

# Mathematics

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# Chapter 1

## Primitive Terms and Axioms

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

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

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

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

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

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

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

**Axiom 1.6** (Axiom of Regularity). *For any nonempty set  $A$ , there exists  $m \in A$  such that  $m$  and  $A$  are disjoint.*

**Axiom 1.7** (Axiom of Union). *For every set  $A$ , there exists a set that contains all the elements that belong to at least one element of  $A$ .*

**Axiom 1.8** (Axiom of Pairing). *For any two sets, there exists a set that they both belong to.*

**Axiom Schema 1.9** (Axiom Schema of Replacement). *For any property  $P(x, y)$ , the following is an axiom:*

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

**Axiom 1.10** (Axiom of Infinity). *There exists a set  $I$  that has an empty element and such that, for all  $x \in I$ , there exists  $y \in I$  such that the elements of  $y$  are exactly  $x$  and the elements of  $x$ .*

**Axiom 1.11** (Power Set Axiom). *For any set  $A$ , there exists a set  $B$  such that every subset of  $A$  belongs to  $B$ .*

**Axiom 1.12** (Axiom of Choice). *Let  $A$  be a set of nonempty, pairwise disjoint sets. Then there exists a set  $C$  such that, for all  $x \in A$ , there is exactly one  $y$  such that  $y \in C$  and  $y \in x$ .*

## Chapter 2

# Basic Properties and Operations on Sets

**Axiom 2.1** (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.*

**Definition 2.2.** 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.  $\square$

**Definition 2.3** ((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.  $\square$

**Axiom 2.4** (Power Set Axiom). *For any set  $A$ , there exists a set that contains all the subsets of  $A$ .*

**Definition 2.5** (Empty). A set is *empty* iff it has no elements; otherwise it is *non-empty*.

**Axiom 2.6** (Axiom of Infinity). *There exists a set  $I$  such that:*

- *$I$  has an element that is empty*
- *for all  $x \in I$ , there exists  $y \in I$  such that the elements of  $y$  are exactly  $x$  and the elements of  $x$ .*

**Definition 2.7** (Ordered Pair). For any sets  $a$  and  $b$ , the *ordered pair*  $(a, b)$  is defined by

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

**Definition 2.8** (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.  $\square$

**Definition 2.9** (Cartesian Product). For any sets  $A$  and  $B$ , the *Cartesian product*  $A \times B$  is

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

**Definition 2.10** (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 2.11** (Function). Let  $X$  and  $Y$  be sets. A *function*, *map*, *mapping*, *transformation* or *operator  $f$  from  $X$  to  $Y$* ,  $f : X \rightarrow Y$ , 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 2.12** (Family). Let  $I$  and  $X$  be sets. A *family* of elements of  $X$  indexed by  $I$  is a function  $a : I \rightarrow X$ . We write  $a_i$  for  $a(i)$ , and  $\{a_i\}_{i \in I}$  for  $a$ .

**Definition 2.13** (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  $\times_{i \in I} A$ .

**Axiom 2.14** (Axiom of Choice). *The Cartesian product of a non-empty family of non-empty sets is non-empty.*

**Axiom 2.15** (Axiom of substitution). *If  $S(a, b)$  is a sentence such that for each  $a$  in  $A$  the set  $\{b : S(a, b)\}$  can be formed, then there exists a function  $F$  with domain  $A$  such that  $F(a) = \{b : S(a, b)\}$  for each  $a$  in  $A$ .*

## 2.1 The Subset Relation

**Theorem 2.16.** *For any set  $A$ , we have  $A \subseteq A$ .*

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

**Theorem 2.17.** *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 2.18.** *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 2.19** (Proper Subset). Let  $A$  and  $B$  be sets. We say that  $A$  is a *proper* subset of  $B$ , or  $B$  *properly* includes  $A$ , and write  $A \subsetneq B$  or  $B \supsetneq A$ , iff  $A \subseteq B$  and  $A \neq B$ .

