Summary of Halmos' Naive Set Theory

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Contents

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 $x \notin A$.

Axiom 1.1 (Axiom of Extensionality). *Two sets are equal if and only if they have the same elements.*

Axiom 1.2 (Axiom of Comprehension, Aussonderungsaxiom). *To every set A and to every condition $S(x)$ there corresponds a set B whose elements are exactly those elements x of A for which $S(x)$ holds.*

Axiom 1.3 (Axiom of Pairing). *For any two sets, there exists a set that they both belong to.*

Axiom 1.4 (Union Axiom). *For every set A, there exists a set that contains all the elements that belong to at least one element of A.*

Definition 1.5 (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 1.6 (Power Set Axiom). *For any set A, there exists a set that contains all the subsets of A.*

Axiom 1.7 (Axiom of Infinity). *There exists a set I such that:*

- *I has an element that has no elements*
- *for all $x \in I$, there exists $y \in I$ such that the elements of y are exactly x and the elements of x.*

Chapter 2

The Subset Relation

Theorem 2.1. *For any set A, we have $A \subseteq A$.*

PROOF: Every element of A is an element of A. $\square$

Theorem 2.2. *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. $\square$

Theorem 2.3. *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. $\square$

Definition 2.4 (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 $A \neq B$.

Chapter 3

Comprehension Notation

Definition 3.1. Given a set A and a condition $S(x)$, we write $\{x \in A : S(x)\}$ for the set whose elements are exactly those elements x of A for which $S(x)$ holds.

PROOF: This exists by the Axiom of Comprehension and is unique by the Axiom of Extensionality. $\square$

Theorem 3.2. *There is no set that contains every set.*

PROOF:
$\langle 1 \rangle 1.$ LET: A be a set.
PROVE: There exists a set B such that $B \notin A$.
$\langle 1 \rangle 2.$ LET: $B = \{x \in A : x \notin x\}$
$\langle 1 \rangle 3.$ If $B \in A$ then we have $B \in B$ if and only if $B \notin B$.
$\langle 1 \rangle 4.$ $B \notin A$
$\square$

Chapter 4

Unordered Pairs

Theorem 4.1. *There exists a set with no elements.*

PROOF: Immediate from the Axiom of Infinity. □

Definition 4.2 (Empty Set)**.** The *empty set* $\varnothing$ is the set with no elements.

Theorem 4.3. *For any set A we have $\varnothing \subset A$.*

PROOF: Vacuous. □

Definition 4.4 ((Unordered) Pair)**.** For any sets a and b, the *(unordered) pair* $\{a, b\}$ is the set whose elements are just a and b.

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

Definition 4.5 (Singleton)**.** For any set a, the *singleton* $\{a\}$ is defined to be $\{a, a\}$.

Chapter 5

Unions

Definition 5.1 (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 5.2.

$$\bigcup \emptyset = \emptyset$$

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

Proposition 5.3. *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 5.4. We write $A \cup B$ for $\bigcup\{A, B\}$.

Proposition 5.5. *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 $x \in A$. □

Proposition 5.6 (Idempotence)**.** *For any set A, we have $A \cup A = A$.*

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

Proposition 5.7. *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 $x \in B$". □

Proposition 5.8. *For any sets a and b, we have $\{a\} \cup \{b\} = \{a, b\}$.*

PROOF: Immediate from definitions. □

Chapter 6

Intersections

Definition 6.1 (Intersection)**.** For any sets A and B, the *intersection* $A \cap B$ is defined to be $\{x \in A : x \in B\}$.

Proposition 6.2. *For any set A, we have $A \cap \emptyset = \emptyset$.*

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

Proposition 6.3. *For any set A, we have*

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

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

Proposition 6.4. *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 $x \in A$". □

Proposition 6.5. *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 "$((x \in A \wedge x \in B) \vee x \in C) \Leftrightarrow (x \in A \wedge (x \in B \vee x \in C))$". □

Definition 6.6 (Disjoint)**.** Two sets A and B are *disjoint* if and only if $A \cap B = \emptyset$.

Definition 6.7 (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 6.8 (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:

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

$\langle 1 \rangle 2$. 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 $I = \{x \in A : \forall X \in \mathcal{C}. x \in X\}$.

