C1 Set Theory

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1 Primitive Notions

Let there be *sets*.

Let there be a binary relation called *membership*, $\in$. When $x \in y$ holds, we say x is a *member* or *element* of y. We write $x \notin y$ iff x is not a member of y.

2 The Axioms

Axiom 1 (Extensionality). *If two sets have exactly the same members, then they are equal.*

As a consequence of this axiom, we may identify a set A with the class $\{x : x \in A\}$. The use of the symbols $\in$ and $=$ is consistent.

Definition 2. We say that a class $\mathbf{A}$ *is a set* iff there exists a set A such that $A = \mathbf{A}$. That is, the class $\{x : P(x)\}$ is a set iff

$$\exists A. \forall x (x \in A \leftrightarrow P(x)) \enspace .$$

Otherwise, $\mathbf{A}$ is a *proper class*.

Definition 3 (Subset). If A is a set and $\mathbf{B}$ is a class, we say A is a *subset* of $\mathbf{B}$ iff $A \subseteq \mathbf{B}$.

Axiom 4 (Empty Set). *The empty class is a set, called the* empty set.

Axiom 5 (Replacement). *For any property $P(x, y)$, the following is an axiom:*

Let A be a set. Assume that, for all $x \in A$, there is at most one y such that $P(x, y)$. Then $\{y : \exists x \in A. P(x, y)\}$ is a set.

Definition 6 (Power Set). For any set A, the *power set* of A, $\mathcal{P}A$, is the class of all subsets of A.

Axiom 7 (Power Set). *For any set A, the class $\mathcal{P}A$ is a set.*

Theorem 8 (Pairing). *For any objects a and b, the class $\{a, b\}$ is a set, called a* pair set.

PROOF: Let a and b be sets. Let $P(x, y)$ be the formula $(x = \emptyset \;\&\; y = a)$ or $(x = \mathcal{P}\emptyset \;\&\; y = b)$. Then we have $(\forall x \in \mathcal{P}\mathcal{P}\emptyset)\forall y_1 \forall y_2 (P(x, y_1) \;\&\; P(x, y_2) \Rightarrow y_1 = y_2)$, hence there exists a set c such that

$$\forall y (y \in c \Leftrightarrow (\exists x \in \mathcal{P}\mathcal{P}\emptyset) P(x, y))$$

The members of c are just a and b. □

Definition 9 (Union)**.** For any class of sets $\mathbf{A}$, the *union* $\bigcup \mathbf{A}$ is the class $\{x : \exists A \in \mathbf{A}. x \in A\}$.

We write $\bigcup_{P[x_1,\ldots,x_n]} t[x_1, \ldots, x_n]$ for $\bigcup \{t[x_1, \ldots, x_n] : P[x_1, \ldots, x_n]\}$.

Proposition 10. *If* $\mathbf{A} \subseteq \mathbf{B}$ *then* $\bigcup \mathbf{A} \subseteq \bigcup \mathbf{B}$.

PROOF: Easy. □

Axiom 11 (Union)**.** *For any set* A*, the union* $\bigcup A$ *is a set.*

Proposition 12. *For any sets* A *and* B*, the class* $A \cup B$ *is a set.*

PROOF: It is $\bigcup \{A, B\}$. □

Proposition Schema 13. *For any objects* $a_1, \ldots, a_n$*, the class* $\{a_1, \ldots, a_n\}$ *is a set.*

PROOF: By repeated application of the Pairing and Union axioms. □

Theorem 14 (Subset Axioms, Aussonderung)**.** *For any class* $\mathbf{A}$ *and set* B*, if* $\mathbf{A} \subseteq B$ *then* $\mathbf{A}$ *is a set.*

PROOF: Let $Q(x, y)$ be the formula $x \in \mathbf{A} \wedge y = x$. Now we reason as follows. Let c be any set. Then we have

$$(\forall x \in B)\forall y_1 \forall y_2 (Q(x, y_1) \;\&\; Q(x, y_2) \Rightarrow y_1 = y_2)$$

Then, by a Replacement Axiom, there exists a set c such that

$$\forall y (y \in c \Leftrightarrow (\exists x \in B) Q(x, y)) \ .$$

This is equivalent to $\forall x (x \in c \Leftrightarrow x \in \mathbf{A})$. □

Proposition 15. *For any set* A *and class* $\mathbf{B}$*, the intersection* $A \cap \mathbf{B}$ *is a set.*

PROOF: By the Subset Axiom since it is a subclass of A. □

Proposition 16. *For any set* A *and class* $\mathbf{B}$*, the relative complement* $A - \mathbf{B}$ *is a set.*

PROOF: By the Subset Axiom since it is a subclass of A. □

Theorem 17. *The universal class* $\mathbf{V}$ *is a proper class.*

PROOF:
$\langle 1 \rangle 1$. ASSUME: $\mathbf{V}$ is a set.
$\langle 1 \rangle 2$. LET: $R = \{x : x \notin x\}$
$\langle 1 \rangle 3$. R is a set.
  PROOF: By the Subset Axiom.
$\langle 1 \rangle 4$. $R \in R$ if and only if $R \notin R$

$\langle 1\rangle 5$. Q.E.D.

PROOF: This is a contradiction.

□

Definition 18 (Intersection)**.** For any class of sets $\mathbf{A}$, the *intersection* $\bigcap \mathbf{A}$ is the class $\{x : \forall A \in \mathbf{A}. x \in A\}$.

We write $\bigcap_{P[x_1,\ldots,x_n]} t[x_1,\ldots,x_n]$ for $\bigcap\{t[x_1,\ldots,x_n] : P[x_1,\ldots,x_n]\}$.

Proposition 19. *For any nonempty class of sets $\mathbf{A}$, the class $\bigcap \mathbf{A}$ is a set.*

PROOF: Pick $A \in \mathbf{A}$. Then $\bigcap \mathbf{A} \subseteq A$. □

Proposition 20. *If $\mathbf{A} \subseteq \mathbf{B}$ then $\bigcap \mathbf{B} \subseteq \bigcap \mathbf{A}$.*

PROOF: Easy. □

Proposition 21. *For any set A and class of sets $\mathbf{B}$, we have*

$$A \cup \bigcap \mathbf{B} = \bigcap \{A \cup X \mid X \in \mathbf{B}\}$$

PROOF: Easy. □

Proposition 22. *For any set A and class of sets $\mathbf{B}$, we have*

$$A \cap \bigcup \mathbf{B} = \bigcup \{A \cap X \mid X \in \mathbf{B}\}$$

PROOF: Easy. □

Proposition 23. *For any set C and class of sets $\mathbf{A}$, we have*

$$C - \bigcup \mathbf{A} = \bigcap \{C - X \mid X \in \mathbf{A}\} \ .$$

PROOF: Easy. □

Proposition 24. *For any set C and class of sets $\mathbf{A}$, we have*

$$C - \bigcap \mathbf{A} = \bigcup \{C - X \mid X \in \mathbf{A}\} \ .$$

PROOF: Easy. □

3 Ordered Pairs

Definition 25 (Ordered Pair)**.** For any objects a and b, the *ordered pair* (a, b) is $\{\{a\}, \{a, b\}\}$. We call a its *first coordinate* and b its *second coordinate*.

Theorem 26. *For any objects (a, b), we have $(a, b) = (c, d)$ if and only if $a = c$ and $b = d$.*

PROOF:

$\langle 1\rangle 1.$ If $(a,b) = (c,d)$ then $a = c$ and $b = d$
  $\langle 2\rangle 1.$ Assume: $(a,b) = (c,d)$
  $\langle 2\rangle 2.$ $a = c$
    Proof: Since $\{a\} = \bigcap(a,b) = \bigcap(c,d) = \{c\}$.
  $\langle 2\rangle 3.$ $\{a,b\} = \{c,d\}$
    Proof: $\{a,b\} = \bigcup(a,b) = \bigcup(c,d) = \{c,d\}$.
  $\langle 2\rangle 4.$ $b = c$ or $b = d$
  $\langle 2\rangle 5.$ Case: $b = c$
    $\langle 3\rangle 1.$ $a = b$
    $\langle 3\rangle 2.$ $\{c,d\} = \{a\}$
    $\langle 3\rangle 3.$ $b = d$
  $\langle 2\rangle 6.$ Case: $b = d$
    Proof: We have $a = c$ and $b = d$ as required.
$\langle 1\rangle 2.$ If $a = c$ and $b = d$ then $(a,b) = (c,d)$
  Proof: Trivial.
□

Definition 27 (Cartesian Product)**.** The *Cartesian product* of classes $\mathbf{A}$ and $\mathbf{B}$ is the class

$$\mathbf{A} \times \mathbf{B} = \{(x,y) : x \in \mathbf{A}, y \in \mathbf{B}\} \ .$$

Lemma 28. *For any objects x and y and set C, if $x \in C$ and $y \in C$ then $(x,y) \in \mathcal{PP}C$.*

Proof: Easy. □

Corollary 28.1. *For any sets A and B, the Cartesian product $A \times B$ is a set.*

Proof: By the Subset Axiom applied to $\mathcal{PP}(A \cup B)$. □

Lemma 29. *If $(x,y) \in \mathbf{A}$ then $x, y \in \bigcup\bigcup\mathbf{A}$.*

Proof: Easy. □

4 Relations

Definition 30 (Relation)**.** A *relation* is a class of ordered pairs. It is *small* iff it is a set.

When $\mathbf{R}$ is a relation, we write $x\mathbf{R}y$ for $(x,y) \in \mathbf{R}$.

Definition 31 (Domain)**.** The *domain* of a class $\mathbf{R}$ is $\operatorname{dom}\mathbf{R} = \{x : \exists y.(x,y) \in \mathbf{R}\}$.

Definition 32 (Range)**.** The *range* of a class $\mathbf{R}$ is $\operatorname{ran}\mathbf{R} = \{y : \exists x.(x,y) \in \mathbf{R}\}$.

Definition 33 (Field)**.** The *field* of a class $\mathbf{R}$ is $\operatorname{fld}\mathbf{R} = \operatorname{dom}\mathbf{R} \cup \operatorname{ran}\mathbf{R}$.

Proposition 34. *If R is a set then $\operatorname{dom} R$, $\operatorname{ran} R$ and $\operatorname{fld} R$ are sets.*

Proof: Apply the Subset Axiom to $\bigcup\bigcup R$. □

Definition 35 (Single-Rooted)**.** A class $\mathbf{R}$ is *single-rooted* iff, for all $y \in \operatorname{ran} \mathbf{R}$, there is only one x such that $x\mathbf{R}y$.

Definition 36 (Inverse)**.** The *inverse* of a class $\mathbf{F}$ is the class $\mathbf{F}^{-1} = \{(y, x) \mid (x, y) \in \mathbf{F}\}$.

Theorem 37. *For any class* $\mathbf{F}$*, we have* $\operatorname{dom} \mathbf{F}^{-1} = \operatorname{ran} \mathbf{F}$ *and* $\operatorname{ran} \mathbf{F}^{-1} = \operatorname{dom} \mathbf{F}$*.*

Proof: Easy. □

Theorem 38. *For a relation* $\mathbf{F}$*,* $(\mathbf{F}^{-1})^{-1} = \mathbf{F}$*.*

Proof: Easy. □

Definition 39 (Composition)**.** The *composition* of classes $\mathbf{F}$ and $\mathbf{G}$ is the class $\mathbf{G} \circ \mathbf{F} = \{(x, z) \mid \exists y.(x, y) \in \mathbf{F} \wedge (y, z) \in \mathbf{G}\}$.

Theorem 40. *For any classes* $\mathbf{F}$ *and* $\mathbf{G}$*,* $(\mathbf{F} \circ \mathbf{G})^{-1} = \mathbf{G}^{-1} \circ \mathbf{F}^{-1}$*.*

Proof: Easy. □

Definition 41 (Restriction)**.** The *restriction* of the class $\mathbf{F}$ to the class $\mathbf{A}$ is the class $\mathbf{F} \restriction \mathbf{A} = \{(x, y) : x \in A \wedge (x, y) \in \mathbf{F}\}$.

Definition 42 (Image)**.** The *image* of the class $\mathbf{A}$ under the class $\mathbf{F}$ is the class $\mathbf{F}(\mathbf{A}) = \{y : \exists x \in \mathbf{A}.(x, y) \in \mathbf{F}\}$.

Theorem 43.
$$\mathbf{F}(\mathbf{A} \cup \mathbf{B}) = \mathbf{F}(\mathbf{A}) \cup \mathbf{F}(\mathbf{B})$$

Proof: Easy. □

Theorem 44.
$$\mathbf{F}(\bigcup \mathbf{A}) = \bigcup \{\mathbf{F}(X) : X \in \mathbf{A}\}$$

Proof: Easy. □

Theorem 45.
$$\mathbf{F}(\mathbf{A} \cap \mathbf{B}) \subseteq \mathbf{F}(\mathbf{A}) \cap \mathbf{F}(\mathbf{B})$$

Equality holds if $\mathbf{F}$ *is single-rooted.*

Proof: Easy. □

Theorem 46.
$$\mathbf{F}(\bigcap \mathbf{A}) \subseteq \bigcap \{\mathbf{F}(X) : X \in \mathbf{A}\}$$

Equality holds if $\mathbf{F}$ *is single-rooted.*

Proof: Easy. □

Theorem 47.

$$\mathbf{F}(\mathbf{A}) - \mathbf{F}(\mathbf{B}) \subseteq \mathbf{F}(\mathbf{A} - \mathbf{B})$$

Equality holds if $\mathbf{F}$ *is single-rooted.*

PROOF: Easy. □

Definition 48 (Reflexive)**.** A binary relation $\mathbf{R}$ on $\mathbf{A}$ is *reflexive* on $\mathbf{A}$ if and only if $\forall x \in \mathbf{A}. x\mathbf{R}x$.