## 2.2 Comprehension Notation

**Theorem 2.20.** *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  $B \notin B$ .

$\langle 1 \rangle 4$ .  $B \notin A$

$\square$

## 2.3 The Empty Set

**Theorem 2.21.** *There exists a set with no elements.*

PROOF: Immediate from the Axiom of Infinity.  $\square$

**Definition 2.22** (Empty Set). The *empty set*  $\emptyset$  is the set with no elements.

**Theorem 2.23.** *For any set  $A$  we have  $\emptyset \subset A$ .*

PROOF: Vacuous.  $\square$

## 2.4 Unordered Pairs

**Definition 2.24** (Singleton). For any set  $a$ , the *singleton*  $\{a\}$  is defined to be  $\{a, a\}$ .

## 2.5 Unions

**Definition 2.25** (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.  $\square$



**Proposition 2.26.**

$$\bigcup \emptyset = \emptyset$$

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

**Proposition 2.27.** *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  $A$ .  $\square$

**Definition 2.28.** We write  $A \cup B$  for  $\bigcup\{A, B\}$ .

**Proposition 2.29.** *For any set  $A$ , we have  $A \cup \emptyset = A$ .*

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

**Proposition 2.30** (Idempotence). *For any set  $A$ , we have  $A \cup A = A$ .*

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

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

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

**Proposition 2.32.** *For any sets  $a$  and  $b$ , we have  $\{a\} \cup \{b\} = \{a, b\}$ .*

PROOF: Immediate from definitions.  $\square$

## 2.6 Intersections

**Definition 2.33** (Intersection). For any sets  $A$  and  $B$ , the *intersection*  $A \cap B$  is defined to be  $\{x \in A : x \in B\}$ .

**Proposition 2.34.** *For any set  $A$ , we have  $A \cap \emptyset = \emptyset$ .*

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

**Proposition 2.35.** *For any set  $A$ , we have*

$$A \cap A = A .$$

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

**Proposition 2.36.** *For any sets  $A$  and  $B$ , we have  $A \subseteq B$  if and only if  $A \cap B = A$ .*

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

**Proposition 2.37.** *For any sets  $A$ ,  $B$  and  $C$ , we have  $C \subseteq A$  if and only if  $(A \cap B) \cup C = A \cap (B \cup C)$ .*

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

**Definition 2.38** (Disjoint). Two sets  $A$  and  $B$  are *disjoint* if and only if  $A \cap B = \emptyset$ .

**Definition 2.39** (Pairwise Disjoint). Let  $A$  be a set. We say the elements of  $A$  are *pairwise disjoint* if and only if, for all  $x, y \in A$ , if  $x \cap y \neq \emptyset$  then  $x = y$ .

**Definition 2.40** (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.

$\square$

## 2.7 Unordered Triples

**Definition 2.41** ((Unordered) Triple). Given sets  $a_1, \dots, a_n$ , define the (*unordered*) *n-tuple*  $\{a_1, \dots, a_n\}$  to be

$$\{a_1, \dots, a_n\} := \{a_1\} \cup \dots \cup \{a_n\} .$$

## 2.8 Relative Complements

**Definition 2.42** (Relative Complement). For any sets  $A$  and  $B$ , the *difference* or *relative complement*  $A - B$  is defined to be

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

**Proposition 2.43.** For any sets  $A$  and  $E$ , we have  $A \subseteq E$  if and only if

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

PROOF:

$\langle 1 \rangle 1$ . LET:  $A$  and  $E$  be sets.

$\langle 1 \rangle 2$ . If  $A \subseteq E$  then  $E - (E - A) = A$

$\langle 2 \rangle 1$ . ASSUME:  $A \subseteq E$

$\langle 2 \rangle 2$ .  $E - (E - A) \subseteq A$

PROOF: If  $x \in E$  and  $x \notin E - A$  then  $x \in A$ .

$\langle 2 \rangle 3$ .  $A \subseteq E - (E - A)$

PROOF: If  $x \in A$  then  $x \in E$  and  $x \notin E - A$ .

$\langle 1 \rangle 3$ . If  $E - (E - A) = A$  then  $A \subseteq E$ .

PROOF: Since  $E - (E - A) \subseteq E$ .

□

**Proposition 2.44.** *For any set  $E$  we have*

$$E - \emptyset = E$$

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

**Proposition 2.45.** *For any set  $E$  we have*

$$E - E = \emptyset .$$

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

**Proposition 2.46.** *For any sets  $A$  and  $E$ , we have*

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

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

**Proposition 2.47.** *Let  $A$  and  $E$  be sets. Then  $A \subseteq E$  if and only if*

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

PROOF:

$\langle 1 \rangle 1$ . LET:  $A$  and  $E$  be sets.

$\langle 1 \rangle 2$ . If  $A \subseteq E$  then  $A \cup (E - A) = E$ .

$\langle 2 \rangle 1$ . ASSUME:  $A \subseteq E$

$\langle 2 \rangle 2$ .  $A \cup (E - A) \subseteq E$

PROOF: If  $x \in A$  or  $x \in E - A$  then  $x \in E$ .

$\langle 2 \rangle 3$ .  $E \subseteq A \cup (E - A)$

PROOF: If  $x \in E$  then either  $x \in A$  or  $x \notin A$ . In the latter case,  $x \in E - A$ .