$\langle 1 \rangle 3$. 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.

$\square$

Chapter 7

Unordered Triples

Definition 7.1 ((Unordered) Triple)**.** Given sets a_1, $\ldots$, a_n, define the *(unordered) n-tuple* $\{a_1, \ldots, a_n\}$ to be

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

Chapter 8

Relative Complements

Definition 8.1 (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 8.2. *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 8.3. *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 8.4. *For any set E we have*

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

PROOF: There is no x such that $x \in E$ and $x \notin E$. □

Proposition 8.5. *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 8.6. *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 8.7. *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 8.8. 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 8.9 (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 8.10 (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 8.11. *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 8.12. *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 8.13. *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 8.14. *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 8.15. *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 8.16. *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 8.17 (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 8.18 (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. ∎

Chapter 9

Symmetric Difference

Definition 9.1 (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 9.2. *For any sets A and B, we have*

$$A + B = B + A$$

PROOF: From the commutativity of union. □

Proposition 9.3. *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 9.4. *For any set A, we have*

$$A + \emptyset = A \ .$$

PROOF:

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

□

Proposition 9.5. *For any set A we have*

$$A + A = \emptyset \ .$$

PROOF:

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

□

Chapter 10

Power Sets

Definition 10.1 (Power Set)**.** For any set A, the *power set* of A, $\mathcal{P}A$, is the set whose elements are exactly the subsets of A.

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

Proposition 10.2.

$$\mathcal{P}\emptyset = \{\emptyset\}$$

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

Proposition 10.3. *For any set a, we have*

$$\mathcal{P}\{a\} = \{\emptyset, \{a\}\} \enspace .$$

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

Proposition 10.4. *For any sets a and b, we have*

$$\mathcal{P}\{a,b\} = \{\emptyset, \{a\}, \{b\}, \{a,b\}\} \enspace .$$

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

Proposition 10.5. *For any nonempty set $\mathcal{C}$ we have*

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

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 10.6. *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 $x \subseteq \bigcup\mathcal{C}$. $\square$

Proposition 10.7. *For any set E, we have*

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

PROOF: Since $\varnothing \in \mathcal{P}E$. $\square$

Proposition 10.8. *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 $X \subseteq F$. $\square$

Chapter 11

Ordered Pairs

Definition 11.1 (Ordered Pair)**.** For any sets a and b, the *ordered pair* (a, b) is defined by

$$(a, b) := \{\{a\}, \{a, b\}\} \ .$$

Proposition 11.2. *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: $\{b\} = \{a, b\} - \{a\} = \{x, y\} - \{x\} = \{y\}$.
□

Definition 11.3 (Cartesian Product)**.** For any sets A and B, the *Cartesian product* $A \times B$ is

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

Proposition 11.4. *For any sets A, B and X, we have*

$$(A - B) \times X = (A \times X) - (B \times X) \ .$$

Proof: Easy. □

Proposition 11.5. *For any sets A and B, we have $A \times B = \varnothing$ if and only if $A = \varnothing$ or $B = \varnothing$.*

Proof: Easy. □

Proposition 11.6. *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 $A \neq \varnothing$ and $B \neq \varnothing$.*

Proof: Easy. □

Chapter 12

Relations

Definition 12.1 (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 12.2 (Domain)**.** The *domain* of a relation R is the set

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

Definition 12.3 (Range)**.** The *range* of a relation R is the set

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

Definition 12.4 (Reflexive)**.** Let R be a relation on X. Then R is *reflexive* iff, for all $x \in X$, we have xRx.

Definition 12.5 (Symmetric)**.** Let R be a relation on X. Then R is *symmetric* iff, whenever xRy, then yRx.

Definition 12.6 (Transitive)**.** Let R be a relation on X. Then R is *transitive* iff, whenever xRy and yRz, then xRz.

Definition 12.7 (Equivalence Relation)**.** Let R be a relation on X. Then R is an *equivalence relation* iff it is reflexive, symmetric and transitive.