Definition 49 (Symmetric)**.** A binary relation $\mathbf{R}$ is *symmetric* iff, whenever $x\mathbf{R}y$, then $y\mathbf{R}x$.

Definition 50 (Transitive)**.** A binary relation $\mathbf{R}$ is *transitive* iff, whenever $x\mathbf{R}y$ and $y\mathbf{R}z$, then $x\mathbf{R}z$.

5 n-ary Relations

Definition 51. Given objects a, b, c, define the *ordered triple* (a, b, c) to be $((a, b), c)$.

Define $(a, b, c, d) = ((a, b, c), d)$, etc.

Define the *1-tuple* (a) to be a.

Definition 52 (n-ary Relation)**.** Given a class $\mathbf{A}$, an *n-ary relation* on $\mathbf{A}$ is a class of ordered n-tuples, all of whose components are in $\mathbf{A}$.

6 Functions

Definition 53 (Function)**.** A *function* is a relation $\mathbf{F}$ such that, for all $x \in \operatorname{dom}\mathbf{F}$, there is only one y such that $x\mathbf{F}y$. We call this unique y the *value* of $\mathbf{F}$ at x and denote it by $\mathbf{F}(x)$.

We say $\mathbf{F}$ is a function *from* $\mathbf{A}$ *into* $\mathbf{B}$, or $\mathbf{F}$ *maps* $\mathbf{A}$ into $\mathbf{B}$, and write $\mathbf{F} : \mathbf{A} \to \mathbf{B}$, iff $\mathbf{F}$ is a function, $\operatorname{dom}\mathbf{F} = \mathbf{A}$, and $\operatorname{ran}\mathbf{F} \subseteq \mathbf{B}$.

If, in addition, $\operatorname{ran}\mathbf{F} = \mathbf{B}$, we say $\mathbf{F}$ is a function from $\mathbf{A}$ *onto* $\mathbf{B}$.

Theorem 54. *For a class* $\mathbf{F}$*,* $\mathbf{F}^{-1}$ *is a function if and only if* $\mathbf{F}$ *is single-rooted.*

PROOF: Easy. □

Theorem 55. *A relation* $\mathbf{F}$ *is a function if and only if* $\mathbf{F}^{-1}$ *is single-rooted.*

PROOF: Easy. □

Theorem 56. *For any function* $\mathbf{G}$ *and classes* $\mathbf{A}$ *and* $\mathbf{B}$*,*

$$\begin{aligned} \mathbf{G}^{-1}(\bigcup \mathbf{A}) &= \bigcup\{\mathbf{G}^{-1}(X) : X \in \mathbf{A}\} \\ \mathbf{G}^{-1}(\bigcap \mathbf{A}) &= \bigcap\{\mathbf{G}^{-1}(X) : X \in \mathbf{A}\} \qquad (\textit{if } \mathbf{A} \neq \emptyset) \\ \mathbf{G}^{-1}(\mathbf{A} - \mathbf{B}) &= \mathbf{G}^{-1}(\mathbf{A}) - \mathbf{G}^{-1}(\mathbf{B}) \end{aligned}$$

PROOF: Easy. □

Theorem 57. *Assume that* $\mathbf{F}$ *and* $\mathbf{G}$ *are functions. Then* $\mathbf{F} \circ \mathbf{G}$ *is a function, its domain is* $\{x \in \operatorname{dom} \mathbf{G} : \mathbf{G}(x) \in \operatorname{dom} \mathbf{F}\}$*, and for* x *in its domain,*

$$(\mathbf{F} \circ \mathbf{G})(x) = \mathbf{F}(\mathbf{G}(x)) \ .$$

PROOF: Easy. □

Definition 58 (One-to-one)**.** A function $\mathbf{F}$ is *one-to-one* or an *injection* iff it is single-rooted.

Theorem 59. *Let* $\mathbf{F}$ *be a one-to-one function. For* $x \in \operatorname{dom} \mathbf{F}$*,* $\mathbf{F}^{-1}(\mathbf{F}(x)) = x$*.*

PROOF: Easy. □

Theorem 60. *Let* $\mathbf{F}$ *be a one-to-one function. For* $y \in \operatorname{ran} \mathbf{F}$*,* $\mathbf{F}(\mathbf{F}^{-1}(y)) = y$*.*

PROOF: Easy. □

Definition 61 (Identity Function)**.** For any class $\mathbf{A}$, the *identity* function on $\mathbf{A}$ is $\mathrm{id}_{\mathbf{A}} = \{(x, x) \mid x \in \mathbf{A}\}$.

Theorem 62. *Let* $F : A \to B$*. Assume* $A \neq \emptyset$*. Then* F *has a left inverse (i.e. there exists* $G : B \to A$ *such that* $G \circ F = \mathrm{id}_A$*) if and only if* F *is one-to-one.*

PROOF:
$\langle 1 \rangle 1$. If F is one-to-one then F has a left inverse.
  $\langle 2 \rangle 1$. ASSUME: F is one-to-one.
  $\langle 2 \rangle 2$. $F^{-1} : \operatorname{ran} F \to A$
  $\langle 2 \rangle 3$. PICK $a \in A$
  $\langle 2 \rangle 4$. Define $G : B \to A$ by:

$$G(x) = \begin{cases} F^{-1}(x) & \text{if } x \in \operatorname{ran} F \\ a & \text{if } x \in B - \operatorname{ran} F \end{cases}$$

  $\langle 2 \rangle 5$. $\forall x \in A . G(F(x)) = x$
$\langle 1 \rangle 2$. If F has a left inverse then F is one-to-one.
  $\langle 2 \rangle 1$. ASSUME: F has a left inverse G.
  $\langle 2 \rangle 2$. LET: $x, y \in A$ with $F(x) = F(y)$
  $\langle 2 \rangle 3$. $x = y$
    PROOF: $x = G(F(x)) = G(F(y)) = y$.
□

Definition 63 (Binary Operation)**.** A *binary operation* on a set A is a function from $A \times A$ into A.

7 The Axiom of Choice

Axiom 64 (Choice)**.** *For any relation* R *there exists a function* $H \subseteq R$ *with* $\operatorname{dom} H = \operatorname{dom} R$*.*

Theorem 65. *Let $F : A \to B$. Then F has a right inverse if and only if F maps A onto B.*

PROOF:
$\langle 1 \rangle 1$. If F has a right inverse then F maps A onto B.
PROOF: If $H : B \to A$ is a right inverse, then for any y in B, we have $y = F(H(y))$.
$\langle 1 \rangle 2$. If F maps A onto B then F has a right inverse.
$\langle 2 \rangle 1$. ASSUME: F maps A onto B.
$\langle 2 \rangle 2$. PICK a function H with $H \subseteq F^{-1}$ and $\mathrm{dom}\, H = \mathrm{dom}\, F^{-1}$
PROOF: By the Axiom of Choice.
$\langle 2 \rangle 3$. $\mathrm{dom}\, H = B$
PROOF: $\mathrm{dom}\, H = \mathrm{dom}\, F^{-1} = \mathrm{ran}\, F = B$ by $\langle 2 \rangle 1$.
$\langle 2 \rangle 4$. For all $y \in B$ we have $F(H(y)) = y$
$\langle 3 \rangle 1$. LET: $y \in B$
$\langle 3 \rangle 2$. $(y, H(y)) \in F^{-1}$
$\langle 3 \rangle 3$. $F(H(y)) = y$
$\square$

8 Sets of Functions

Definition 66. Let A be a set and $\mathbf{B}$ be a class. Then $\mathbf{B}^A$ is the class of all functions $A \to \mathbf{B}$.

9 Dependent Products

Definition 67. Let I be a set and H_i a set for all $i \in I$. Define

$$\prod_{i \in I} H_i = \{f : f \text{ is a function}, \mathrm{dom}\, f = I, \forall i \in I. f(i) \in H_i\} \ .$$

Theorem 68. *The Axiom of Choice is equivalent to the statement: For any set I and any function H with domain I, if $H(i) \neq \emptyset$ for all $i \in I$, then $\prod_{i \in I} H(i) \neq \emptyset$*

PROOF:
$\langle 1 \rangle 1$. If the Axiom of Choice is true then, for any set I and any function H with domain I, if $H(i) \neq \emptyset$ for all $i \in I$, then $\prod_{i \in I} H(i) \neq \emptyset$.
$\langle 2 \rangle 1$. ASSUME: The Axiom of Choice.
$\langle 2 \rangle 2$. LET: I be a set.
$\langle 2 \rangle 3$. LET: H be a function with domain I.
$\langle 2 \rangle 4$. ASSUME: $H(i) \neq \emptyset$ for all $i \in I$.
$\langle 2 \rangle 5$. LET: $R = \{(i, x) : i \in I, x \in H(i)\}$
$\langle 2 \rangle 6$. PICK a function $F \subseteq R$ with $\mathrm{dom}\, F = \mathrm{dom}\, R$
PROVE: $F \in \prod_{i \in I} H(i)$
PROOF: By the Axiom of Choice.

⟨2⟩7. $\operatorname{dom} H = I$

PROOF: We have $\operatorname{dom} R = I$ since for all $i \in I$ there exists x such that $x \in H(i)$.

⟨2⟩8. $\forall i \in I . F(i) \in H(i)$

PROOF: Since $iRF(i)$.

⟨1⟩2. If, for any set I and any function H with domain I, if $H(i) \neq \emptyset$ for all $i \in I$, then $\prod_{i \in I} H(i) \neq \emptyset$, then the Axiom of Choice is true.

⟨2⟩1. ASSUME: For any set I and any function H with domain I, if $H(i) \neq \emptyset$ for all $i \in I$, then $\prod_{i \in I} H(i) \neq \emptyset$

⟨2⟩2. LET: R be a relation

⟨2⟩3. LET: $I = \operatorname{dom} R$

⟨2⟩4. Define the function H with domain I by: for $i \in I$, $H(i) = \{y : iRy\}$

⟨2⟩5. $H(i) \neq \emptyset$ for all $i \in I$

⟨2⟩6. PICK $F \in \prod_{i \in I} H(i)$

PROOF: By ⟨2⟩1

⟨2⟩7. F is a function

⟨2⟩8. $F \subseteq R$

PROOF: For all $i \in I$ we have $F(i) \in H(i)$ and so $iRF(i)$.

⟨2⟩9. $\operatorname{dom} F = \operatorname{dom} R$

□

Theorem 69. *The following are equivalent.*

1. *The Axiom of Choice.*

2. *Let $\mathcal{A}$ be a set such that (a) every member of $\mathcal{A}$ is a nonempty set, and (b) any two distinct members of $\mathcal{A}$ are disjoint. Then there exists a set C such that, for all $B \in \mathcal{A}$, we have $C \cap B$ is a singleton.*

3. *For any set A, there exists a function $F : \mathcal{P}A - \{\emptyset\} \to A$ such that $F(X) \in X$ for all $X \in \mathcal{P}A - \{\emptyset\}$.*

PROOF:

⟨1⟩1. $1 \Rightarrow 2$

PROOF: Let $\mathcal{A}$ be a set matching the two condtions. By the Multiplicative Axiom, pick a function $f \in \prod_{B \in \mathcal{A}} B$. Let $C = \operatorname{ran} f$. Then $C \cap B = \{f(B)\}$ for all $B \in \mathcal{A}$.

⟨1⟩2. $2 \Rightarrow 3$

⟨2⟩1. ASSUME: 2

⟨2⟩2. LET: A be a set.

⟨2⟩3. LET: $\mathcal{A} = \{\{B\} \times B : B \in \mathcal{P}A - \{\emptyset\}\}$

⟨2⟩4. PICK a set C such that $C \cap (\{B\} \times B)$ is a singleton for all $B \in \mathcal{P}A - \{\emptyset\}$

⟨2⟩5. LET: $F = C \cap \bigcup \mathcal{A}$

⟨2⟩6. $F : \mathcal{P}A - \{\emptyset\} \to A$ is a function and $F(X) \in X$ for all X

⟨1⟩3. $3 \Rightarrow 1$

⟨2⟩1. ASSUME: 3

⟨2⟩2. LET: R be a relation

⟨2⟩3. PICK a choice function G for $\operatorname{ran} R$

$\langle 2 \rangle 4.$ Define $F : \operatorname{dom} R \to \operatorname{ran} R$ by $F(x) = G(R(x))$
$\langle 2 \rangle 5.$ $F \subseteq R$
$\square$

10 Equivalence Relations

Definition 70 (Equivalence Relation)**.** An *equivalence relation* on $\mathbf{A}$ is a binary relation on $\mathbf{A}$ that is reflexive on $\mathbf{A}$, symmetric and transitive.

