. □

Proposition 9.16. *Let $\{\kappa_i\}_{i \in I}$ and $\{\lambda_i\}_{i \in I}$ be families of cardinal numbers with the same index set. If $\kappa_i < \lambda_i$ for all i, then $\sum_{i \in I} \kappa_i < \prod_{i \in I} \lambda_i$.*

PROOF:
⟨1⟩1. Choose a one-to-one function $f_i : \kappa_i \to \lambda_i$ for each $i \in I$
⟨1⟩2. $\sum_{i \in I} \kappa_i \leqslant \prod_{i \in I} \lambda_i$
  PROOF: Define $g : \sum_{i \in I} \kappa_i \to \prod_{i \in I} \lambda_i$ by
$$g(i, \eta)(j) = \begin{cases} f_i(\eta) & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases}$$
⟨1⟩3. There is no surjective function $\sum_{i \in I} \kappa_i < \prod_{i \in I} \lambda_i$
  ⟨2⟩1. LET: $h : \sum_i \kappa_i \to \prod_i \lambda_i$
  ⟨2⟩2. Choose $t(i) < \lambda_i$ for each $i \in I$ such that, for all $\eta < \kappa_i$, we have $t(i) \neq h(i, \eta)(i)$.
    PROOF: Since the function that maps η to $h(i, \eta)(i)$ cannot be surjective $\kappa_i \to \lambda_i$.
  ⟨2⟩3. For all $i \in I$ and $\eta < \kappa_i$ we have $h \neq t(i, \eta)$.
□

Proposition 9.17. *If κ is an infinite cardinal then $\kappa\kappa = \kappa$.*

PROOF:
⟨1⟩1. LET: A be an infinite set.
⟨1⟩2. LET: $\mathcal{F}$ be the set of all functions f such that there exists $X \subseteq A$ such that $f : X \times X \sim X$
⟨1⟩3. $\mathcal{F}$ is nonempty.
  PROOF: Pick a countably infinite $X \subseteq A$. Then $X \times X \sim X$.
⟨1⟩4. $\mathcal{F}$ is partially ordered by extension.
⟨1⟩5. Every chain in $\mathcal{F}$ has an upper bound.
⟨1⟩6. PICK $f \in \mathcal{F}$ maximal.
⟨1⟩7. PICK $X \subseteq A$ such that $f : X \times X \sim X$.
⟨1⟩8. $\operatorname{card} X = \operatorname{card} A$
  ⟨2⟩1. ASSUME: for a contradiction $\operatorname{card} X < \operatorname{card} A$
  ⟨2⟩2. $\operatorname{card} A = \operatorname{card}(A - X)$

PROOF: Corollary 9.11.1.

⟨2⟩3. $\text{card}\, X < \text{card}(A - X)$

⟨2⟩4. PICK $Y \subseteq A - X$ such that $Y \sim X$

⟨2⟩5. PICK $g : (X \times Y) \cup (Y \times X) \cup (Y \times Y) \sim Y$

PROOF:

$$\begin{aligned}
(X \times Y) \cup (Y \times X) \cup (Y \times Y) &\sim 3 \times X \times X && (\langle 2\rangle 4) \\
&\sim 3 \times X && (\langle 1\rangle 7) \\
&\sim X && (\text{Corollary 9.11.1}) \\
&\sim Y && (\langle 2\rangle 4)
\end{aligned}$$

⟨2⟩6. $f \cup g : (X \cup Y) \times (X \cup Y) \sim X \cup Y$

⟨2⟩7. Q.E.D.

PROOF: This contradicts the maximality of f.

□

Corollary 9.17.1. *If κ and λ are non-zero cardinals that are not both finite, then*

$$\kappa\lambda = \max(\kappa, \lambda) \ .$$

Definition 9.18 (Exponentiation)**.** Given cardinal numbers κ and λ, let κ^λ be the cardinality of the set of all functions $\lambda \to \kappa$.