Definition 12.8 (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 12.9 (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 12.10 (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 12.11. *Let R be an equivalence relation on X. Then X/R is a partition of X that induces the relation R.*

PROOF: Easy. ☐

Theorem 12.12. *Let P be a partition of X. Then X/P is an equivalence relation on X, and $P = X/(X/P)$.*

PROOF: Easy. ☐

Definition 12.13 (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

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

Proposition 12.14. *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*

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

PROOF: Easy. ☐

Example 12.15. 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 12.16. *A relation R is transitive if and only if $RR \subseteq R$.*

PROOF: Easy. ☐

Definition 12.17 (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

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

Proposition 12.18. *For any relation R, we have*

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

PROOF: Easy. ☐

Proposition 12.19. *For any relation R, we have*

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

PROOF: Easy. ☐

Proposition 12.20. *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 12.21. *A relation R is symmetric if and only if $R \subseteq R^{-1}$.*

PROOF: Easy. □

Definition 12.22 (Identity Relation)**.** For any set X, the *identity relation* I_X on X is

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

Proposition 12.23. *Let R be a relation between X and Y. Then*

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

PROOF: Easy. □

Proposition 12.24. *A relation R on a set X is reflexive if and only if $I_X \subseteq R$.*

PROOF: Easy. □

Chapter 13

Functions

Definition 13.1 (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 13.2 (Onto)**.** Let $f : X \to Y$. We say f maps X *onto* Y iff $\operatorname{ran} f = Y$.

Definition 13.3 (Image)**.** Let $f : X \to Y$ and $A \subseteq X$. The *image* of A under f is

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

Definition 13.4 (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 13.5. *For any set X, the identity relation I_X is a function $X \to X$.*

Proof: Easy. □

Definition 13.6 (Restriction)**.** Let $f : Y \to Z$ and $X \subseteq Y$. The *restriction* of f to X is the function $f \restriction X : X \to Z$ defined by

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

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 13.7 (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 13.8 (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 $\pi(x) = x/R$.

Definition 13.9 (One-to-One)**.** A function $f : X \to Y$ is *one-to-one*, or a *one-to-one correspondence*, iff, for all $x, y \in X$, if $f(x) = f(y)$ then $x = y$.

Proposition 13.10. *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 13.11. *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. □

Chapter 14

Families

Definition 14.1 (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.

Proposition 14.2 (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*

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

PROOF: Easy. □

Proposition 14.3 (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*

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

PROOF: Easy. □

Proposition 14.4 (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*

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

PROOF: Easy. □

Proposition 14.5 (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*

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

PROOF: Easy. □

Proposition 14.6. *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 14.7. *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 14.8 (Cartesian Product of a Family of Sets)**.** Let $\{A_i\}_{i\in I}$ be a family of sets. The *Cartesian product* $\times_{i\in I} A_i$ 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 $\times_{i\in I} A$.

Definition 14.9 (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 14.10. *Let $\{A_i\}_{i\in I}$ and $\{B_j\}_{j\in J}$ be families of sets. Then*

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

PROOF: Easy. □

Proposition 14.11. *Let $\{A_i\}_{i\in I}$ and $\{B_j\}_{j\in J}$ be nonempty families of sets. Then*

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

PROOF: Easy. □

Proposition 14.12. *Let $f : X \to Y$. Let $\{A_i\}_{i\in I}$ be a family of subsets of X. Then*

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

PROOF: Easy. □

Example 14.13. 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 $f\left(\bigcap_{i\in I} A_i\right) = f(\emptyset) = \emptyset$ but $\bigcap_{i\in I} f(A_i) = \{c\}$.

Chapter 15

Inverses and Composites

Definition 15.1 (Inverse)**.** Given a function $f : X \to Y$, the *inverse* of f is the function $f^{-1} : \mathcal{P}Y \to \mathcal{P}X$ defined by

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

We call $f^{-1}(B)$ the *inverse image* of B under f.