Theorem 71. *If* $\mathbf{R}$ *is a symmetric and transitive relation then* $\mathbf{R}$ *is an equivalence relation on* $\operatorname{fld} \mathbf{R}$*.*

PROOF:
$\langle 1 \rangle 1.$ LET: $x \in \operatorname{fld} \mathbf{R}$
$\langle 1 \rangle 2.$ PICK y such that either $x\mathbf{R}y$ or $y\mathbf{R}x$
$\langle 1 \rangle 3.$ $x\mathbf{R}y$ and $y\mathbf{R}x$
PROOF: Since $\mathbf{R}$ is symmetric.
$\langle 1 \rangle 4.$ $x\mathbf{R}x$
PROOF: Since $\mathbf{R}$ is transitive.
$\square$

Definition 72 (Equivalence Class)**.** If $\mathbf{R}$ is an equivalence relation and $x \in \operatorname{fld} \mathbf{R}$, the *equivalence class* of x modulo $\mathbf{R}$ is

$$[x]_{\mathbf{R}} = \{t : x\mathbf{R}t\} \enspace .$$

Lemma 73. *Assume that* $\mathbf{R}$ *is an equivalence relation on* $\mathbf{A}$ *and that* x *and* y *belong to* $\mathbf{A}$*. Then*

$$[x]_{\mathbf{R}} = [y]_{\mathbf{R}} \text{ iff } x\mathbf{R}y \enspace .$$

PROOF:
$\langle 1 \rangle 1.$ If $[x]_{\mathbf{R}} = [y]_{\mathbf{R}}$ then $x\mathbf{R}y$
$\langle 2 \rangle 1.$ ASSUME: $[x]_{\mathbf{R}} = [y]_{\mathbf{R}}$
$\langle 2 \rangle 2.$ $y \in [y]_{\mathbf{R}}$
PROOF: Since $\mathbf{R}$ is reflexive on $\mathbf{A}$.
$\langle 2 \rangle 3.$ $y \in [x]_{\mathbf{R}}$
$\langle 2 \rangle 4.$ $x\mathbf{R}y$
$\langle 1 \rangle 2.$ If $x\mathbf{R}y$ then $[x]_{\mathbf{R}} = [y]_{\mathbf{R}}$
$\langle 2 \rangle 1.$ ASSUME: $x\mathbf{R}y$
$\langle 2 \rangle 2.$ $[y]_{\mathbf{R}} \subseteq [x]_{\mathbf{R}}$
$\langle 3 \rangle 1.$ LET: $z \in [y]_{\mathbf{R}}$
$\langle 3 \rangle 2.$ $y\mathbf{R}z$
$\langle 3 \rangle 3.$ $x\mathbf{R}z$
PROOF: Since $\mathbf{R}$ is transitive.
$\langle 3 \rangle 4.$ $z \in [x]_{\mathbf{R}}$
$\langle 2 \rangle 3.$ $y\mathbf{R}x$
PROOF: Since $\mathbf{R}$ is symmetric.

$\langle 2\rangle 4.$ $[x]_{\mathbf{R}} \subseteq [y]_{\mathbf{R}}$
PROOF: Similar.
□

Definition 74 (Partition)**.** A *partition* of a set A is a set $P \subseteq \mathcal{P}A$ such that:

- Every member of P is nonempty.
- Any two distinct members of P are disjoint.
- $A = \bigcup P$

Theorem 75. *Let R be an equivalence relation on the set A. Then the set of all equivalence classes is a partition of A.*

PROOF:
$\langle 1\rangle 1.$ Every equivalence class is nonempty.
PROOF: For any $x \in A$ we have $x \in [x]_R$.
$\langle 1\rangle 2.$ Any two distinct equivalence classes are disjoint.
$\langle 2\rangle 1.$ LET: $x, y \in A$
$\langle 2\rangle 2.$ ASSUME: $z \in [x]_R \cap [y]_R$
PROVE: $[x]_R = [y]_R$
$\langle 2\rangle 3.$ xRy
$\langle 3\rangle 1.$ xRz
$\langle 3\rangle 2.$ yRz
$\langle 3\rangle 3.$ zRy
PROOF: By $\langle 3\rangle 2$ and symmetry.
$\langle 3\rangle 4.$ xRy
PROOF: By $\langle 3\rangle 1$, $\langle 3\rangle 3$ and transitivity.
$\langle 2\rangle 4.$ $[x]_R = [y]_R$
PROOF: By Lemma 3N.
$\langle 1\rangle 3.$ A is the union of all the equivalence classes.
PROOF: For any $x \in A$ we have $x \in [x]_R$.
□

Definition 76 (Quotient Set)**.** If R is an equivalence relation on the set A, then the *quotient set* A/R is the set of all equivalence classes, and the *natural map* or *canonical map* $\phi : A \to A/R$ is defined by $\phi(x) = [x]_R$.

Theorem 77. *Assume that R is an equivalence relation on A and that $F : A \to B$. Assume that F is* compatible *with R; that is, whenever xRy, then $F(x) = F(y)$. Then there exists a unique $\overline{F} : A/R \to B$ such that $F = \overline{F} \circ \phi$.*

PROOF: The unique such $\overline{F}$ is $\{([x], F(x)) : x \in A\}$. □

11 Partial Orders

Definition 78 (Strict Partial Order)**.** A *strict partial order* is an irreflexive, transitive relation.

If $<$ is a strict partial order, we write $x \leq y$ for $x < y \vee x = y$.

Theorem 79. *Assume that $<$ is a partial order. Then for any x, y and z:*

1. At most *one of the three alternatives,*

$$x < y, x = y, y < x,$$

can hold.

2. $x \leq y \leq x \Rightarrow x = y$.

PROOF: Easy. □

Definition 80 (Minimal)**.** Let $<$ be a partial order on D. An element $m \in D$ is *minimal* iff there is no $x \in D$ such that $x < m$.

Definition 81 (Maximal)**.** Let $<$ be a partial order on D. An element $m \in D$ is *maximal* iff there is no $x \in D$ such that $m < x$.

Definition 82 (Least)**.** Let $<$ be a partial order on D. An element $m \in D$ is *least*, *smallest* or the *minimum* iff $\forall x \in D.m \leq x$.

Definition 83 (Greatest)**.** Let $<$ be a partial order on D. An element $m \in D$ is *greatest*, *largest* or the *maximum* iff $\forall x \in D.x \leq m$.

Proposition 84. *If R is a partial ordering on D then so is R^{-1}.*

PROOF: Easy. □

Definition 85 (Upper Bound)**.** Let $<$ be a partial order on A and $C \subseteq A$. An *upper bound* for C is an element $b \in A$ such that $\forall x \in C.x \leq b$.

Definition 86 (Least Upper Bound)**.** Let $<$ be a partial order on A and $C \subseteq A$. The *least upper bound* or *supremum* for C is the least element in the set of upper bounds for C.

Definition 87 (Lower Bound)**.** Let $<$ be a partial order on A and $C \subseteq A$. A *lower bound* for C is an element $b \in A$ such that $\forall x \in C.b \leq x$.

Definition 88 (Greatest Lower Bound)**.** Let $<$ be a partial order on A and $C \subseteq A$. The *greatest lower bound* or *infimum* for C is the greatest element in the set of lower bounds for C.

Definition 89 (Initial Segment)**.** Let $<$ be a partial order on A and $t \in A$. The *initial segment* up to t is

$$\operatorname{seg} t = \{x \in A : x < t\} \ .$$

Definition 90 (Isomorphism)**.** Let A and B be posets. An *isomorphism* between A and B is a bijection f between A and B such that, for all $x, y \in A$, we have $x < y$ if and only if $f(x) < f(y)$.

Proposition 91. *Isomorphism is an equivalence relation on the class of posets.*

PROOF: Easy. □

Proposition 92. *Let $(A, <)$ be a poset and $B \subseteq A$. Then $< \cap B^2$ is a partial order on B.*

PROOF: Easy. □

12 Linear Orders

Definition 93 (Linear Ordering)**.** Let $\mathbf{A}$ be a class. A *linear ordering* or *total ordering* on $\mathbf{A}$ is a relation $\mathbf{R}$ on $\mathbf{A}$ such that:

- $\mathbf{R}$ is transitive.
- $\mathbf{R}$ satisfies *trichotomy* on $\mathbf{A}$; i.e. for any $x, y \in \mathbf{A}$, exactly one of

  $$x\mathbf{R}y, x = y, y\mathbf{R}x$$

  holds.

Theorem 94. *Let* $\mathbf{R}$ *be a linear ordering on* $\mathbf{A}$*.*

1. *There is no* x *such that* $x\mathbf{R}x$*.*
2. *For distinct* x *and* y *in* $\mathbf{A}$*, either* $x\mathbf{R}y$ *or* $y\mathbf{R}x$*.*

Proof: Immediate from trichotomy. □

Definition 95 (Strictly Monotone Functions)**.** Let A and B be linearly ordered sets. A function $f : A \to B$ is *strictly monotone* iff, for all $x, y \in A$, if $x < y$ then $f(x) < f(y)$.

Theorem 96. *Let* A *and* B *be linearly ordered sets and* $f : A \to B$ *be strictly monotone. For all* $x, y \in A$*, if* $f(x) < f(y)$ *then* $x < y$*.*

Proof: We have $f(x) \neq f(y)$ and $f(y) \not< f(x)$ by trichotomy, hence $x \neq y$ and $y \not< x$ since f is strictly monotone, hence $x < y$ by trichotomy. □

Theorem 97. *Every strictly monotone function is injective.*

Proof: If $f(x) = f(y)$, then we have $f(x) \not< f(y)$ and $f(y) \not< f(x)$ by trichotomy, hence $x \not< y$ and $y \not< x$ since f is strictly monotone, hence $x = y$ by trichotomy. □

Proposition 98. *Let* $(A, <)$ *be a linearly ordered set and* $B \subseteq A$*. Then* $< \cap B^2$ *is a linear order on* B*.*

Proof: Easy. □

13 Well Orderings

Definition 99 (Well Ordering)**.** A *well ordering* on a set A is a linear ordering on A such that every nonempty subset of A has a least element.

Theorem 100 (Transfinite Induction Principle)**.** *Let* $<$ *be a well ordering on* A*. Let* $B \subseteq A$*. Suppose that*

$$\forall x \in A(\operatorname{seg} x \subseteq B \Rightarrow x \in B) \enspace .$$

Then $B = A$*.*

PROOF:
$\langle 1\rangle 1$. ASSUME: for a contradiction $B \neq A$
$\langle 1\rangle 2$. LET: t be the least element of $A - B$
$\langle 1\rangle 3$. $\operatorname{seg} t \subseteq B$
$\langle 1\rangle 4$. $t \notin B$
$\langle 1\rangle 5$. Q.E.D.
PROOF: This is a contradiction.
□

Theorem 101. *Assume that $<$ is a linear ordering on A. Assume that the only $<$-inductive subset of A is A itself. Then $<$ is a well ordering on A.*

PROOF:
$\langle 1\rangle 1$. ASSUME: for a contradiction $B \subseteq A$ has no least element.
$\langle 1\rangle 2$. $A - B$ is $<$-inductive.
$\langle 2\rangle 1$. LET: $t \in A$
$\langle 2\rangle 2$. ASSUME: $\operatorname{seg} t \subseteq A - B$
$\langle 2\rangle 3$. $t \notin B$
PROOF: If it were, it would be the least element of B.
$\langle 2\rangle 4$. $t \in A - B$
$\langle 1\rangle 3$. $A - B = A$
$\langle 1\rangle 4$. $B = \emptyset$
□

Theorem 102 (Transfinite Recursion Theorem Schema)**.** *For any property $P(x, y)$ the following is a theorem:*

Assume that $<$ is a well ordering on A. Assume that $\forall x \exists! y P(x, y)$. Then there exists a unique function F with domain A such that

$$\forall t \in A . P(F \restriction \operatorname{seg} t, F(t)) \ .$$

PROOF:
$\langle 1\rangle 1$. Given $t \in A$, let us say that a function v is *P-constructed up to t* iff $\operatorname{dom} v = \{x \in A : x \leq t\}$ and $\forall x \in \operatorname{dom} v . P(v \restriction \operatorname{seg} x, v(x))$
$\langle 1\rangle 2$. Let $t_1, t_2 \in A$ with $t_1 \leq t_2$. Let v_1 be a function that is P-constructed up to t_1, and v_2 a function that is P-constructed up to t_2. Then $\forall x \leq t_1 . v_1(x) = v_2(x)$
$\langle 2\rangle 1$. LET: $x \leq t_1$
$\langle 2\rangle 2$. ASSUME: $\forall y < x . v_1(y) = v_2(y)$
$\langle 2\rangle 3$. $v_1 \restriction \operatorname{seg} x = v_2 \restriction \operatorname{seg} x$
$\langle 2\rangle 4$. $P(v_1 \restriction \operatorname{seg} x, v_1(x))$
$\langle 2\rangle 5$. $P(v_2 \restriction \operatorname{seg} x, v_2(x))$
$\langle 2\rangle 6$. $v_1(x) = v_2(x)$
PROOF: Since there is only one y such that $P(v_1 \restriction \operatorname{seg} x, y)$.
$\langle 2\rangle 7$. Q.E.D.
PROOF: By transfinite induction.
$\langle 1\rangle 3$. LET: $\mathcal{H} = \{v : \exists t \in A . v \text{ is } P\text{-constructed up to } t\}$

$\langle 1\rangle 4.$ $\mathcal{H}$ is a set.

PROOF: By a Replacement Axiom since, if v_1 and v_2 are both P-constructed up to t then $v_1 = v_2$ by $\langle 1\rangle 2$.