Proposition 9.19.

$$\begin{aligned}
\kappa^{\lambda+\mu} &= \kappa^\lambda \kappa^\mu \\
(\kappa\lambda)^\mu &= \kappa^\mu \lambda^\mu \\
\kappa^{\lambda\mu} &= (\kappa^\lambda)^\mu
\end{aligned}$$

PROOF: Easy. □

Proposition 9.20. *Cardinal exponentiation and ordinal exponentiation agree on the natural numbers.*

PROOF: Easy. □

Proposition 9.21.

$$\text{card}\, \mathcal{P}X = 2^{\text{card}\, X}$$

PROOF: Define $\chi : \mathcal{P}X \sim 2^X$ to be the function that maps S to the function $\chi_S : X \to 2$ where $\chi_S(x) = 1$ if $x \in S$ and $\chi_S(x) = 0$ if $x \notin S$. □

Proposition 9.22. *For any infinite cardinal κ we have $\kappa < 2^\kappa$.*

PROOF: Proposition 9.16. □

Proposition 9.23. *If $\kappa \leqslant \lambda$ then $\kappa^\mu \leqslant \lambda^\mu$.*

PROOF: Easy. □

9.2 Alephs

Definition 9.24 (Aleph)**.** Define the cardinal $\aleph_\alpha$ for every ordinal α as follows: $\aleph_\alpha$ is the least infinite cardinal greater than $\aleph_\beta$ for all $\beta < \alpha$.

Proposition 9.25.

$$\aleph_0 = \omega$$

PROOF: Easy. $\square$

Definition 9.26 (Continuum Hypothesis)**.** The *continuum hypothesis* is the statement $\aleph_1 = 2^{\aleph_0}$.

Definition 9.27 (Generalized Continuum Hypothesis)**.** The *generalized continuum hypothesis* is the statement: for every ordinal α we have $\aleph_{\alpha+1} = 2^{\aleph_\alpha}$.

Chapter 10

Field Theory

Definition 10.1 (Field)**.** A *field* is a triple $(K, +, \cdot)$ such that K is a set, $+$ and $\cdot$ are functions $K^2 \to K$, and:

1. $\forall x, y, z \in K. x + (y + z) = (x + y) + z$
2. $\forall x, y, z \in K. x(yz) = (xy)z$
3. $\forall x, y \in K. x + y = y + x$
4. $\forall x, y \in K. xy = yx$
5. There exists a unique $0 \in K$ such that $\forall x \in K. x + 0 = x$
6. There exists a unique $1 \in K$ such that $\forall x \in K. x1 = x$
7. $0 \neq 1$
8. $\forall x \in K. \exists!(-x) \in K. x + (-x) = 0$
9. For all $x \in K$, if $x \neq 0$ then $\exists!(1/x) \in K. x \cdot 1/x = 1$
10. $\forall x, y, z \in K. x(y + z) = xy + xz$

We call $-x$ the *negation* of x.

Definition 10.2 (Subtraction)**.** In any field K, define *subtraction* $- : K^2 \to K$ by $x - y = x + (-y)$.

Definition 10.3 (Ordered Field)**.** An *ordered field* is a quadruple $(K, +, \cdot, \leqslant)$ such that $(K, +, \cdot)$ is a field and $\leqslant$ is a linear order on K, and:

1. For all $x, y, z \in K$, if $x < y$ then $x + z < y + z$
2. For all $x, y, z \in K$, if $x < y$ and $0 < z$ then $xz < yz$

Chapter 11

Real Numbers

11.1 Axioms for Real Numbers

Let there be a set $\mathbb{R}$, whose elements are called *real numbers*.

Let there be two functions $+, \cdot : \mathbb{R}^2 \to \mathbb{R}$.

Let there be a relation $< \subseteq \mathbb{R}^2$.

Axiom 11.1 (Associativity of Addition)**.**

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

Axiom 11.2 (Associativity of Multiplication)**.**

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

Axiom 11.3 (Commutativity of Addition)**.**

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

Axiom 11.4 (Commutativity of Multiplication)**.**

$$\forall x, y \in \mathbb{R}. xy = yx$$

Axiom 11.5 (Identity for Addition)**.** *There exists a unique $z \in \mathbb{R}$ such that $\forall x \in \mathbb{R}. x + z = x$.*

Definition 11.6 (Zero)**.** The real number *zero*, 0, is the unique real number such that $\forall x \in \mathbb{R}. x + 0 = x$.