Proposition 15.2. *Let $f : X \to Y$. Then f maps X onto Y if and only if the inverse image of any nonempty subset of Y is nonempty.*

Proof: Easy. □

Proposition 15.3. *Let $f : X \to Y$. Then f is one-to-one if and only if the inverse image of any singleton subset of Y is a singleton.*

Proof: Easy. □

Proposition 15.4. *Let $f : X \to Y$. Let $B \subseteq Y$. Then*

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

Proof: Easy. □

Proposition 15.5. *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: Easy. □

Proposition 15.6. *Let $f : X \to Y$. Let $\{B_i\}_{i \in I}$ be a family of subsets of Y. Then*

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

PROOF: Easy. □

Proposition 15.7. *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. □

Proposition 15.8. *Let $f : X \to Y$ and $B \subseteq Y$. Then $f^{-1}(Y - B) = X - f^{-1}(B)$.*

PROOF: Easy. □

Proposition 15.9. *Let $f : X \to Y$ be one-to-one. Then the inverse of f as a relation, f^{-1}, is a function $f^{-1} : \operatorname{ran} f \to X$, and for all $y \in \operatorname{ran} f$, we have $f^{-1}(y)$ is the unique x such that $f(x) = y$.*

PROOF: Easy. □

Proposition 15.10. *Let $f : X \to Y$ and $g : Y \to Z$. Then $gf : X \to Z$ and, for all $x \in X$, we have*

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

PROOF: Easy. □

Example 15.11. Example 12.15 shows that function composition is not commutative in general.

Proposition 15.12. *Let $f : X \to Y$ and $g : Y \to Z$. Then*

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

PROOF: Easy. □

Proposition 15.13. *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. □

Chapter 16

Numbers

Definition 16.1 (Successor)**.** The *successor* of a set x, x^+, is defined by

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

Definition 16.2. We define

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

etc.

Definition 16.3 (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 16.4. *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 16.5. 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 16.6 (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 16.7. *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: $m^+ \in n^{++}$
□

Chapter 17

The Peano Axioms

Theorem 17.1 (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 17.2.

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

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

Corollary 17.2.2. *For any natural number n we have $n \neq n^+$.*

Definition 17.3 (Transitive Set)**.** A set E is a *transitive* set iff, whenever $x \in y \in E$, then $x \in E$.

Proposition 17.4. *Every natural number is a transitive set.*

Proof:
⟨1⟩1. 0 is a transitive set.

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

Proposition 17.5. *For any natural numbers m and n, if $m^+ = n^+$ then $m = n$.*

PROOF:
$\langle 1\rangle 1$. LET: m and n be natural numbers.
$\langle 1\rangle 2$. ASSUME: $m^+ = n^+$
$\langle 1\rangle 3$. $m \in m^+ = n^+$
$\langle 1\rangle 4$. $m \in n$ or $m = n$
$\langle 1\rangle 5$. $n \in n^+ = m^+$
$\langle 1\rangle 6$. $n \in m$ or $n = m$
$\langle 1\rangle 7$. We cannot have $m \in n$ and $n \in m$
$\langle 2\rangle 1$. ASSUME: for a contradiction $m \in n$ and $n \in m$
$\langle 2\rangle 2$. $m \in m$
PROOF: Since m is a transitive set (Proposition 17.4).
$\langle 2\rangle 3$. Q.E.D.
PROOF: This contradicts Proposition 17.2.
$\langle 1\rangle 8$. $m = n$
$\square$

Theorem 17.6 (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.

⟨2⟩1. LET: $P(n)$ be the property: $\forall x, y \in X.(n,x) \in u \wedge (n,y) \in u \Rightarrow x = y$
⟨2⟩2. $P(0)$
⟨3⟩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.
⟨2⟩3. For every natural number n, if $P(n)$ then $P(n^+)$.
⟨3⟩1. LET: n be a natural number.
⟨3⟩2. ASSUME: $P(n)$
⟨3⟩3. LET: $x, y \in X$
⟨3⟩4. ASSUME: $(n^+, x), (n^+, y) \in u$
⟨3⟩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'.
⟨3⟩6. $x' = y'$
PROOF: ⟨3⟩2
⟨3⟩7. $x = y$
□

Proposition 17.7. *For any natural number n, either $n = 0$ or there exists a natural number m such that $n = m^+$.*

PROOF: Easy induction on n. □

Proposition 17.8. *ω is a transitive set.*

PROOF:
⟨1⟩1. LET: $P(n)$ be the property $\forall x \in n.x \in \omega$
⟨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: $x \in n^+$
⟨2⟩4. $x \in n$ or $x = n$
⟨2⟩5. CASE: $x \in n$
PROOF: Then $x \in \omega$ by ⟨2⟩2.
⟨2⟩6. CASE: $x = n$
PROOF: Then $x \in \omega$ by ⟨2⟩1.
□

Proposition 17.9. *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.