$\langle 1\rangle 5.$ LET: $F = \bigcup \mathcal{H}$

$\langle 1\rangle 6.$ F is a function

$\langle 2\rangle 1.$ ASSUME: tFx and tFy

$\langle 2\rangle 2.$ PICK $v_1, v_2 \in \mathcal{H}$ such that $v_1(t) = x$ and $v_2(t) = y$

$\langle 2\rangle 3.$ PICK $t_1, t_2 \in A$ such that v_1 is P-constructed up to t_1 and v_2 is P-constructed up to t_2

$\langle 2\rangle 4.$ ASSUME: w.l.o.g. $t_1 \leq t_2$

$\langle 2\rangle 5.$ $v_1(t) = v_2(t)$

PROOF: By $\langle 1\rangle 2$

$\langle 2\rangle 6.$ $x = y$

$\langle 1\rangle 7.$ $\forall x \in \operatorname{dom} F. P(F \restriction \operatorname{seg} x, F(x))$

$\langle 2\rangle 1.$ LET: $x \in \operatorname{dom} F$

$\langle 2\rangle 2.$ PICK $v \in \mathcal{H}$ such that $x \in \operatorname{dom} v$

$\langle 2\rangle 3.$ $P(v \restriction \operatorname{seg} x, v(x))$

$\langle 2\rangle 4.$ $v \restriction \operatorname{seg} x = F \restriction \operatorname{seg} x$

PROOF: $\forall y < x.(y, v(y)) \in \bigcup \mathcal{H} = F$

$\langle 2\rangle 5.$ $v(x) = F(x)$

PROOF: $(x, v(x)) \in \bigcup \mathcal{H} = F$

$\langle 1\rangle 8.$ $\operatorname{dom} F = A$

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

$\langle 2\rangle 2.$ ASSUME: $\forall y < x. y \in \operatorname{dom} F$

$\langle 2\rangle 3.$ LET: z be the object such that $P(F \restriction \operatorname{seg} x, z)$

$\langle 2\rangle 4.$ $F \restriction \operatorname{seg} x \cup \{(x, z)\}$ is P-constructed up to x

$\langle 2\rangle 5.$ $x \in \operatorname{dom} F$

$\langle 2\rangle 6.$ Q.E.D.

PROOF: By transfinite induction, this proves $\forall x \in A. x \in \operatorname{dom} F$.

$\langle 1\rangle 9.$ F is unique.

$\langle 2\rangle 1.$ LET: G be a function with domain A such that $\forall x \in A. P(G \restriction \operatorname{seg} x, G(x))$

PROVE: $\forall x \in A. F(x) = G(x)$

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

$\langle 2\rangle 3.$ ASSUME: $\forall y < x. F(y) = G(y)$

$\langle 2\rangle 4.$ $F \restriction \operatorname{seg} x = G \restriction \operatorname{seg} x$

$\langle 2\rangle 5.$ $F(x) = G(x)$

$\langle 2\rangle 6.$ Q.E.D.

PROOF: This completes the proof by transfinite induction.

$\square$

Proposition 103. *Let $(A, <)$ be a well ordered set and $B \subseteq A$. Then $< \cap B^2$ is a well order on B.*

PROOF: Easy. $\square$

Theorem 104. *Let A and B be well-ordered sets. Then one of the following holds:*

- $A \cong B$
- $\exists b \in B. A \cong \operatorname{seg} b$
- $\exists a \in A. \operatorname{seg} a \cong B$

PROOF:
⟨1⟩1. PICKe that is not a member of A or B
⟨1⟩2. Define $F : A \to B \cup \{e\}$ by:

$$F(t) = \begin{cases} \text{the least element of } B - F(\operatorname{seg} t) & \text{if } B - F(\operatorname{seg} t) \neq \emptyset \\ e & \text{if } B - F(\operatorname{seg} t) = \emptyset \end{cases}$$

⟨1⟩3. CASE: $e \in \operatorname{ran} F$
 ⟨2⟩1. LET: $a \in A$ be least such that $B - F(\operatorname{seg} a) = \emptyset$
 ⟨2⟩2. $F \restriction \operatorname{seg} a : \operatorname{seg} a \cong B$
⟨1⟩4. CASE: $\operatorname{ran} F = B$
 PROOF: In this case $F : A \cong B$.
⟨1⟩5. CASE: $\operatorname{ran} F \subset B$
 ⟨2⟩1. LET: $b \in B$ be least such that $b \notin \operatorname{ran} F$
 ⟨2⟩2. $F : A \cong \operatorname{seg} b$
□

14 Epsilon-Images

Lemma 105. *Let $<$ be a well ordering on A. Let E be the function on A defined by transfinite recursion thus:*

$$E(t) = \{E(x) : x < t\} \qquad (t \in A) \ .$$

Let $\alpha = \operatorname{ran} E$. Then:

1. $\forall t \in A. E(t) \notin E(t)$
2. *E is injective.*
3. $\forall s, t \in A. (s < t \Leftrightarrow E(s) \in E(t))$
4. *α is a transitive set.*

PROOF:
⟨1⟩1. $\forall t \in A. E(t) \notin E(t)$
 ⟨2⟩1. LET: $t \in A$
 ⟨2⟩2. ASSUME: $\forall s < t. E(s) \notin E(s)$
 ⟨2⟩3. ASSUME: for a contradiction $E(t) \in E(t)$
 ⟨2⟩4. PICK $x < t$ such that $E(t) = E(x)$
 ⟨2⟩5. $E(x) \in E(x)$
 ⟨2⟩6. Q.E.D.
  PROOF: This is a contradiction. The result follows by transfinite induction.
⟨1⟩2. E is injective.

⟨2⟩1. ASSUME: for a contradiction $E(x) = E(y)$ where $x \neq y$
⟨2⟩2. ASSUME: w.l.o.g. $x < y$
⟨2⟩3. $E(x) \in E(y)$
⟨2⟩4. Q.E.D.
PROOF: This contradicts ⟨1⟩1.
⟨1⟩3. $\forall s, t \in A(s < t \Leftrightarrow E(s) \in E(t))$
⟨2⟩1. LET: $s, t \in A$
⟨2⟩2. If $s < t$ then $E(s) \in E(t)$
PROOF: Immediate from definition of E.
⟨2⟩3. If $E(s) \in E(t)$ then $s < t$
⟨3⟩1. ASSUME: $E(s) \in E(t)$
⟨3⟩2. PICK $x < t$ such that $E(s) = E(x)$
⟨3⟩3. $s = x$
PROOF: ⟨1⟩2.
⟨3⟩4. $s < t$
⟨1⟩4. α is a transitive set.
PROOF: From definition of E.

Corollary 105.1. *For any well-ordered set $(A, <)$, if α is its epsilon-image, then $(A, <)$ is isomorphic to $(\alpha, \in)$.*

Corollary 105.2. *The epsilon-image of any well-ordered set is well ordered by $\in$.*

Theorem 106. *Two well-ordered sets are isomorphic iff they have the same ϵ-image.*

PROOF:
⟨1⟩1. LET: A and B be well-ordered sets.
⟨1⟩2. If A and B have the same ϵ-image then they are isomorphic.
PROOF: From Corollary 105.1.
⟨1⟩3. If $A \cong B$ then A and B have the same epsilon-image.
⟨2⟩1. LET: $f : A \cong B$
⟨2⟩2. LET: $E : A \cong \alpha$ and $F : B \cong \beta$ be the canonical isomorphisms between A and B and their epsilon-images.
⟨2⟩3. $\forall x \in A.E(x) = F(f(x))$
⟨3⟩1. LET: $x \in A$
⟨3⟩2. ASSUME: $\forall y < x.E(y) = F(f(y))$
⟨3⟩3. $E(x) = F(f(x))$
PROOF:

$$\begin{aligned} E(x) &= \{E(y) : y < x\} \\ &= \{F(f(y)) : y < x\} \\ &= \{F(z) : z < f(x)\} \\ &= F(f(x)) \end{aligned}$$

⟨2⟩4. $\alpha = \beta$
□

15 Ordinal Numbers

Definition 107 (Ordinal Number)**.** The *ordinal number* of a well-ordered set is its epsilon-image.

Definition 108 (Well-ordered by Epsilon)**.** A set A is *well-ordered by epsilon* iff $\{(x,y) : x, y \in A, x \in y\}$ is a well ordering on A.

Theorem 109. *A set is an ordinal number if and only if it is a transitive set that is well-ordered by epsilon.*

PROOF:
$\langle 1 \rangle 1$. Every ordinal number is a transitive set.
  PROOF: Lemma 105.
$\langle 1 \rangle 2$. Every ordinal number is well-ordered by epsilon.
  PROOF: Corollary 105.2.
$\langle 1 \rangle 3$. Every transitive set that is well-ordered by epsilon is an ordinal number.
  $\langle 2 \rangle 1$. LET: α be a transitive set well-ordered by epsilon.
  $\langle 2 \rangle 2$. LET: β be the epsilon-image of $(\alpha, \in)$ with $E : \alpha \cong \beta$ the canonical isomorphism.
  $\langle 2 \rangle 3$. $\forall x \in \alpha . E(x) = x$
    $\langle 3 \rangle 1$. LET: $x \in \alpha$
    $\langle 3 \rangle 2$. ASSUME: $\forall y < x . E(y) = y$
    $\langle 3 \rangle 3$. $E(x) = x$
      PROOF:
$$\begin{aligned} E(x) &= \{E(y) : y \in \alpha, y \in x\} \\ &= \{E(y) : y \in x\} && (\alpha \text{ is a transitive set}) \\ &= \{y : y \in x\} && (\langle 3 \rangle 2) \\ &= x \end{aligned}$$
  $\langle 2 \rangle 4$. $\alpha = \beta$
□

Theorem 110. *Every member of an ordinal number is an ordinal number.*

PROOF:
$\langle 1 \rangle 1$. LET: α be an ordinal number.
$\langle 1 \rangle 2$. LET: $\beta \in \alpha$
$\langle 1 \rangle 3$. β is a transitive set.
  $\langle 2 \rangle 1$. LET: $x \in y \in \beta$
  $\langle 2 \rangle 2$. $y \in \alpha$
    PROOF: Since α is a transitive set.
  $\langle 2 \rangle 3$. $x \in \alpha$
    PROOF: Since α is a transitive set.
  $\langle 2 \rangle 4$. $x \in \beta$
    PROOF: Since α is a partially ordered by epsilon.
$\langle 1 \rangle 4$. β is well-ordered by epsilon.
  PROOF: Since $\{(x,y) : x, y \in \beta, x \in y\}$ is the restriction of $\{(x,y) : x, y \in \alpha, x \in y\}$ to β.

⟨1⟩5. β is an ordinal number.
Proof: Theorem 109.
□

Proposition 111. *The class of ordinals is well-ordered by epsilon.*

Proof:
⟨1⟩1. For any ordinals α, β, γ, if $\alpha \in \beta \in \gamma$ then $\alpha \in \gamma$.
Proof: Since γ is a transitive set (Lemma 105).
⟨1⟩2. For any ordinal α we have $\alpha \notin \alpha$.
Proof: Since α is well-ordered by epsilon.
⟨1⟩3. For any ordinals α, β, exactly one of $\alpha \in \beta$, $\beta \in \alpha$, $\alpha = \beta$ holds.
⟨2⟩1. Let: α, β be ordinals.
⟨2⟩2. Either $\alpha \cong \beta$ or $\exists \gamma \in \beta . \alpha \cong \gamma$ or $\exists \gamma \in \alpha . \gamma \cong \alpha$
Proof: Theorem 104.
⟨2⟩3. Either $\alpha = \beta$ or $\exists \gamma \in \beta . \alpha = \gamma$ or $\exists \gamma \in \alpha . \gamma = \alpha$
Proof: Since any ordinal is its own epsilon-image, and isomorphic well-orderings have equal epsilon-images.
⟨1⟩4. Any nonempty set of ordinals has a least element.
⟨2⟩1. Let: A be a nonempy set of ordinals.
⟨2⟩2. Pick $\alpha \in A$
⟨2⟩3. Case: $A \cap \alpha = \emptyset$
Proof: In this case, α is least in A.
⟨2⟩4. Case: $A \cap \alpha \neq \emptyset$
Proof: In this case, the least element of $A \cap \alpha$ is the least element in A.
□

Corollary 111.1. *Any transitive set of ordinal numbers is an ordinal number.*

Corollary 111.2. $\emptyset$ *is an ordinal number.*

We write 0 for $\emptyset$ considered as an ordinal number.

Definition 112 (Successor)**.** The *successor* of a set a is the set $a^+ = a \cup \{a\}$.

Corollary 112.1. *The successor of an ordinal number is an ordinal number.*

Corollary 112.2. *For any set A of ordinal numbers, the set $\bigcup A$ is an ordinal number.*

Theorem 113 (Burali-Forti)**.** *The class of ordinal numbers is not a set.*

Proof:
⟨1⟩1. Assume: for a contradiction the class **On** is a set.
⟨1⟩2. **On** is an ordinal number.
Proof: Corollary 111.1.
⟨1⟩3. $\mathbf{On} \in \mathbf{On}$
⟨1⟩4. Q.E.D.
Proof: This contradicts Lemma 105.