Axiom 11.7 (Identity for Multiplication)**.** *There exists a unique $i \in \mathbb{R}$ such that $\forall x \in \mathbb{R}. xi = x$. Further, we have $i \neq 0$.*

Definition 11.8 (One)**.** The real number *one*, 1, is the unique real number such that $\forall x \in \mathbb{R}. x1 = x$.

Axiom 11.9 (Additive Inverses)**.** *For all $x \in \mathbb{R}$, there exists a unique $y \in \mathbb{R}$ such that $x + y = 0$.*

Axiom 11.10 (Multiplicative Inverses)**.** *For all $x \in \mathbb{R}$, if $x \neq 0$ then there exists a unique $y \in \mathbb{R}$ such that $xy = 1$.*

Axiom 11.11 (Distributive Law)**.**

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

Axiom 11.12 (Monotonicity of Addition)**.** *For all $x, y, z \in \mathbb{R}$, if $x < y$ then $x + z < y + z$.*

Axiom 11.13 (Monotonicity of Multiplication)**.** *For all $x, y, z \in \mathbb{R}$, if $x < y$ and $0 < z$ then $xz < yz$.*

Axiom 11.14 (Least Upper Bound Property)**.** *The relation $<$ is a strict linear order on $\mathbb{R}$ with the least upper bound property.*

11.2 Consequences of the Axioms

11.2.1 Negation

Theorem 11.15. *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 11.16.

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

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 11.15, $\langle 1 \rangle 2$.

$\square$

Theorem 11.17.

$$-0 = 0$$

Proof: Since $0 + 0 = 0$. $\square$

Theorem 11.18.

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

Proof: Since $-x + x = 0$. $\square$

Theorem 11.19.

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

Proof:

$$\begin{aligned} x(-y) + xy &= x((-y) + y) && \text{(Distributive Law)} \\ &= x0 && \text{(Definition of } -y\text{)} \\ &= 0 && \text{(Theorem 11.16)} \end{aligned}$$ $\square$

Theorem 11.20.

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

Proof:

$$\begin{aligned} (-1)x &= -(1 \cdot x) && \text{(Theorem 11.19)} \\ &= -x && \text{(Definition of 1)} \end{aligned}$$ $\square$

11.2.2 Subtraction

Theorem 11.21.

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

Proof:

$$\begin{aligned} x(y - z) &= x(y + (-z)) && \text{(Definition of subtraction)} \\ &= xy + x(-z) && \text{(Distributive Law)} \\ &= xy + (-(xz)) && \text{(Theorem 11.19)} \\ &= xy - xz && \text{(Definition of subtraction)} \end{aligned}$$ $\square$

Theorem 11.22.

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

Proof:

$$\begin{aligned} -(x + y) &= (-1)(x + y) && \text{(Theorem 11.20)} \\ &= (-1)x + (-1)y && \text{(Distributive Law)} \\ &= -x + (-y) && \text{(Theorem 11.20)} \\ &= -x - y && \text{(Definition of subtraction)} \end{aligned}$$ $\square$

Theorem 11.23.

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

PROOF:

$$\begin{aligned} -(x-y) &= -(x + (-y)) && \text{(Definition of subtraction)} \\ &= -x - (-y) && \text{(Theorem 11.22)} \\ &= -x + (-(-y)) && \text{(Definition of subtraction)} \\ &= -x + y && \text{(Theorem 11.18)} \ \square \end{aligned}$$

Definition 11.24 (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 11.25. *For any real numbers x and y, if $x \neq 0$ and $xy = x$ then $y = 1$.*

PROOF:
$\langle 1 \rangle 1$. LET: $x, y \in \mathbb{R}$
$\langle 1 \rangle 2$. ASSUME: $x \neq 0$
$\langle 1 \rangle 3$. ASSUME: $xy = x$
$\langle 1 \rangle 4$. $y = 1$
PROOF:

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

$\square$

Definition 11.26 (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 11.27. *For any real number x, if $x \neq 0$ then $x/x = 1$.*

PROOF: Immediate from definitions. $\square$

Theorem 11.28.