$\langle 1 \rangle 3$. 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: E be a nonempty subset of n^+

$\langle 2 \rangle 4$. CASE: $E - \{n\} = \emptyset$

PROOF: Then $E = \{n\}$ so take $k = n$.

$\langle 2 \rangle 5$. CASE: $E - \{n\} \neq \emptyset$

$\langle 3 \rangle 1$. PICK $k \in E - \{n\}$ such that $\forall m \in E - \{n\}. k = m \vee k \in m$

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

$\langle 3 \rangle 2$. $\forall m \in E. k = m \vee k \in m$

PROOF: Since $k \in n$.

□

Chapter 18

Arithmetic

Definition 18.1 (Addition)**.** Define *addition* $+$ on ω by recursion thus:

$$\begin{aligned} m + 0 &= m \\ m + n^+ &= (m + n)^+ \end{aligned}$$

Proposition 18.2. *For all* $m, n, p \in \omega$ *we have*

$$m + (n + p) = (m + n) + p \enspace .$$

Proof:
$\langle 1 \rangle 1$. Let: $P(p)$ be the property $\forall m, n \in \omega . m + (n + p) = (m + n) + p$
$\langle 1 \rangle 2$. $P(0)$
Proof: $m + (n + 0) = m + n = (m + n) + 0$.
$\langle 1 \rangle 3$. $\forall p \in \omega . P(p) \Rightarrow P(p^+)$
$\langle 2 \rangle 1$. Let: $p \in \omega$
$\langle 2 \rangle 2$. Assume: $P(p)$
$\langle 2 \rangle 3$. Let: $m, n \in \omega$
$\langle 2 \rangle 4$. $m + (n + p^+) = (m + n) + p^+$
Proof:

$$\begin{aligned} m + (n + p^+) &= m + (n + p)^+ \\ &= (m + (n + p))^+ \\ &= ((m + n) + p)^+ \\ &= (m + n) + p^+ \end{aligned}$$

□

Proposition 18.3. *For all* $m, n \in \omega$, *we have*

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

Proof:
$\langle 1 \rangle 1$. Let: $P(m)$ be the property $\forall n \in \omega . m + n = n + m$

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

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

$\langle 1\rangle 3.$ $\forall m \in \omega . P(m) \Rightarrow P(m^+)$
$\langle 2\rangle 1.$ LET: $m \in \omega$
$\langle 2\rangle 2.$ ASSUME: $P(m)$
$\langle 2\rangle 3.$ LET: $Q(n)$ be the property $m^+ + n = n + m^+$
$\langle 2\rangle 4.$ $Q(0)$
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:

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

$\square$

Definition 18.4 (Multiplication)**.** Define *multiplication* $\cdot$ on ω by

$$\begin{aligned} m0 &= 0 \\ mn^+ &= mn + m \end{aligned}$$

Proposition 18.5. *For all $m, n, p \in \omega$, we have*

$$m(n+p) = mn + mp \ .$$

PROOF:
$\langle 1\rangle 1.$ LET: $P(p)$ be the statement $\forall m, n \in \omega . m(n+p) = mn + mp$

$\langle 1 \rangle 2.$ $P(0)$

PROOF:

$$\begin{aligned} m(n+0) &= mn \\ &= mn + 0 \\ &= mn + m0 \end{aligned}$$

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

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

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

$\langle 2 \rangle 3.$ LET: $m, n \in \omega$

$\langle 2 \rangle 4.$ $m(n + p^+) = mn + mp^+$

PROOF:

$$\begin{aligned} m(n+p^+) &= m(n+p)^+ \\ &= m(n+p) + m \\ &= (mn + mp) + m && (\langle 2 \rangle 2) \\ &= mn + (mp + m) && \text{(Proposition 18.2)} \\ &= mn + mp^+ \end{aligned}$$