$\langle 1 \rangle 3$ . If  $A \cup (E - A) = E$  then  $A \subseteq E$

PROOF: Since  $A \subseteq A \cup (E - A)$ .

□

**Proposition 2.48.** *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:

$\langle 1 \rangle 1$ . LET:  $A$ ,  $B$  and  $E$  be sets.

$\langle 1 \rangle 2$ . If  $A \subseteq B$  then  $E - B \subseteq E - A$ .

PROOF: If  $A \subseteq B$ ,  $x \in E$  and  $x \notin B$ , then we have  $x \in E$  and  $x \notin A$ .

⟨1⟩3. If  $A \subseteq E$  and  $E - B \subseteq E - A$  then  $A \subseteq B$ .

⟨2⟩1. ASSUME:  $A \subseteq E$

⟨2⟩2. ASSUME:  $E - B \subseteq E - A$

⟨2⟩3. LET:  $x \in A$

⟨2⟩4.  $x \in E$

⟨2⟩5.  $x \notin E - A$

⟨2⟩6.  $x \notin E - B$

⟨2⟩7.  $x \in B$

□

**Example 2.49.** 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  $A \not\subseteq B$ .

**Proposition 2.50** (De Morgan's Law). *For any sets  $A$ ,  $B$  and  $E$ , we have  $E - (A \cup B) = (E - A) \cap (E - B)$ .*

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

**Proposition 2.51** (De Morgan's Law). *For any sets  $A$ ,  $B$  and  $E$ , we have  $E - (A \cap B) = (E - A) \cup (E - B)$ .*

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

**Proposition 2.52.** *For any sets  $A$ ,  $B$  and  $E$ , if  $A \subseteq E$  then*

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

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

**Proposition 2.53.** *For any sets  $A$  and  $B$ , we have  $A \subseteq B$  if and only if  $A - B = \emptyset$ .*

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

**Proposition 2.54.** *For any sets  $A$  and  $B$ , we have*

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

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

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

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

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

**Proposition 2.56.** *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:

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

**Proposition 2.57.** *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  $x \in A \vee x \in B$ .  $\square$

**Proposition 2.58** (De Morgan's Law). *Let  $E$  be a set and  $\mathcal{C}$  a nonempty set. Then*

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

PROOF: Easy.  $\square$

**Proposition 2.59** (De Morgan's Law). *Let  $E$  be a set and  $\mathcal{C}$  a nonempty set. Then*

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

PROOF: Easy.  $\square$

## 2.9 Symmetric Difference

**Definition 2.60** (Symmetric Difference). For any sets  $A$  and  $B$ , the *symmetric difference*  $A + B$  is defined to be

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

**Proposition 2.61.** *For any sets  $A$  and  $B$ , we have*

$$A + B = B + A$$

PROOF: From the commutativity of union.  $\square$

**Proposition 2.62.** *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  $C$ .  $\square$

**Proposition 2.63.** *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 2.64.** *For any set  $A$  we have*

$$A + A = \emptyset .$$

PROOF:

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

□

## 2.10 Power Sets

**Proposition 2.65.**

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

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

**Proposition 2.66.** *For any set  $a$ , we have*

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

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

**Proposition 2.67.** *For any sets  $a$  and  $b$ , we have*

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

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

**Proposition 2.68.** *For any nonempty set  $\mathcal{C}$  we have*

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

PROOF:

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

□

**Proposition 2.69.** *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 2.70.** *For any set  $E$ , we have*

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

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

**Proposition 2.71.** *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 3

# Relations and Functions

### 3.1 Ordered Pairs

**Proposition 3.1.** *For any sets  $a, b, x$  and  $y$ , if  $(a, b) = (x, y)$  then  $a = x$  and  $b = y$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $a, b, x$  and  $y$  be sets.

$\langle 1 \rangle 2$ . ASSUME:  $(a, b) = (x, y)$

$\langle 1 \rangle 3$ .  $a = x$

PROOF:  $\{a\} = \bigcap(a, b) = \bigcap(x, y) = \{x\}$ .

$\langle 1 \rangle 4$ .  $\{a, b\} = \{x, y\}$

$\langle 1 \rangle 5$ . CASE:  $a = b$

$\langle 2 \rangle 1$ .  $x = y$

PROOF: Since  $\{x, y\} = \{a, b\}$  is a singleton.

$\langle 2 \rangle 2$ .  $b = y$

PROOF:  $b = a = x = y$

$\langle 1 \rangle 6$ . CASE:  $a \neq b$

$\langle 2 \rangle 1$ .  $x \neq y$

PROOF: Since  $\{x, y\} = \{a, b\}$  is not a singleton.