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

PROOF:
$\langle 1 \rangle 1$. LET: $x \in \mathbb{R}$
$\langle 1 \rangle 2$. $1/1 = 1$
PROOF: Since $1 \cdot 1 = 1$.
$\langle 1 \rangle 3$. $x/1 = x$
PROOF: Since $x/1 = x \cdot 1/1 = x \cdot 1 = x$.
$\square$

Theorem 11.29. *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:

$$\begin{aligned} y &= 1y && \text{(Definition of 1)} \\ &= (1/x)xy && \text{(Definition of } 1/x, \langle 1 \rangle 2) \\ &= (1/x)0 && (\langle 1 \rangle 2) \\ &= 0 && \text{(Theorem 11.16)} \end{aligned}$$

□

Theorem 11.30. *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 11.30.1. *For any real numbers x, y, z, w with $y \neq 0 \neq w$, we have $(x/y)(z/w) = (xz)/(yw)$.*

Theorem 11.31. *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:

$$\begin{aligned} yw\left(\frac{x}{y} + \frac{z}{w}\right) &= yw\frac{x}{y} + yw\frac{z}{w} \\ &= wx + yz \end{aligned}$$ □

Theorem 11.32. *For any real number x, if $x \neq 0$ then $1/x \neq 0$.*

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

Theorem 11.33. *For any real numbers w, z, if $w \neq 0 \neq z$ then $1/(w/z) = z/w$.*

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

Theorem 11.34. *For any real numbers a, x and y, if $y \neq 0$ then $(ax)/y = a(x/y)$*

PROOF: Since $ya(x/y) = ax$. □

Theorem 11.35. *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 11.34.

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

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

$\square$

Theorem 11.36. *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 11.36.1. *For any real numbers x and y, if $x > 0$ and $y > 0$ then $x + y > 0$.*

Theorem 11.37. *For any real numbers x and y, if $x > 0$ and $y > 0$ then $xy > 0$.*

PROOF:

$$\begin{aligned} xy &> 0y && \text{(Monotonicity of Multiplication)} \\ &= 0 && \text{(Theorem 11.16)} \end{aligned}$$ $\square$

Theorem 11.38. *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 11.39. *For any real numbers x and y, we have $x > y$ iff $-x < -y$.*

PROOF:

$\langle 1\rangle 1.$ If $y < x$ then $-x < -y$.

PROOF: By Monotonicity of Addition adding $-x - y$ to both sides.

$\langle 1\rangle 2.$ If $-x < -y$ then $y < x$.

PROOF: By Monotonicity of Addition adding $x + y$ to both sides.

$\square$

Theorem 11.40. *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 11.38, $\langle 1\rangle 3$.

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

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

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

Proof: Theorem 11.19, $\langle 1 \rangle 5$.

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

Proof: Theorem 11.38, $\langle 1 \rangle 6$.

□

Theorem 11.41. *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 11.40.

□

Theorem 11.42.

$$0 < 1$$

Proof: By Theorem 11.41 since $1 = 1 \cdot 1$. □

Definition 11.43 (Positive)**.** A real number x is *positive* iff $x > 0$.

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

Theorem 11.44. *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 11.40. □

Corollary 11.44.1. *For any real number x, if $x > 0$ then $1/x > 0$.*

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

Theorem 11.45. *For any real numbers x and y, if $x > y > 0$ then $1/x < 1/y$.*

Proof: If $1/y \leqslant 1/x$ then $1 < 1$ by Monotonicity of Multiplication. □

Theorem 11.46. *For any real numbers x and y, if $x < y$ then $x < (x+y)/2 < y$.*

Proof: We have $2x < x + y$ and $x + y < 2y$ by Monotonicity of Addition, hence $x < (x + y)/2 < y$ by Monotonicity of Multiplication since $1/2 > 0$. □

Corollary 11.46.1. $\mathbb{R}$ *is a linear continuum.*

Definition 11.47 (Negative)**.** A real number x is *negative* iff $x < 0$.

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

Theorem 11.48. *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.