□

Proposition 18.6. *For all* $m, n, p \in \omega$ *we have*

$$m(np) = (mn)p \ .$$

PROOF:

$\langle 1 \rangle 1.$ LET: $P(p)$ be the statement $\forall m, n \in \omega . m(np) = (mn)p$

$\langle 1 \rangle 2.$ $P(0)$

PROOF:

$$\begin{aligned} m(n0) &= m0 \\ &= 0 \\ &= (mn)0 \end{aligned}$$

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

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

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

$\langle 2 \rangle 3.$ LET: $m, n \in \omega$

$\langle 2 \rangle 4.$ $m(np^+) = (mn)p^+$

PROOF:

$$\begin{aligned} m(np^+) &= m(np + n) \\ &= m(np) + mn && \text{(Proposition 18.5)} \\ &= (mn)p + mn && (\langle 2 \rangle 2) \\ &= (mn)p^+ \end{aligned}$$

□

Proposition 18.7. *For all* $m, n \in \omega$, *we have*

$$mn = nm \ .$$

PROOF:
$\langle 1\rangle 1.$ LET: $P(m)$ be the statement $\forall n \in \omega . mn = nm$
$\langle 1\rangle 2.$ $P(0)$
$\langle 2\rangle 1.$ LET: $Q(n)$ be the statement $0n = n0$
$\langle 2\rangle 2.$ $Q(0)$
PROOF: Trivial.
$\langle 2\rangle 3.$ $\forall n \in \omega . Q(n) \Rightarrow Q(n^+)$
$\langle 3\rangle 1.$ LET: $n \in \omega$
$\langle 3\rangle 2.$ ASSUME: $Q(n)$
$\langle 3\rangle 3.$ $Q(n^+)$
PROOF:

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

$\langle 1\rangle 3.$ $\forall m \in \omega . P(m) \Rightarrow P(m^+)$
$\langle 2\rangle 1.$ 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:

$$\begin{aligned} m^+n^+ &= m^+n + m^+ \\ &= (m^+n + m)^+ \\ &= (nm^+ + m)^+ && (\langle 3\rangle 2) \\ &= (nm + n + m)^+ \\ &= (mn + m + n)^+ && (\langle 2\rangle 2, \text{Proposition 18.2, Proposition 18.3}) \\ &= (mn^+ + n)^+ \\ &= (n^+m + n)^+ && (\langle 2\rangle 2) \\ &= n^+m + n^+ \\ &= n^+m^+ \end{aligned}$$

$\square$

Definition 18.8 (Exponentiation)**.** Define *exponentiation* on ω by recursion:

$$\begin{aligned} m^0 &= 1 \\ m^{n^+} &= m^n m \end{aligned}$$

Proposition 18.9. *For all $m, n, p \in \omega$ we have*

$$m^{n+p} = m^n m^p \ .$$

PROOF:
⟨1⟩1. $m^{n+0} = m^n m^0$
PROOF:

$$\begin{aligned} m^{n+0} &= m^n \\ &= m^n 1 \\ &= m^n m^0 \end{aligned}$$

⟨1⟩2. If $m^{n+p} = m^n m^p$ then $m^{n+p^+} = m^n m^{p^+}$
PROOF:

$$\begin{aligned} m^{n+p^+} &= m^{n+p} m \\ &= m^n m^p m \\ &= m^n m^{p^+} \end{aligned}$$

□

Proposition 18.10. *For all $m, n, p \in \omega$ we have*

$$(m^n)^p = m^{np} \ .$$

PROOF:
⟨1⟩1. $(m^n)^0 = m^{n0}$
PROOF: Both are equal to 1.
⟨1⟩2. If $(m^n)^p = m^{np}$ then $(m^n)^{p^+} = m^{np^+}$
PROOF:

$$\begin{aligned} (m^n)^{p^+} &= (m^n)^p m^n \\ &= m^{np} m^n \\ &= m^{np+n} && \text{(Proposition 18.9)} \\ &= m^{np^+} \end{aligned}$$

□

Proposition 18.11. *For any natural numbers m and n, either $m \in n$ or $m = n$ or $n \in m$.*