□

Theorem 114 (Hartogs)**.** *For any set A, there exists an ordinal not dominated by A.*

PROOF:
$\langle 1 \rangle 1$. LET: A be a set.
$\langle 1 \rangle 2$. LET: $\alpha = \{\beta : \beta$ is an ordinal $, \beta \preccurlyeq A\}$.
$\langle 1 \rangle 3$. LET: $W = \{(B, <) : B \subseteq A, <$ is a well ordering on $B\}$
$\langle 1 \rangle 4$. $\forall \beta \in \alpha . \exists (B, <) \in W . \beta$ is the epsilon-image of $(B, <)$
  $\langle 2 \rangle 1$. LET: $\beta \in \alpha$
  $\langle 2 \rangle 2$. PICK an injection $f : \beta \to A$
  $\langle 2 \rangle 3$. Define $<$ on $f(\beta)$ by: $f(\gamma) < f(\delta)$ iff $\gamma \in \delta$
  $\langle 2 \rangle 4$. $<$ well orders $f(\beta)$
  $\langle 2 \rangle 5$. β is the epsilon-image of $(f(\beta), <)$ with f^{-1} the canonical isomorphism.
$\langle 1 \rangle 5$. α is a set.
  PROOF: By a Replacement Axiom applied to W.
$\langle 1 \rangle 6$. α is an ordinal.
  $\langle 2 \rangle 1$. α is a transitive set.
    $\langle 3 \rangle 1$. LET: $\beta \in \gamma \in \alpha$
    $\langle 3 \rangle 2$. $\beta \subseteq \gamma \preccurlyeq A$
    $\langle 3 \rangle 3$. $\beta \preccurlyeq A$
    $\langle 3 \rangle 4$. $\beta \in \alpha$
  $\langle 2 \rangle 2$. Q.E.D.
    PROOF: By Corollary 111.1.
$\langle 1 \rangle 7$. $\alpha \not\preccurlyeq A$
  PROOF: Because $\alpha \notin \alpha$.
□

Theorem 115 (Well-Ordering Theorem (Choice))**.** *For any set A, there exists a well ordering on A.*

PROOF:
$\langle 1 \rangle 1$. LET: A be a set.
$\langle 1 \rangle 2$. PICK an ordinal α not dominated by A
$\langle 1 \rangle 3$. $A \preccurlyeq \alpha$
$\langle 1 \rangle 4$. PICK an injection $f : A \to \alpha$
$\langle 1 \rangle 5$. Define $<$ on A by: $x < y$ iff $f(x) \in f(y)$
$\langle 1 \rangle 6$. $<$ is a well ordering on A.
□

16 Natural Numbers

Definition 116 (Inductive)**.** A class $\mathbf{A}$ is *inductive* iff $\emptyset \in \mathbf{A}$ and $\forall a \in \mathbf{A} . a^+ \in \mathbf{A}$.

Axiom 117 (Infinity)**.** *There exists an inductive set.*

Definition 118 (Natural Number)**.** A *natural number* is a set that belongs to every inductive set.

We write ω for the class of all natural numbers.

Theorem 119. *The class ω is a set.*

PROOF: Pick an inductive set I (by the Axiom of Infinity), then apply a Subset Axiom to I. $\square$

Theorem 120. *The set ω is inductive, and is a subset of every inductive set.*

PROOF: Easy. $\square$

Corollary 120.1 (Proof by Induction)**.** *Any inductive subclass of ω is equal to ω.*

Theorem 121. *Every natural number except 0 is the successor of some natural number.*

PROOF: Easy proof by induction. $\square$

Definition 122 (Peano System)**.** A *Peano system* is a triple $\langle N, S, e\rangle$ consisting of a set N, a function $S : N \to N$ and an element $e \in N$ such that:

1. $e \notin \operatorname{ran} S$
2. S is one-to-one
3. Any subset $A \subseteq N$ that contains e and is closed under S equals N.

Definition 123 (Transitive Set)**.** A set A is a *transitive set* iff every member of a member of A is a member of A.

Theorem 124. *For any transitive set a, $\bigcup(a^+) = a$.*

PROOF:

$$\begin{aligned}\bigcup(a^+) &= \bigcup(a \cup \{a\}) \\ &= \bigcup a \cup \bigcup\{a\} \\ &= \bigcup a \cup a \\ &= a\end{aligned}$$

since $\bigcup a \subseteq a$. $\square$

Theorem 125. *Every natural number is a transitive set.*

PROOF:
$\langle 1\rangle 1.$ 0 is a transitive set.
  PROOF: Vacuous.
$\langle 1\rangle 2.$ 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 that is a transitive set.

$\langle 2\rangle 2.$ $\bigcup(n^+) \subseteq n^+$
PROOF: Theorem 124.
□

Theorem 126. *$\langle \omega, \sigma, 0\rangle$ is a Peano system, where $0 = \emptyset$ and $\sigma = \{\langle n, n^+\rangle : n \in \omega\}$.*

PROOF:
$\langle 1\rangle 1.$ $0 \notin \operatorname{ran}\sigma$
PROOF: For any $n \in \omega$ we have $0 \neq n^+$ since $n \in n^+$ and $n \notin 0$.
$\langle 1\rangle 2.$ σ is one-to-one.
PROOF: If $m^+ = n^+$ then $m = \bigcup(m^+) = \bigcup(n^+) = n$ using Theorems 124 and 125.
$\langle 1\rangle 3.$ Any subset $A \subseteq \omega$ that contains 0 and is closed under σ equals ω.
□

Theorem 127. *The set ω is a transitive set.*

PROOF:
$\langle 1\rangle 1.$ For every natural number n we have $\forall m \in n.\ m$ is a natural number.
$\langle 2\rangle 1.$ $\forall m \in 0.\ m$ is a natural number.
PROOF: Vacuous.
$\langle 2\rangle 2.$ If n is a natural number and $\forall m \in n.\ m$ is a natural number, then $\forall m \in n^+.\ m$ is a natural number.
PROOF: Since if $m \in n^+$ we have either $m \in n$ or $m = n$, and m is a natural number in either case.
□

Theorem 128 (Recursion Theorem on ω)**.** *Let A be a set, $a \in A$ and $F : A \to A$. Then there exists a unique function $h : \omega \to A$ such that*

$$h(0) = a \ ,$$

and for every n in ω,

$$h(n^+) = F(h(n)) \ .$$

PROOF:
$\langle 1\rangle 1.$ Let us call a function v *acceptable* iff $\operatorname{dom} v \subseteq \omega$, $\operatorname{ran} v \subseteq A$ and:

1. If $0 \in \operatorname{dom} v$ then $v(0) = a$
2. For all $n \in \omega$, if $n^+ \in \operatorname{dom} v$ then $n \in \operatorname{dom} v$ and $v(n^+) = F(v(n))$.

$\langle 1\rangle 2.$ LET: $\mathcal{K}$ be the set of acceptable functions.
$\langle 1\rangle 3.$ LET: $h = \bigcup \mathcal{K}$
$\langle 1\rangle 4.$ h is a function.
$\langle 2\rangle 1.$ LET: $S = \{n \in \omega : \text{for at most one } y, (n, y) \in h\}$
$\langle 2\rangle 2.$ S is inductive.
$\langle 3\rangle 1.$ $0 \in S$
$\langle 4\rangle 1.$ LET: $\langle 0, y_1\rangle, \langle 0, y_2\rangle \in h$

$\langle 4\rangle 2$. Pick acceptable v_1 and v_2 such that $v_1(0) = y_1$ and $v_2(0) = y_2$
$\langle 4\rangle 3$. $y_1 = a$
$\langle 4\rangle 4$. $y_2 = a$
$\langle 4\rangle 5$. $y_1 = y_2$
$\langle 3\rangle 2$. $\forall k \in S. k^+ \in S$
$\langle 4\rangle 1$. Let: $k \in S$
$\langle 4\rangle 2$. Let: $(k^+, y_1), (k^+, y_2) \in h$
$\langle 4\rangle 3$. Pick acceptable v_1, v_2 such that $v_1(k^+) = y_1$ and $v_2(k^+) = y_2$
$\langle 4\rangle 4$. $y_1 = F(v_1(k))$
$\langle 4\rangle 5$. $f_2 = F(v_2(k))$
$\langle 4\rangle 6$. $v_1(k) = v_2(k)$
$\langle 5\rangle 1$. $(k, v_1(k)), (k, v_2(k)) \in h$
$\langle 5\rangle 2$. Q.E.D.
Proof: By $\langle 4\rangle 1$
$\langle 4\rangle 7$. $y_1 = y_2$
$\langle 2\rangle 3$. $S = \omega$
$\langle 1\rangle 5$. h is acceptable.
$\langle 2\rangle 1$. If $0 \in \operatorname{dom} h$ then $h(0) = a$
$\langle 3\rangle 1$. Assume: $0 \in \operatorname{dom} h$
$\langle 3\rangle 2$. Pick v acceptable with $v(0) = h(0)$
$\langle 3\rangle 3$. $v(0) = a$
$\langle 3\rangle 4$. $h(0) = a$
$\langle 2\rangle 2$. For all $n \in \omega$, if $n^+ \in \operatorname{dom} h$ then $n \in \operatorname{dom} h$ and $h(n^+) = F(h(n))$
$\langle 3\rangle 1$. Let: $n \in \omega$ with $n^+ \in \operatorname{dom} h$
$\langle 3\rangle 2$. Pick v acceptable with $v(n^+) = h(n^+)$
$\langle 3\rangle 3$. $n \in \operatorname{dom} v$
$\langle 3\rangle 4$. $v(n) = h(n)$
$\langle 3\rangle 5$. $h(n^+) = F(h(n))$
Proof:

$$\begin{aligned} h(n^+) &= v(n^+) \\ &= F(v(n)) \\ &= F(h(n)) \end{aligned}$$

$\langle 1\rangle 6$. $\operatorname{dom} h = \omega$
$\langle 2\rangle 1$. $0 \in \operatorname{dom} h$
Proof: Since $\{(0, a)\}$ is an acceptable function.
$\langle 2\rangle 2$. $\forall n \in \operatorname{dom} h. n^+ \in \operatorname{dom} h$
$\langle 3\rangle 1$. Let: $n \in \operatorname{dom} h$
$\langle 3\rangle 2$. Pick an acceptable v such that $n \in \operatorname{dom} v$
$\langle 3\rangle 3$. Assume: w.l.o.g. $n^+ \notin \operatorname{dom} v$
$\langle 3\rangle 4$. $v \cup \{(n^+, F(v(n)))\}$ is acceptable.
$\langle 1\rangle 7$. For any acceptable function $h' : \omega \to A$ we have $h' = h$
$\langle 2\rangle 1$. Let: $h' : \omega \to A$ be acceptable.
$\langle 2\rangle 2$. $h'(0) = h(0)$
Proof: $h'(0) = h(0) = a$
$\langle 2\rangle 3$. $\forall n \in \omega. h'(n) = h(n) \Rightarrow h'(n^+) = h(n^+)$

PROOF: We have $h'(n^+) = F(h'(n)) = F(h(n)) = h(n^+)$.
$\square$

Theorem 129. *Let (N, S, e) be a Peano system. Then $(\omega, \sigma, 0)$ is isomorphic to (N, S, e), i.e. there is a function h mapping ω one-to-one onto N in a way that preserves the successor operation*

$$h(\sigma(n)) = S(h(n))$$

and the zero element

$$h(0) = e \ .$$

PROOF:
$\langle 1\rangle 1$. There exists a function h that satisfies those two conditions.
  PROOF: By the Recursion Theorem.
$\langle 1\rangle 2$. For all $m, n \in \omega$, if $m \neq n$ then $h(m) \neq h(n)$
  $\langle 2\rangle 1$. For all $n \in \omega$, if $n \neq 0$ then $h(n) \neq h(0)$
    $\langle 3\rangle 1$. LET: $n \in \omega$
    $\langle 3\rangle 2$. ASSUME: $n \neq 0$
    $\langle 3\rangle 3$. PICK p such that $n = p^+$
    $\langle 3\rangle 4$. $h(n) \neq h(0)$
      PROOF: $h(n) = S(h(p)) \neq e = h(0)$.
  $\langle 2\rangle 2$. For all $m \in \omega$, if $\forall n(m \neq n \Rightarrow h(m) \neq h(n))$ then $\forall n(m^+ \neq n \Rightarrow h(m^+) \neq h(n))$
    $\langle 3\rangle 1$. LET: $m \in \omega$
    $\langle 3\rangle 2$. ASSUME: $\forall n(m \neq n \Rightarrow h(m) \neq h(n))$
    $\langle 3\rangle 3$. LET: $n \in \omega$
    $\langle 3\rangle 4$. ASSUME: $m^+ \neq n$
      PROVE: $h(m^+) \neq h(n)$
    $\langle 3\rangle 5$. CASE: $n = 0$
      PROOF: $h(m^+) = S(h(m)) \neq e = h(n)$
    $\langle 3\rangle 6$. CASE: $n = p^+$
      $\langle 4\rangle 1$. $m \neq p$
      $\langle 4\rangle 2$. $h(m) \neq h(p)$
      $\langle 4\rangle 3$. $S(h(m)) \neq S(h(p))$
      $\langle 4\rangle 4$. $h(m^+) \neq h(p^+)$
$\langle 1\rangle 3$. For all $x \in N$, there exists $n \in \omega$ such that $h(n) = x$
  PROOF: An easy induction on x.
$\square$

17 Finite Sets

Definition 130 (Finite)**.** A set is *finite* iff it is equinumerous with a natural number. Otherwise it is infinite.