⟨1⟩2. For any real numbers x and h, if $0 \leqslant h < 1$, then
$$(x+h)^2 < x^2 + h(2x+1) \ .$$
⟨2⟩1. Let: x and h be real numbers.
⟨2⟩2. Assume: $0 \leqslant h < 1$
⟨2⟩3. $(x+h)^2 < x^2 + h(2x+1)$
Proof:
$$\begin{aligned}(x+h)^2 &= x^2 + 2hx + h^2 \\ &< x^2 + 2hx + h && (\langle 2\rangle 2) \\ &= x^2 + h(2x+1)\end{aligned}$$
⟨1⟩3. For any real numbers x and h, if $h > 0$ then
$$(x-h)^2 > x^2 - 2hx \ .$$
⟨2⟩1. Let: x and h be real numbers.
⟨2⟩2. Assume: $h > 0$
⟨2⟩3. $(x-h)^2 > x^2 - 2hx$
Proof:
$$\begin{aligned}(x-h)^2 &= x^2 - 2hx + h^2 \\ &> x^2 - 2hx && (\langle 2\rangle 2)\end{aligned}$$
⟨1⟩4. For any positive real x, if $x^2 < a$ then there exists $h > 0$ such that $(x+h)^2 < a$.
⟨2⟩1. Let: x be a positive real.
⟨2⟩2. Assume: $x^2 < a$
⟨2⟩3. Let: $h = \min((a - x^2)/(2x+1), 1/2)$
⟨2⟩4. $0 < h < 1$
⟨2⟩5. $(x+h)^2 < a$
Proof:
$$\begin{aligned}(x+h)^2 &< x^2 + h(2x+1) && (\langle 1\rangle 2) \\ &\leqslant a\end{aligned}$$
⟨1⟩5. For any positive real x, if $x^2 > a$ then there exists $h > 0$ such that $(x-h)^2 > a$.
⟨2⟩1. Let: x be a positive real.
⟨2⟩2. Assume: $x^2 > a$
⟨2⟩3. Let: $h = (x^2 - a)/2x$
⟨2⟩4. $h > 0$
⟨2⟩5. $(x-h)^2 > a$
Proof:
$$\begin{aligned}(x-h)^2 &> x^2 - 2hx \\ &= a && (\langle 2\rangle 3)\end{aligned}$$
⟨1⟩6. Let: $B = \{x \in \mathbb{R} : x^2 < a\}$
⟨1⟩7. B is bounded above.
Proof: If $a \geqslant 1$ 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 $a \geqslant 1$ then $1 \in B$. If $a < 1$ then $a \in B$.
⟨1⟩9. Let: $b = \sup B$
⟨1⟩10. $b^2 = a$

$\langle 2 \rangle 1.$ $b^2 \geqslant a$

$\langle 3 \rangle 1.$ Assume: for a contradiction $b^2 < a$

$\langle 3 \rangle 2.$ Pick $h > 0$ such that $(b+h)^2 < a$

Proof: $\langle 1 \rangle 4$

$\langle 3 \rangle 3.$ $b + h \in B$

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

Proof: This contradicts $\langle 1 \rangle 9$.

$\langle 2 \rangle 2.$ $b^2 \leqslant a$

$\langle 3 \rangle 1.$ Assume: for a contradiction $b^2 > a$

$\langle 3 \rangle 2.$ Pick $h > 0$ such that $(b-h)^2 > a$

Proof: $\langle 1 \rangle 5$

$\langle 3 \rangle 3.$ Pick $x \in B$ such that $b - h < x$

Proof: $\langle 1 \rangle 9$

$\langle 3 \rangle 4.$ $(b-h)^2 < x^2 < a$

$\langle 3 \rangle 5.$ Q.E.D.

Proof: This contradicts $\langle 3 \rangle 2$

$\langle 1 \rangle 11.$ For any positive reals b and c, if $b^2 = c^2$ then $b = c$.

$\langle 2 \rangle 1.$ Let: b and c be positive reals.