PROOF:
⟨1⟩1. LET: $P(n)$ be the property: for all $m \in \omega$, either $m \in n$ or $m = n$ or $n \in m$
⟨1⟩2. $P(0)$
⟨2⟩1. LET: $Q(m)$ be the property: either $m = 0$ or $0 \in m$
⟨2⟩2. $Q(0)$
PROOF: Since $0 = 0$.
⟨2⟩3. For all $m \in \omega$, if $Q(m)$ then $Q(m^+)$
PROOF: If $m = 0$ or $0 \in m$ then $0 \in m^+$.
⟨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: $m \in \omega$
⟨2⟩4. $m \in n$ or $m = n$ or $n \in m$
PROOF: ⟨2⟩2
⟨2⟩5. CASE: $m \in n$ or $m = n$
PROOF: Then $m \in n^+$.
⟨2⟩6. CASE: $n \in m$
⟨3⟩1. PICK p such that $m = p^+$
⟨3⟩2. $n \in p$ or $n = p$
⟨3⟩3. CASE: $n \in p$
PROOF: Then $n^+ \in p^+ = m$ by Proposition 18.11.
⟨3⟩4. CASE: $n = p$
PROOF: Then $m = n^+$.
□

Corollary 18.11.1 (Trichotomy)**.** *For any natural numbers m and n, exactly one of $m \in n$, $m = n$, $n \in m$ holds.*

PROOF:
⟨1⟩1. We never have $m \in n$ and $m = n$.
PROOF: By Corollary 17.2.1.
⟨1⟩2. We never have $m \in n$ and $n \in m$.
PROOF: Since m is a transitive set this would imply $m \in m$ contradicting Corollary 17.2.1.
⟨1⟩3. We never have $m = n$ and $n \in m$.
PROOF: By Corollary 17.2.1.
□

Proposition 18.12. *For any natural numbers m and n, we have $m \in n$ if and only if $m \subsetneq n$.*

PROOF:
⟨1⟩1. LET: m and n be natural numbers.
⟨1⟩2. If $m \in n$ then $m \subsetneq n$.
PROOF: Since n is a transitive set, and $m \neq n$ by Corollary 17.2.1.
⟨1⟩3. If $m \subsetneq n$ then $m \in n$.
⟨2⟩1. ASSUME: $m \subsetneq n$
⟨2⟩2. $n \notin m$
PROOF: Proposition 17.2.
⟨2⟩3. $m \neq n$
⟨2⟩4. $m \in n$
PROOF: Trichotomy.
□

Definition 18.13. Given natural numbers m and n, we write $m < n$ iff $m \in n$.
We write $m \leqslant n$ iff $m < n \vee m = n$.

Proposition 18.14. *For natural numbers m and n, if $m \leqslant n$ and $n \leqslant m$ then $m = n$.*

Proof: We cannot have $m < n$ and $n < m$ by trichotomy. □

Proposition 18.15. *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 18.11.
□

Proposition 18.16. *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:

$$\begin{aligned} m(k+1) &= mk + m \\ &< mk + n && \text{(Proposition 18.16)} \\ &< nk + n && \text{(Proposition 18.16)} \\ &= n(k+1) \end{aligned}$$

□

Proposition 18.17. *For any nonempty set of natural numbers E, there exists $k \in E$ such that $\forall m \in E . k \leqslant m$.*

Proof:
⟨1⟩1. Let: $E \subseteq \omega$
⟨1⟩2. Assume: there is no $k \in E$ such that $\forall m \in E . k \leqslant m$.
Prove: $E = \varnothing$
⟨1⟩3. $\forall n \in \omega . n \notin E$
⟨2⟩1. Let: $P(n)$ be the property: $\forall m < n . m \notin E$
⟨2⟩2. $P(0)$
Proof: Vacuous.
⟨2⟩3. $\forall n \in \omega . P(n) \Rightarrow P(n+1)$
⟨3⟩1. Let: $n \in \omega$
⟨3⟩2. Assume: $\forall m < n . m \notin E$
⟨3⟩3. $n \notin E$
Proof: From ⟨1⟩2.