Theorem 131. *No natural number is equinumerous with a proper subset of itself.*

PROOF:
$\langle 1\rangle 1$. Any injective function $f : 0 \to 0$ has range 0.
PROOF: Since the only such function is $\emptyset$.
$\langle 1\rangle 2$. For any natural number n, if every injective function $f : n \to n$ has range n, then every injective function $f : n^+ \to n^+$ has range n^+.
$\langle 2\rangle 1$. LET: $n \in \omega$
$\langle 2\rangle 2$. ASSUME: Every injective function $f : n \to n$ has range n.
$\langle 2\rangle 3$. LET: $f : n^+ \to n^+$ be injective.
$\langle 2\rangle 4$. Define $g : n \to n$ by

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

PROOF: If $k \in n$ and $f(k) = n$ then $f(n) \in n$ since f is injective.
$\langle 2\rangle 5$. g is injective.
$\langle 3\rangle 1$. LET: $i, j \in n$
$\langle 3\rangle 2$. ASSUME: $g(i) = g(j)$
$\langle 3\rangle 3$. CASE: $f(i) \in n$, $f(j) \in n$
PROOF: Then $f(i) = f(j)$ so $i = j$
$\langle 3\rangle 4$. CASE: $f(i) \in n$, $f(j) \notin n$
PROOF: Then $f(i) = f(n)$ which is impossible as f is injective.
$\langle 3\rangle 5$. CASE: $f(i) \notin n$, $f(j) \in n$
PROOF: Then $f(n) = f(j)$ which is impossible as f is injective.
$\langle 3\rangle 6$. CASE: $f(i) \notin n$, $f(j) \notin n$
PROOF: Then $f(i) = f(j) = n$ so $i = j$.
$\langle 2\rangle 6$. $\operatorname{ran} g = n$
PROOF: By $\langle 2\rangle 2$.
$\langle 2\rangle 7$. $\operatorname{ran} f = n^+$
$\langle 3\rangle 1$. $\forall k \in n. k \in \operatorname{ran} f$
PROOF: Since $\operatorname{ran} g \subseteq \operatorname{ran} f$.
$\langle 3\rangle 2$. $n \in \operatorname{ran} f$
$\langle 4\rangle 1$. CASE: $f(n) \in n$
$\langle 5\rangle 1$. PICK k such that $g(k) = f(n)$
$\langle 5\rangle 2$. $f(k) = n$
$\langle 4\rangle 2$. CASE: $f(n) = n$
PROOF: Then $n \in \operatorname{ran} f$.
□

Corollary 131.1. *No finite set is equinumerous with a proper subset of itself.*

Corollary 131.2. *The set ω is infinite.*

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

Corollary 131.3. *Every finite set is equinumerous with a unique natural number.*

Lemma 132. *Let n be a natural number and $C \subseteq n$. Then there exists $m \underline{\in} n$ such that $C \approx m$.*

PROOF:
⟨1⟩1. For all $C \subseteq 0$, there exists $m \underline{\in} 0$ such that $C \approx m$.
PROOF: In this case $C = \emptyset$ and so $C \approx 0$.
⟨1⟩2. Let $n \in \omega$. Assume that, for all $C \subseteq n$, there exists $m \underline{\in} n$ such that $C \approx m$. Let $C \subseteq n^+$. Then there exists $m \underline{\in} n^+$ such that $C \approx m$.
⟨2⟩1. LET: $n \in \omega$
⟨2⟩2. ASSUME: For all $C \subseteq n$, there exists $m \underline{\in} n$ such that $C \approx m$.
⟨2⟩3. LET: $C \subseteq n^+$
⟨2⟩4. CASE: $n \in C$
⟨3⟩1. PICK $m \underline{\in} n$ such that $C - \{n\} \approx m$
⟨3⟩2. $C \approx m^+$
⟨2⟩5. CASE: $n \notin C$
PROOF: Then $C \subseteq n$ so $C \approx m$ for some $m \underline{\in} n$.
$\square$

Corollary 132.1. *Any subset of a finite set is finite.*

18 Cardinal Numbers

Definition 133 (Cardinality)**.** TODO

Theorem 134. *For any sets A and B, $|A| = |B|$ if and only if $A \approx B$.*

PROOF: TODO $\square$

Theorem 135. *For any finite set A, $|A|$ is the natural number such that $A \approx |A|$.*

PROOF: TODO $\square$

Definition 136. We write $\aleph_0$ for $|\omega$.

19 Cardinal Arithmetic

Definition 137 (Addition)**.** Let κ and λ be any cardinal numbers. Then $\kappa+\lambda = |K \cup L|$, where K and L are any disjoint sets of cardinality κ and λ respectively.

To show this is well-defined, we must prove that, if $K_1 \approx K_2$, $L_1 \approx L_2$, and $K_1 \cap L_1 = K_2 \cap L_2 = \emptyset$, then $K_1 \cup L_1 \approx K_2 \cup L_2$.

PROOF: Easy.

Lemma 138. *For any cardinal number κ we have $\kappa + 0 = \kappa$.*

PROOF: Since for any set K we have $K \cup \emptyset = K$.

Lemma 139. *For any natural number n we have $n + \aleph_0 = \aleph_0$.*

PROOF: Easy. $\square$

Lemma 140.

$$\aleph_0 + \aleph_0 = \aleph_0$$

Proof: Define $f : (\omega \times \{0\}) \cup (\omega \times \{1\}) \to \omega$ by $f(n, 0) = 2n$ and $f(n, 1) = 2n+1$. Then f is a bijection. □

Theorem 141.

$$\kappa + \lambda = \lambda + \kappa$$

Proof: Easy. □

Theorem 142.

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

Proof: Easy. □

Definition 143 (Multiplication)**.** Let κ and λ be any cardinal numbers. Then $\kappa\lambda = |K \times L|$, where K and L are any sets of cardinality κ and λ respectively.

It is easy to prove this well-defined.

Lemma 144. *For any cardinal number κ we have $\kappa 0 = 0$.*

Proof: For any set K we have $K \times \emptyset = \emptyset$. □

Lemma 145. *For any natural number n we have $n\aleph_0 = \aleph_0$.*

Proof: Induction on n using Lemma 140. □

Lemma 146.

$$\aleph_0 \aleph_0 = \aleph_0$$

Proof: Define $f : \omega \times \omega \to \omega$ by $f(m, n) = 2^m(2n + 1) - 1$. Then f is a bijection. □

Lemma 147.

$$\kappa 1 = \kappa$$

Proof: Easy. □

Theorem 148.

$$\kappa\lambda = \lambda\kappa$$

Proof: Easy. □

Theorem 149.

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

Proof: Easy. □

Theorem 150.

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

Proof: Easy. □

Definition 151 (Exponentiation)**.** Let κ and λ be any cardinal numbers. Then $\kappa^\lambda = |K^L|$, where K and L are any sets of cardinality κ and λ respectively.

It is easy to prove this well-defined.

Theorem 152. *For any cardinal κ, $\kappa^0 = 1$.*

PROOF: For any set K, there is only one function $\emptyset \to K$, namely $\emptyset$. $\square$

Theorem 153. *For any non-zero cardinal κ, we have $0^\kappa = 0$.*

PROOF: For any nonempty set K, there is no function $K \to \emptyset$. $\square$

Theorem 154. *For any set A, $|\mathcal{P}A| = 2^{|A|}$.*

PROOF: Define the bijection $f : \mathcal{P}A \to 2^A$ by $f(S)(a) = 1$ if $a \in S$, 0 if $a \notin S$. $\square$

Corollary 154.1. *For any cardinal κ, we have $\kappa \neq 2^\kappa$.*

Theorem 155.

$$\kappa^{\lambda+\mu} = \kappa^\lambda \kappa^\mu$$

PROOF: Easy. $\square$

Theorem 156.

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

PROOF: Easy. $\square$

Theorem 157.

$$(\kappa^\lambda)^\mu = \kappa^{\lambda\mu}$$

PROOF: Easy. $\square$

20 Arithmetic

Lemma 158. *For any natural numbers m and n, we have $m + n^+ = (m+n)^+$.*

PROOF: Easy. $\square$

Corollary 158.1. *The union of two finite sets is finite.*

Lemma 159. *For any natural numbers m and n we have $mn^+ = mn + m$.*

PROOF: Easy. $\square$

Corollary 159.1. *The Cartesian product of two finite sets is finite.*

Lemma 160. *For any natural numbers m and n we have $m^{n^+} = m^n m$.*

PROOF: Easy. $\square$

Corollary 160.1. *If A and B are finite sets then A^B is finite.*

21 Ordering on the Natural Numbers

Lemma 161. *For any natural numbers m and n, $m \in n$ if and only if $m^+ \in n^+$.*

PROOF:
$\langle 1 \rangle 1.$ $\forall m, n \in \omega (m \in n \Rightarrow m^+ \in n^+)$
  $\langle 2 \rangle 1.$ $\forall m \in \omega (m \in 0 \Rightarrow m^+ \in 0^+)$
    PROOF: Vacuous.
  $\langle 2 \rangle 2.$ For all $n \in \omega$, if $\forall m \in n . m^+ \in n^+$ then $\forall m \in n^+ . m^+ \in n^{++}$
    $\langle 3 \rangle 1.$ LET: $n \in \omega$
    $\langle 3 \rangle 2.$ ASSUME: $\forall m \in n . m^+ \in n^+$
    $\langle 3 \rangle 3.$ LET: $m \in n^+$
    $\langle 3 \rangle 4.$ CASE: $m \in n$
      $\langle 4 \rangle 1.$ $m^+ \in n^+$
        PROOF: By $\langle 3 \rangle 2$
      $\langle 4 \rangle 2.$ $m^+ \in n^{++}$
    $\langle 3 \rangle 5.$ CASE: $m = n$
      PROOF: $m^+ = n^+ \in n^{++}$
$\langle 1 \rangle 2.$ $\forall m, n \in \omega (m^+ \in n^+ \Rightarrow m \in n)$
  $\langle 2 \rangle 1.$ LET: $m, n \in \omega$
  $\langle 2 \rangle 2.$ ASSUME: $m^+ \in n^+$
  $\langle 2 \rangle 3.$ $m \in m^+$
  $\langle 2 \rangle 4.$ $m^+ \in n$ or $m^+ = n$
  $\langle 2 \rangle 5.$ $m \in n$
    PROOF: If $m^+ \in n$ this follows because n is transitive (Theorem 125).
□

Lemma 162. *For any natural number n we have $n \notin n$.*

PROOF:
$\langle 1 \rangle 1.$ $0 \notin 0$
$\langle 1 \rangle 2.$ For all $n \in \omega$, if $n \notin n$ then $n^+ \notin n^+$
  $\langle 2 \rangle 1.$ LET: $n \in \omega$
  $\langle 2 \rangle 2.$ ASSUME: $n^+ \in n^+$
    PROVE: $n \in n$
  $\langle 2 \rangle 3.$ $n^+ \in n$ or $n^+ = n$
  $\langle 2 \rangle 4.$ $n \in n^+$
  $\langle 2 \rangle 5.$ $n \in n$
    PROOF: If $n^+ \in n$ this follows because n is transitive (Theorem 125).
□

Theorem 163 (Trichotomy Law for ω)**.** *For any natural numbers m and n, exactly one of*

$$m \in n, m = n, n \in m$$

holds.

PROOF:

$\langle 1\rangle 1$. For any $m, n \in \omega$, at most one of $m \in n$, $m = n$, $n \in m$ holds.
Proof: If $m \in n$ and $m = n$ then $m \in m$ contradicting Lemma 162.
If $m \in n$ and $n \in m$ then $m \in m$ by Theorem 125, contradicting Lemma 162.
$\langle 1\rangle 2$. For any $m, n \in \omega$, at least one of $m \in n$, $m = n$, $n \in m$ holds.
$\langle 2\rangle 1$. For all $n \in \omega$, either $0 \in n$ or $0 = n$
$\langle 3\rangle 1$. $0 = 0$
$\langle 3\rangle 2$. For all $n \in \omega$, if $0 \in n$ or $0 = n$ then $0 \in n^+$
$\langle 2\rangle 2$. For all $m \in \omega$, if $\forall n \in \omega(m \in n \vee m = n \vee n \in m)$ then $\forall n \in \omega(m^+ \in n \vee m^+ = n \vee n \in m^+)$
$\langle 3\rangle 1$. Let: $m \in \omega$
$\langle 3\rangle 2$. Assume: $\forall n \in \omega(m \in n \vee m = n \vee n \in m)$
$\langle 3\rangle 3$. Let: $n \in \omega$
$\langle 3\rangle 4$. Case: $m \in n$
Proof: Then $m \in n^+$
$\langle 3\rangle 5$. Case: $m = n$
Proof: Then $m \in n^+$
$\langle 3\rangle 6$. Case: $n \in m$
Proof: Then $n^+ \in m^+$ by Lemma 161 so $n^+ \in m$ or $n^+ = m$.
□

Corollary 163.1. *The relation $\in$ is a linear ordering on ω.*

Corollary 163.2. *For any natural numbers m and n,*

$$m \in n \Leftrightarrow m \subset n \ .$$

Proof:
$\langle 1\rangle 1$. Let: $m, n \in \omega$
$\langle 1\rangle 2$. If $m \in n$ then $m \subset n$.
$\langle 2\rangle 1$. Assume: $m \in n$
$\langle 2\rangle 2$. $m \subseteq n$
Proof: Theorem 125.
$\langle 2\rangle 3$. $m \neq n$
Proof: Lemma 162.
$\langle 1\rangle 3$. If $m \subset n$ then $m \in n$.
Proof: We have $m \neq n$ and $n \notin m$ by $\langle 1\rangle 2$, hence $m \in n$ by trichotomy.
□

Theorem 164. *For any natural number p, the function that maps n to $n + p$ is strictly monotone. For any natural numbers m, n and p, we have $m \in n$ if and only if $m + p \in n + p$.*

Proof: We prove that $m \in n \Rightarrow m + p \in n + p$. This is an easy induction on p using Lemma 161. □

Theorem 165. *For any non-zero natural number p, the function that maps n to np is strictly monotone.*

Proof: Easy induction on p using Theorem 164. □

Theorem 166 (Strong Induction)**.** *Let A be a subset of ω and suppose that, for all $n \in \omega$, we have*

$$(\forall m < n.m \in A) \Rightarrow n \in A \ .$$

Then $A = \omega$.