$\langle 2 \rangle 2.$ Assume: $b^2 = c^2$

$\langle 2 \rangle 3.$ $b^2 - c^2 = 0$

$\langle 2 \rangle 4.$ $(b-c)(b+c) = 0$

$\langle 2 \rangle 5.$ $b - c = 0$ or $b + c = 0$

$\langle 2 \rangle 6.$ $b + c \neq 0$

Proof: Since $b + c > 0$

$\langle 2 \rangle 7.$ $b - c = 0$

$\langle 2 \rangle 8.$ $b = c$

$\square$

Chapter 12

Integers and Rationals

12.1 Positive Integers

Definition 12.1 (Inductive)**.** A set of real numbers A is *inductive* iff $1 \in A$ and $\forall x \in A. x + 1 \in A$.

Definition 12.2 (Positive Integer)**.** The set $\mathbb{Z}_+$ of *positive integers* is the intersection of the set of inductive sets.

Proposition 12.3. *Every positive integer is positive.*

PROOF: The set of positive reals is inductive. □

Proposition 12.4. *1 is the least element of $\mathbb{Z}_+$.*

PROOF: Since $\{x \in \mathbb{R} : x \geqslant 1\}$ is inductive. □

Proposition 12.5. *$\mathbb{Z}_+$ 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 $x + 1$. □

Theorem 12.6 (Principle of Induction)**.** *If A is an inductive set of positive integers then $A = \mathbb{Z}_+$.*

PROOF: Immediate from definitions. □

Theorem 12.7 (Well-Ordering Property)**.** *$\mathbb{Z}_+$ is well ordered.*

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

Theorem 12.8 (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.
□

12.1.1 Exponentiation

Definition 12.9. For a a real number and n a positive integer, define the real number a^n recursively as follows:

$$a^1 = a$$
$$a^{n+1} = a^n a$$

Theorem 12.10. *For all $a \in \mathbb{R}$ and $m, n \in mathbbZ_+$, 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 12.11. *For all $a \in \mathbb{R}$ and $m, n \in \mathbb{Z}_+$,*

$$(a^n)^m = a^{nm} \quad .$$

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: $(a^n)^1 = a^n = a^{n \cdot 1}$

$\langle 1 \rangle 3.$ $\forall m \in \mathbb{Z}_+ . P(m) \Rightarrow P(m+1)$
PROOF:

$$\begin{aligned}
(a^n)^{m+1} &= (a^n)^m a^n \\
&= a^{nm} a^n \\
&= a^{nm+n} && \text{(Theorem 12.10)} \\
&= a^{n(m+1)}
\end{aligned}$$

□

Theorem 12.12. *For any real numbers a and b and positive integer m,*

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

PROOF: Induction on m. □

12.2 Integers

Definition 12.13 (Integer)**.** The set $\mathbb{Z}$ of *integers* is

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

Proposition 12.14. *The sum, difference and product of two integers is an integer.*

PROOF: Easy. □

Example 12.15. $1/2$ is not an integer.

Proposition 12.16. *For any integer n, there is no integer a such that $n < a < n+1$.*

PROOF:
$\langle 1 \rangle 1.$ For any positive integer n, there is no integer a such that $n < a < n+1$.
$\langle 2 \rangle 1.$ There is no integer a such that $1 < a < 2$.
$\langle 3 \rangle 1.$ There is no positive integer a such that $1 < a < 2$.
$\langle 4 \rangle 1.$ We do not have $1 < 1 < 2$.
$\langle 4 \rangle 2.$ For any positive integer n, we do not have $1 < n+1 < 2$.
PROOF: Since $n \geqslant 1$ so $n+1 \geqslant 2$.
$\langle 3 \rangle 2.$ We do not have $1 < 0 < 2$.
$\langle 3 \rangle 3.$ For any positive integer a, we do not have $1 < -a < 2$.
PROOF: Since $-a < 0 < 1$.
$\langle 2 \rangle 2.$ 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 $n < a-1 < n+1$.
$\langle 1 \rangle 2.$ There is no integer a such that $0 < a < 1$.
PROOF: If $0 < a < 1$ then $1 < a+1 < 2$.
$\langle 1 \rangle 3.$ 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 12.17. *Every nonempty subset of $\mathbb{Z}$ bounded above has a largest element.*