$\langle 3\rangle 4.$ $\forall m < n + 1 . m \notin E$

□

Definition 18.18 (Equivalent)**.** Sets E and F are *equivalent*, $E \sim F$, iff there exists a one-to-one correspondence between them.

Proposition 18.19. *For any set X, equivalence is an equivalence relation on $\mathcal{P}X$.*

PROOF: Easy.

Proposition 18.20. *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:
$\langle 1\rangle 1.$ LET: $P(n)$ be the property: for every proper subset $X \subsetneq n$, there exists $m < n$ such that $X \sim m$.
$\langle 1\rangle 2.$ $P(0)$
PROOF: Vacuous.
$\langle 1\rangle 3.$ $\forall n \in \omega . P(n) \Rightarrow P(n+1)$
$\langle 2\rangle 1.$ LET: $n \in \omega$
$\langle 2\rangle 2.$ ASSUME: $P(n)$
$\langle 2\rangle 3.$ LET: X be a proper subset of $n + 1$
$\langle 2\rangle 4.$ CASE: $X - \{n\} = n$
PROOF: Then $X = n$ so $X \sim n < n + 1$.
$\langle 2\rangle 5.$ CASE: $X - \{n\} \subsetneq n$
$\langle 3\rangle 1.$ PICK $m < n$ such that $X - \{n\} \sim m$
$\langle 3\rangle 2.$ $X \sim m$ or $X \sim m + 1$
PROOF: If $n \in X$ then $X \sim m + 1$. If $n \notin X$ then $X \sim m$.

□

Proposition 18.21. *For every natural number n, we have n is not equivalent to a proper subset of n.*

PROOF:
$\langle 1\rangle 1.$ LET: $P(n)$ be the property: every one-to-one function $n \to n$ is onto.
$\langle 1\rangle 2.$ $P(0)$
PROOF: The only function $0 \to 0$ is $\emptyset$.
$\langle 1\rangle 3.$ $\forall n \in \omega . P(n) \Rightarrow P(n+1)$
$\langle 2\rangle 1.$ LET: $n \in \omega$
$\langle 2\rangle 2.$ ASSUME: $P(n)$
$\langle 2\rangle 3.$ ASSUME: $f : n + 1 \to n + 1$ is one-to-one.
$\langle 2\rangle 4.$ 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.
$\langle 2\rangle 5.$ g is one-to-one.
$\langle 3\rangle 1.$ 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 18.21.1. *Equivalent natural numbers are equal.*

Definition 18.22 (Finite)**.** A set is *finite* iff it is equivalent to a natural number; otherwise, it is *infinite*.

Proposition 18.23. *No finite set is equivalent to one of its proper subsets.*

Proof: From Proposition 18.22. □

Proposition 18.24. *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 18.25. *Every subset of a finite set is finite.*

Proof: Proposition 18.21. □

Definition 18.26 (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 18.27. *Let E and F be finite sets. If $E \subseteq F$ then $\sharp(E) \leqslant \sharp(F)$.*

Proof: Proposition 18.21. □

Proposition 18.28. *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 18.28.1. *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 18.29. *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 18.29.

□

Proposition 18.30. *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:
$$\begin{aligned}
\sharp(E^F) &= \sharp(E^{F-\{f\}} \times E) \\
&= \sharp(E^{F-\{f\}})\sharp(E) && \text{(Proposition 18.30)} \\
&= m^n m && (\langle 2\rangle 2, \langle 2\rangle 4) \\
&= m^{n+1}
\end{aligned}$$

□

Corollary 18.30.1. *If E is finite then $\mathcal{P}E$ is finite and $\sharp(\mathcal{P}E) = 2^{\sharp(E)}$.*

Proposition 18.31. *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: $E \sim n+1$
⟨2⟩4. PICK $X \in E$
⟨2⟩5. $E - \{X\} \sim n$
⟨2⟩6. $\bigcup(E - \{X\})$ is finite.
PROOF: ⟨2⟩2

⟨2⟩7. $\bigcup E = \bigcup(E - \{X\}) \cup X$
⟨2⟩8. $\bigcup E$ is finite.
PROOF: Corollary 18.29.1.
□

Proposition 18.32. *Every nonempty finite set of natural numbers has a greatest element.*

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