PROOF: Prove $\forall n \in \omega.\forall m < n.m \in A$ by induction on n. □

Theorem 167 (Well-Ordering of ω)**.** *The ordering $<$ on ω is a well-ordering.*

PROOF: If A is a subset of ω with no least element, we prove $\forall n \in \omega.n \notin A$ by strong induction on n. □

Theorem 168 (Choice)**.** *Let $<$ be a linear ordering on A. Then $<$ is a well-ordering on A iff there does not exist any function $f : \omega \to \omega$ such that $f(n+1) < f(n)$ for all $n \in \omega$.*

PROOF:
⟨1⟩1. If $<$ is a well-ordering on A then there does not exist any function $f : \omega \to \omega$ such that $f(n+1) < f(n)$ for all $n \in \omega$.
  PROOF: If there is such a function f then $\operatorname{ran} f$ is a nonempty subset of A with no least element.
⟨1⟩2. If there does not exist any function $f : \omega \to A$ such that $f(n+1) < f(n)$ for all $n \in \omega$ then $<$ is a well-ordering on A.
  ⟨2⟩1. LET: $X \subseteq A$ be a nonempty subset of A with no least element.
    PROVE: There exists a function $f : \omega \to A$ such that $f(n+1) < f(n)$ for all $n \in \omega$
  ⟨2⟩2. PICK $a_0 \in X$
  ⟨2⟩3. $\forall x \in X.\exists y \in X.y < x$
  ⟨2⟩4. PICK a function $g : X \to X$ such that $\forall x \in X.g(x) < x$
    PROOF: By the Axiom of Choice.
  ⟨2⟩5. Define $f : \omega \to A$ recursively by:

$$f(0) = a_0$$
$$f(n^+) = g(f(n))$$

  ⟨2⟩6. $\forall n \in \omega.f(n^+) < f(n)$

□

Lemma 169. *For any natural numbers m and n, we have $m \in n$ if and only if there exists a natural number p such that $n = m + p^+$.*

PROOF:
⟨1⟩1. For all m, p, we have $m \in m + p^+$
  PROOF: $m = m + 0 \in m + p^+$
⟨1⟩2. For all m, n, if $m \in n$ then there exists p such that $n = m + p^+$
  ⟨2⟩1. For all m, if $m \in 0$ then there exists p such that $0 = m + p^+$
    PROOF: Vacuous.
  ⟨2⟩2. For all $n \in \omega$, if $\forall m \in n.\exists p \in \omega.n = m + p^+$ then $\forall m \in n^+.\exists p \in \omega.n^+ = m + p^+$

$\langle 3 \rangle 1.$ LET: $n \in \omega$
$\langle 3 \rangle 2.$ ASSUME: $\forall m \in n . \exists p \in \omega . n = m + p^+$
$\langle 3 \rangle 3.$ LET: $m \in n^+$
$\langle 3 \rangle 4.$ CASE: $m \in n$
$\langle 4 \rangle 1.$ PICK p such that $n = m + p^+$
$\langle 4 \rangle 2.$ $n^+ = m + p^{++}$
$\langle 3 \rangle 5.$ CASE: $m = n$
PROOF: $n^+ = m + 0^+$
□

Lemma 170. *For natural numbers m, n, p and q, if $m \in n$ and $p \in q$ then $mp + nq \in mq + np$.*

$\langle 1 \rangle 1.$ PICK natural numbers a and b such that $n = m + a^+$ and $q = p + b^+$
PROOF: Lemma 169.
$\langle 1 \rangle 2.$ $mp + nq = mq + np + (a^+ + b)^+$
$\langle 1 \rangle 3.$ $mp + nq \in mq + np$
PROOF: Lemma 169.

22 The Integers

Theorem 171. *The relation $\sim$ is an equivalence relation on $\omega \times \omega$, where $(m, n) \sim (p, q)$ iff $m + q = n + p$.*

PROOF:
$\langle 1 \rangle 1.$ The relation $\sim$ is reflexive on ω^2
PROOF: For any m, n, we have $m + n = m + n$ and so $(m, n) \sim (m, n)$.
$\langle 1 \rangle 2.$ The relation $\sim$ is symmetric.
PROOF: If $m + q = n + p$ then $p + n = q + m$.
$\langle 1 \rangle 3.$ The relation $\sim$ is transitive.
$\langle 2 \rangle 1.$ ASSUME: $(m, n) \sim (p, q) \sim (r, s)$
$\langle 2 \rangle 2.$ $m + q = n + p$
$\langle 2 \rangle 3.$ $p + s = q + r$
$\langle 2 \rangle 4.$ $m + p + q + s = n + p + q + r$
$\langle 2 \rangle 5.$ $m + s = n + r$
PROOF: By cancellation of addition in ω.
□

Definition 172. The set $\mathbb{Z}$ of *integers* is the quotient set $(\omega \times \omega)/\sim$.

Lemma 173. *If $(m, n) \sim (m', n')$ and $(p, q) \sim (p', q')$ then $(m + p, n + q) \sim (m' + p', n' + q')$.*

PROOF: Assume $m + n' = m' + n$ and $p + q' = p' + q$. Then $m + p + n' + q' = m' + p' + n + q$. □

Definition 174 (Addition)**.** Addition $+$ on $\mathbb{Z}$ is the binary operation such that

$$[(m, n)] + [(p, q)] = [(m + p, n + q)]$$

Theorem 175. *Addition on $\mathbb{Z}$ is commutative.*

PROOF: From the definition. $\square$

Theorem 176. *Addition on $\mathbb{Z}$ is associtative.*

PROOF: Easy. $\square$

Definition 177 (Zero)**.** The zero in the integers is $0 = [(0,0)]$.

Theorem 178. *For any integer a we have $a + 0 = 0$.*

PROOF: Easy. $\square$

Theorem 179. *For any integer a, there exists an integer b such that $a+b=0$.*

PROOF: If $a = [(m,n)]$ take $b = [(n,m)]$. $\square$

Lemma 180. *If $(m,n) \sim (m',n')$ and $(p,q) \sim (p',q')$ then $(mp+nq, mq+np) \sim (m'p' + n'q', m'q' + n'p')$.*

PROOF:
$\langle 1 \rangle 1$. ASSUME: $m + n' = m' + n$ and $p + q' = p' + q$
$\langle 1 \rangle 2$. $mp + n'p = m'p + np$
$\langle 1 \rangle 3$. $m'q + nq = mq + n'q$
$\langle 1 \rangle 4$. $mp + mq' = mp' + mq$
$\langle 1 \rangle 5$. $n'p' + n'q = n'p + n'q'$
$\langle 1 \rangle 6$. $mp + n'p + m'q + nq + mp + mq' + n'p' + n'q = m'p + np + mq + n'q + mp' + mq + n'p + n'q'$
$\langle 1 \rangle 7$. $mp + nq + m'q' + n'p' = mq + np + m'p' + n'q'$
$\square$

Definition 181 (Multiplication)**.** *Multiplication* $\cdot$ is the binary operation on $\mathbb{Z}$ such that

$$[(m,n)][(p,q)] = [(mp + nq, mq + np)]$$

Theorem 182. *Multiplication is commutative.*

PROOF: Easy. $\square$

Theorem 183. *Multiplication is associative.*

PROOF: Easy. $\square$

Theorem 184. *Multiplication is distributive over addition.*

PROOF: Easy. $\square$

Definition 185. The integer one is $1 = [(1,0)]$.

Theorem 186. *For any integer a we have $a1 = a$.*

PROOF: Easy. $\square$

Theorem 187. $0 \neq 1$

PROOF: Easy. □

Lemma 188. *If $(m,n) \sim (m',n')$ and $(p,q) \sim (p',q')$ then $m+q \in p+n$ iff $m'+q' \in p'+n'$.*

PROOF:

$$\begin{aligned} m+q \in p+n &\Leftrightarrow m+q+n'+q' \in p+n+n'+q' \\ &\Leftrightarrow m'+n+q+q' \in p'+n+n'+q \\ &\Leftrightarrow m'+q' \in p'+n' \end{aligned}$$ □

Definition 189 (Ordering)**.** The ordering $<$ on $\mathbb{Z}$ is defined by: $[(m,n)] < [(p,q)]$ iff $m+q \in n+p$.

Theorem 190. *The relation $<$ is a linear ordering on $\mathbb{Z}$.*

PROOF:
⟨1⟩1. $<$ is transitive.
  ⟨2⟩1. ASSUME: $[(m,n)] < [(p,q)]$ and $[(p,q)] < [(r,s)]$
  ⟨2⟩2. $m+q \in n+p$ and $p+s \in q+r$
  ⟨2⟩3. $m+q+s \in n+p+s$
  ⟨2⟩4. $n+p+s \in n+q+r$
  ⟨2⟩5. $m+q+s \in n+q+r$
  ⟨2⟩6. $m+s \in n+r$
⟨1⟩2. $<$ satisfies trichotomy.
  PROOF: From trichotomy on ω.
□

Theorem 191. *For any integers a, b and c, we have $a < b$ iff $a+c < b+c$.*

PROOF: An easy consequence of the corresponding property in ω.

Corollary 191.1. *If $a+c = b+c$ then $a = b$.*

Theorem 192. *If $0 < c$, then the function that maps an integer a to ac is strictly monotone.*

PROOF:
⟨1⟩1. LET: a, b and c be integers.
⟨1⟩2. ASSUME: $0 < c$ and $a < b$
⟨1⟩3. LET: $a = [(m,n)]$
⟨1⟩4. LET: $b = [(p,q)]$
⟨1⟩5. LET: $c = [(r,s)]$
⟨1⟩6. $s \in r$
⟨1⟩7. $m+q \in p+n$
⟨1⟩8. $(m+q)r + (p+n)s \in (m+q)s + (p+n)r$
  PROOF: Lemma 170.
⟨1⟩9. $ac < bc$

□

Lemma 193. *For integers a and b, $a(-b) = -(ab)$*

PROOF: This follows from the fact that $ab + a(-b) = a(b + (-b)) = a0 = 0$. □

Theorem 194. *For integers a, b and c, if $a < b$ and $c < 0$ then $ac > bc$.*

PROOF: We have $0 < -c$ so $a(-c) < b(-c)$ hence $-(ac) < -(bc)$ so $bc < ac$. □

Theorem 195. *For any integers a and b, if $ab = 0$ then $a = 0$ or $b = 0$.*

PROOF: We prove if $a \neq 0$ and $b \neq 0$ then $ab \neq 0$.
If $a > 0$ and $b > 0$ then $ab > 0$. Similarly for the other four cases. □

Theorem 196. *If $ac = bc$ and $c \neq 0$ then $a = b$.*

PROOF: We have $(a - b)c = 0$ so $a - b = 0$ hence $a = b$. □

Definition 197 (Positive)**.** An integer a is *positive* iff $0 < a$.

Theorem 198. *Define $E : \omega \to \mathbb{Z}$ by $E(n) = [(n, 0)]$. Then E maps ω one-to-one into $\mathbb{Z}$, and:*

1. $E(m + n) = E(m) + E(n)$
2. $E(mn) = E(m)E(n)$
3. $m \in n$ *if and only if* $E(m) < E(n)$.

PROOF: Routine calculations. □

23 Equinumerosity

Definition 199 (Equinumerous)**.** Two sets A and B are *equinumerous*, $A \approx B$, iff there exists a bijection between them.

Theorem 200. *Equinumerosity is an equivalence relation on the class of sets.*

PROOF: Easy. □

Theorem 201 (Cantor 1873)**.** *No set is equinumerous with its power set.*

PROOF:
$\langle 1 \rangle 1$. LET: $g : A \to \mathcal{P}A$
PROVE: g is not surjective.
$\langle 1 \rangle 2$. LET: $B = \{x \in A : x \notin g(x)\}$
$\langle 1 \rangle 3$. $\forall x \in A . g(x) \neq B$
PROOF: Because $x \in B$ iff $x \notin g(x)$.
□

24 Ordering Cardinal Numbers

Definition 202 (Dominated)**.** A set A is *dominated* by a set B, $A \preccurlyeq B$, iff there exists an injection $f : A \to B$.

Lemma 203. *Domination is a preorder on the class of sets.*

Proof: Easy. $\square$

Lemma 204. *If $A \subseteq B$ then $A \preccurlyeq B$.*

Proof: The inclusion from A to B is an injection. $\square$

Lemma 205. *If $A \preccurlyeq B$, $A \approx A'$ and $B \approx B'$ then $A' \preccurlyeq B'$.*

Proof: Easy. $\square$

Definition 206. Given cardinal numbers κ and λ, we write $\kappa \leq \lambda$ iff $K \preccurlyeq L$, where K is any set of cardinality κ and L is any set of cardinality λ.

We write $\kappa < \lambda$ iff $\kappa \leq \lambda$ and $\kappa \neq \lambda$.