PROOF:
$\langle 1\rangle 1$. LET: S be a nonempty subset of $\mathbb{Z}$ bounded above.
$\langle 1\rangle 2$. LET: u be an upper bound for S.
$\langle 1\rangle 3$. PICK an integer $n > u$
  PROOF: Archimedean property.
$\langle 1\rangle 4$. LET: k be the least positive integer such that $n - k \in S$.
  $\langle 2\rangle 1$. PICK $m \in S$
  $\langle 2\rangle 2$. $n - m$ is a positive integer.
  $\langle 2\rangle 3$. There exists a positive integer k such that $n - k \in S$.
$\langle 1\rangle 5$. $n - k$ is the greatest element in S.
  $\langle 2\rangle 1$. LET: $m \in S$
  $\langle 2\rangle 2$. $n - m \geqslant k$
  $\langle 2\rangle 3$. $m \leqslant n - k$
□

Theorem 12.18. *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:
$\langle 1\rangle 1$. $\{n \in \mathbb{Z} : n < x\}$ is a nonempty set of integers bounded above.
  $\langle 2\rangle 1$. PICK $m > -x$
    PROOF: Archimedean property.
  $\langle 2\rangle 2$. $-m < x$
  $\langle 2\rangle 3$. $\{n \in \mathbb{Z} : n < x\}$ is nonempty.
$\langle 1\rangle 2$. LET: n be the greatest integer such that $n < x$
$\langle 1\rangle 3$. $x < n + 1$
$\langle 1\rangle 4$. If n' is an integer with $n' < x < n' + 1$ then $n' = n$.
  PROOF: We have $n' < n + 1$ so $n' \leqslant n$, and $n < n' + 1$ so $n \leqslant n'$.
□

Definition 12.19 (Even)**.** An integer n is *even* iff $n/2$ is an integer; otherwise, n is *odd*.

Theorem 12.20. *If the integer m is odd then there exists an integer n such that $m = 2n + 1$.*

PROOF:
$\langle 1\rangle 1$. LET: n be the integer such that $n < m/2 < n + 1$
  PROOF: Theorem 12.18.
$\langle 1\rangle 2$. $2n < m < 2n + 2$
$\langle 1\rangle 3$. $m = 2n + 1$
□

Theorem 12.21. *The product of two odd integers is odd.*

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

Corollary 12.21.1. *If p is an odd integer and n is a positive integer then p^n is an odd integer.*

Definition 12.22 (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:

$$a^0 = 1$$
$$a^{-n} = 1/a^n \qquad (n \text{ a positive integer})$$

Theorem 12.23 (Laws of Exponents)**.** *For all non-zero reals a and b and integers m and n,*

$$a^n a^m = a^{n+m}$$
$$(a^n)^m = a^{nm}$$
$$a^m b^m = (ab)^m$$

PROOF: Easy. □

12.3 Rational Numbers

Definition 12.24 (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 12.25. *$\sqrt{2}$ is irrational.*

PROOF:
⟨1⟩1. For any positive rational a, there exist positive integers m and n not both even such that $a = m/n$.
  ⟨2⟩1. LET: a be a positive rational.
  ⟨2⟩2. LET: n be the least positive integer such that na is a positive integer.
  ⟨2⟩3. LET: $m = na$
  ⟨2⟩4. ASSUME: for a contradiction m and n are both even.
  ⟨2⟩5. $m/2 = (n/2)a$
  ⟨2⟩6. Q.E.D.
    PROOF: This contradicts the leastness of n (⟨2⟩2).
⟨1⟩2. ASSUME: for a contradiction $\sqrt{2}$ is rational.
⟨1⟩3. PICK positive integers m and n not both even such that $\sqrt{2} = m/n$.
⟨1⟩4. $m^2 = 2n^2$
⟨1⟩5. m^2 is even.

$\langle 1 \rangle 6.$ m is even.
PROOF: Theorem 12.21.
$\langle 1 \rangle 7.$ 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 12.21.
$\langle 1 \rangle 12.$ Q.E.D.
PROOF: $\langle 1 \rangle 3$, $\langle 1 \rangle 6$ and $\langle 1 \rangle 11$ form a contradiction.
$\square$