Theorem 207 (Schröder-Bernstein)**.** *If $A \preccurlyeq B$ and $B \preccurlyeq A$ then $A \approx B$.*

Proof:
$\langle 1 \rangle 1.$ Let: $f : A \to B$ and $g : B \to A$ be one-to-one.
$\langle 1 \rangle 2.$ Define the sequence of sets $C_n \subseteq A$ by:

$$C_0 = A - \operatorname{ran} g$$
$$C_{n+1} = g(f(C_n))$$

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

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

$\langle 1 \rangle 4.$ h is injective.
$\langle 2 \rangle 1.$ Let: $x, y \in A$
$\langle 2 \rangle 2.$ Assume: $h(x) = h(y)$
$\langle 2 \rangle 3.$ Case: $x \in C_m$, $y \in C_n$
Proof: We have $f(x) = f(y)$ so $x = y$
$\langle 2 \rangle 4.$ Case: $x \in C_m$, $y \notin \bigcup_n C_n$
Proof: This case is impossible because we would have $y = g(f(x))$ and so $y \in C_{m+1}$.
$\langle 2 \rangle 5.$ Case: $x, y \notin \bigcup_n C_n$
Proof: We have $g^{-1}(x) = g^{-1}(y)$ so $x = y$.
$\langle 1 \rangle 5.$ h is surjective.
$\langle 2 \rangle 1.$ Let: $y \in B$
$\langle 2 \rangle 2.$ Assume: $y \notin f(C_n)$ for all n
$\langle 2 \rangle 3.$ $g(y) \notin C_n$ for all n
$\langle 2 \rangle 4.$ $y = h(g(y))$
$\square$

Corollary 207.1. *The relation $\leq$ is a partial order on the class of cardinal numbers.*

Theorem 208. *Let κ, λ and μ be cardinal numbers.*

1. $\kappa \leq \lambda \Rightarrow \kappa + \mu \leq \lambda + \mu$
2. $\kappa \leq \lambda \Rightarrow \kappa\mu \leq \lambda\mu$
3. $\kappa \leq \lambda \Rightarrow \kappa^\mu \leq \lambda^\mu$
4. $\kappa \leq \lambda \Rightarrow \mu^\kappa \leq \mu^\lambda$ *if κ and μ are not both zero.*

Proof: Parts 1–3 are easy. For part 4:
Let $|K| = \kappa$, $|L| = \lambda$ and $|M| = \mu$ with $K \subseteq L$.
If $M = \emptyset$ then $\kappa \neq 0$ so $\mu^\kappa = 0 \leq \mu^\lambda$.
Otherwise, pick $a \in M$. Define $\Phi : M^K \to M^L$ by:

$$\Phi(f)(x) = \begin{cases} f(x) & \text{if } x \in K \\ a & \text{if } x \notin K \end{cases}$$

Then Φ is an injection. $\square$

Theorem 209 (Zorn's Lemma)**.** *The Axiom of Choice is equivalent to this statement:*

Let $\mathcal{A}$ be a set such that, for every chain $\mathcal{B} \subseteq \mathcal{A}$, we have $\bigcup \mathcal{B} \in \mathcal{A}$. Then $\mathcal{A}$ has a maximal element.

Proof:
$\langle 1 \rangle 1$. If the Axiom of Choice then Zorn's Lemma.
  Proof: TODO
$\langle 1 \rangle 2$. If Zorn's Lemma then the Axiom of Choice.
  $\langle 2 \rangle 1$. Assume: Zorn's Lemma
  $\langle 2 \rangle 2$. Let: R be a relation.
  $\langle 2 \rangle 3$. Let: $\mathcal{A}$ be the set of all functions that are subsets of R.
  $\langle 2 \rangle 4$. For any chain $\mathcal{B} \subseteq \mathcal{A}$ we have $\bigcup \mathcal{B} \in \mathcal{A}$
  $\langle 2 \rangle 5$. Pick $F \in \mathcal{A}$ maximal.
  $\langle 2 \rangle 6$. $\operatorname{dom} F = \operatorname{dom} R$
$\square$

Theorem 210 (Cardinal Comparability)**.** *The Axiom of Choice is equivalent to the statement: for any sets C and D, either $C \preccurlyeq D$ or $D \preccurlyeq C$.*

Proof:
$\langle 1 \rangle 1$. If Zorn's Lemma then Cardinal Comparability.
  $\langle 2 \rangle 1$. Assume: Zorn's Lemma
  $\langle 2 \rangle 2$. Let: C and D be sets.
  $\langle 2 \rangle 3$. Let: $\mathcal{A}$ be the set of all injective functions f with $\operatorname{dom} f \subseteq C$ and $\operatorname{ran} f \subseteq D$
  $\langle 2 \rangle 4$. For every chain $\mathcal{B} \subseteq \mathcal{A}$ we have $\bigcup \mathcal{B} \in \mathcal{A}$
  $\langle 2 \rangle 5$. Let: $f \in \mathcal{A}$ be maximal
  $\langle 2 \rangle 6$. $\operatorname{dom} f = C$ or $\operatorname{ran} f = D$
  $\langle 2 \rangle 7$. f is an injective function $C \to D$ or f^{-1} is an injective function $D \to C$

$\langle 1 \rangle 2$. If Cardinal Comparability then the Axiom of Choice.
PROOF: TODO
$\square$

Theorem 211 (Choice)**.** *For any infinite set A, we have $\omega \preccurlyeq A$.*

PROOF:
$\langle 1 \rangle 1$. LET: A be an infinite set.
$\langle 1 \rangle 2$. PICK a choice function F for A
$\langle 1 \rangle 3$. Define $f : \omega \to A$ by recursion by: $f(n) = F(A - \{f(0), f(1), \ldots, f(n-1)\})$
PROOF: $A - \{f(0), f(1), \ldots, f(n-1)\}$ is nonempty because A is infinite.
$\langle 1 \rangle 4$. f is injective.
$\square$

Corollary 211.1 (Choice)**.** *For any infinite cardinal κ we have $\aleph_0 \leq \kappa$.*

Corollary 211.2 (Choice)**.** *A set is infinite iff it is equinumerous to a proper subset of itself.*

Proposition 212 (Choice)**.** *If there exists a surjection $A \to B$ then $B \preccurlyeq A$.*

PROOF: Any surjection $A \to B$ has a right inverse which is an injection $B \to A$.

25 Countable Sets

Definition 213 (Countable)**.** A set is *countable* iff it is dominated by ω.

Proposition 214. *Any subset of a countable set is countable.*

PROOF: Easy. $\square$

The union of two countable sets is countable.

PROOF: Because $\aleph_0 + \aleph_0 = \aleph_0$ $\square$

Proposition 215. *The product of two countable sets is countable.*

PROOF: Because $\aleph_0 \aleph_0 = \aleph_0$. $\square$

Proposition 216 (Choice)**.** *For any infinite set A, the set $\mathcal{P}A$ is uncountable.*

PROOF: If $|A| \geq \aleph_0$ then $|\mathcal{P}A| \geq 2^{\aleph_0}$. $\square$

Theorem 217 (Choice)**.** *A countable union of countable sets is countable.*

PROOF:
$\langle 1 \rangle 1$. LET: $\mathcal{A}$ be a countable set of countable sets.
$\langle 1 \rangle 2$. ASSUME: w.l.o.g. $\mathcal{A} \neq \emptyset$ and $\emptyset \notin \mathcal{A}$
$\langle 1 \rangle 3$. PICK a surjection $G : \omega \to A$
$\langle 1 \rangle 4$. PICK a function F with domain ω such that, for all m, $F(m)$ is a surjection $\omega \to G(m)$
PROOF: By the Axiom of Choice.
$\langle 1 \rangle 5$. Define $f : \omega \times \omega \to \bigcup A$ by $f(m,n) = F(m)(n)$
$\langle 1 \rangle 6$. f is surjective.
$\langle 1 \rangle 7$. $A \preccurlyeq \omega \times \omega$
$\square$

26 Arithmetic of Infinite Cardinals

Lemma 218 (Choice)**.** *For any infinite cardinal κ we have $\kappa \cdot \kappa = \kappa$.*

Proof:
$\langle 1\rangle 1$. Let: κ be an infinite cardinal.
$\langle 1\rangle 2$. Let: B be a set of cardinality κ.
$\langle 1\rangle 3$. Let: $\mathcal{H} = \{f : f = \emptyset$ or for some infinite $A \subseteq B, f$ is a bijection between $A \times A$ and $A\}$
$\langle 1\rangle 4$. For any chain $\mathcal{C} \subseteq \mathcal{H}$, we have $\bigcup \mathcal{C} \in \mathcal{H}$
$\langle 2\rangle 1$. Let: $\mathcal{C} \subseteq \mathcal{H}$ be a chain.
$\langle 2\rangle 2$. Assume: w.l.o.g. $\mathcal{C}$ has a nonempty element.
Proof: Otherwise $\bigcup \mathcal{C} = \emptyset \in \mathcal{H}$.
$\langle 2\rangle 3$. $\bigcup \mathcal{C}$ is an injective function.
$\langle 2\rangle 4$. Let: $A = \operatorname{ran} \bigcup \mathcal{C}$
$\langle 2\rangle 5$. A is infinite.
$\langle 2\rangle 6$. $\bigcup \mathcal{C}$ is a bijection between $A \times A$ and A.
$\langle 3\rangle 1$. Let: $a_1, a_2 \in A$
$\langle 3\rangle 2$. Pick $f_1, f_2 \in \mathcal{C}$ such that $a_1 \in \operatorname{ran} f_1$ and $a_2 \in \operatorname{ran} f_2$
$\langle 3\rangle 3$. Assume: w.l.o.g. $f_1 \subseteq f_2$
$\langle 3\rangle 4$. $\langle a_1, a_2\rangle \in \operatorname{dom} f_2$
$\langle 3\rangle 5$. $\langle a_1, a_2\rangle \in \operatorname{dom} \bigcup \mathcal{C}$
$\langle 1\rangle 5$. Pick a maximal $f_0 \in \mathcal{H}$
Proof: Zorn's Lemma.
$\langle 1\rangle 6$. $f_0 \neq \emptyset$
Proof: B has a countable subset A, say, and $A \times A \approx A$.
$\langle 1\rangle 7$. Pick $A_0 \subseteq B$ infinite such that f_0 is a bijection between $A_0 \times A_0$ and A_0.
$\langle 1\rangle 8$. Let: $\lambda = |A_0|$
$\langle 1\rangle 9$. λ is infinite
$\langle 1\rangle 10$. $\lambda = \lambda \cdot \lambda$
$\langle 1\rangle 11$. $\lambda = \kappa$
$\langle 2\rangle 1$. $|B - A_0| < \lambda$
$\langle 3\rangle 1$. Assume: for a contradiction $\lambda \leq |B - A_0|$
$\langle 3\rangle 2$. Pick $D \subseteq B - A_0$ with $|D| = \lambda$
$\langle 3\rangle 3$. $(A_0 \cup D) \times (A_0 \cup D) = (A_0 \times A_0) \cup (A_0 \times D) \cup (D \times A_0) \cup (D \times D)$
$\langle 3\rangle 4$. $f_0 : A_0 \times A_0 \approx A_0$
$\langle 3\rangle 5$. $|(A_0 \times D) \cup (D \times A_0) \cup (D \times D)| = \lambda$
Proof:

$$\begin{aligned}
|(A_0 \times D) \cup (D \times A_0) \cup (D \times D)| &= \lambda \cdot \lambda + \lambda \cdot \lambda + \lambda \cdot \lambda \\
&= \lambda + \lambda + \lambda && (\langle 1\rangle 10) \\
&= 3 \cdot \lambda \\
&\leq \lambda \cdot \lambda \\
&= \lambda && (\langle 1\rangle 10)
\end{aligned}$$

$\langle 3\rangle 6$. Pick a bijection $g : (A_0 \times D) \cup (D \times A_0) \cup (D \times D) \approx D$
$\langle 3\rangle 7$. $f_0 \cup g : (A_0 \cup D) \times (A_0 \cup D) \approx A_0 \cup D$
$\langle 3\rangle 8$. Q.E.D.

Proof: This contradicts the maximality of f_0.

$\langle 2\rangle 2.$ $\lambda = \kappa$

Proof:

$$\begin{aligned}\kappa &= |B| \\ &= |A_0| + |B - A_0| \\ &\leq \lambda + \lambda \\ &= 2 \cdot \lambda \\ &\leq \lambda \cdot \lambda \\ &= \lambda \\ &\leq \kappa\end{aligned}$$

□

Corollary 218.1 (Absorption Law of Cardinal Arithmetic (Choice)). *Let κ and λ be cardinal numbers, the larger of which is infinite and the smaller of which is nonzero. Then*

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

Proof:

$\langle 1\rangle 1.$ Assume: w.l.o.g. $\kappa \leq \lambda$

$\langle 1\rangle 2.$ $\kappa + \lambda = \lambda$

Proof:

$$\begin{aligned}\lambda &\leq \kappa + \lambda \\ &\leq \lambda + \lambda \\ &= 2 \cdot \lambda \\ &\leq \lambda \cdot \lambda \\ &= \lambda\end{aligned}$$

$\langle 1\rangle 3.$ $\kappa \cdot \lambda = \lambda$

Proof:

$$\begin{aligned}\lambda &= 1 \cdot \lambda \\ &\leq \kappa \cdot \lambda \\ &\leq \lambda \cdot \lambda \\ &= \lambda\end{aligned}$$

□