$\langle 2 \rangle 2$ .  $b = y$

PROOF:  $\{b\} = \{a, b\} - \{a\} = \{x, y\} - \{x\} = \{y\}$ .

□

**Proposition 3.2.** *For any sets  $A, B$  and  $X$ , we have*

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

PROOF: Easy. □

**Proposition 3.3.** *For any sets  $A$  and  $B$ , we have  $A \times B = \emptyset$  if and only if  $A = \emptyset$  or  $B = \emptyset$ .*

PROOF: Easy. □



**Proposition 3.4.** For any sets  $A, B, X$  and  $Y$ , if  $A \subseteq X$  and  $B \subseteq Y$  then  $A \times B \subseteq X \times Y$ . The converse holds assuming  $A \neq \emptyset$  and  $B \neq \emptyset$ .

PROOF: Easy.  $\square$

## 3.2 Relations

**Definition 3.5** (Domain). The *domain* of a relation  $R$  is the set

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

**Definition 3.6** (Range). The *range* of a relation  $R$  is the set

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

**Definition 3.7** (Reflexive). Let  $R$  be a relation on  $X$ . Then  $R$  is *reflexive* iff, for all  $x \in X$ , we have  $xRx$ .

**Definition 3.8** (Symmetric). Let  $R$  be a relation on  $X$ . Then  $R$  is *symmetric* iff, whenever  $xRy$ , then  $yRx$ .

**Definition 3.9** (Antisymmetric). A relation  $R$  is *antisymmetric* iff, whenever  $xRy$  and  $yRx$ , then  $x = y$ .

**Definition 3.10** (Transitive). Let  $R$  be a relation on  $X$ . Then  $R$  is *transitive* iff, whenever  $xRy$  and  $yRz$ , then  $xRz$ .

**Definition 3.11** (Identity Relation). For any set  $X$ , the *identity relation*  $I_X$  on  $X$  is

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

## 3.3 Composition

**Definition 3.12** (Composition). Let  $R$  be a relation between  $X$  and  $Y$ , and  $S$  a relation between  $Y$  and  $Z$ . The *composite* or *relative product*  $S \circ R = SR$  is the relation between  $X$  and  $Z$  defined by

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

**Proposition 3.13.** Let  $R$  be a relation between  $X$  and  $Y$ ,  $S$  a relation between  $Y$  and  $Z$ , and  $T$  a relation between  $Z$  and  $W$ . Then

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

PROOF: Easy.  $\square$

**Example 3.14.** Composition of relations is not commutative in general. Let  $X = \{a, b\}$  where  $a \neq b$ . Let  $R = \{(a, a), (b, a)\}$  and  $S = \{(a, b), (b, b)\}$ . Then  $SR = S$  but  $RS = R \neq S$ .

**Proposition 3.15.** A relation  $R$  is transitive if and only if  $RR \subseteq R$ .

PROOF: Easy.  $\square$

### 3.4 Inverses

**Definition 3.16** (Inverse). Let  $R$  be a relation between  $X$  and  $Y$ . The *inverse* or *converse*  $R^{-1}$  is the relation between  $Y$  and  $X$  defined by

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

**Proposition 3.17.** For any relation  $R$ , we have

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

PROOF: Easy.  $\square$

**Proposition 3.18.** For any relation  $R$ , we have

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

PROOF: Easy.  $\square$

**Proposition 3.19.** 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.  $\square$

**Proposition 3.20.** A relation  $R$  is symmetric if and only if  $R \subseteq R^{-1}$ .

PROOF: Easy.  $\square$

**Proposition 3.21.** Let  $R$  be a relation between  $X$  and  $Y$ . Then

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

PROOF: Easy.  $\square$

**Proposition 3.22.** A relation  $R$  on a set  $X$  is reflexive if and only if  $I_X \subseteq R$ .

PROOF: Easy.  $\square$

**Proposition 3.23.** Let  $R$  be a relation on a set  $X$ . Then  $R$  is antisymmetric iff  $R \cap R^{-1} \subseteq I_X$ .

PROOF: Easy.  $\square$

### 3.5 Equivalence Relations

**Definition 3.24** (Equivalence Relation). Let  $R$  be a relation on  $X$ . Then  $R$  is an *equivalence relation* iff it is reflexive, symmetric and transitive.

**Definition 3.25** (Partition). Let  $X$  be a set. A *partition* of  $X$  is a pairwise disjoint set of nonempty subsets of  $X$  whose union is  $X$ .

**Definition 3.26** (Equivalence Class). Let  $R$  be an equivalence relation on  $X$ . Let  $x \in X$ . The *equivalence class* of  $x$  with respect to  $R$  is

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

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

**Definition 3.27** (Induced). Let  $P$  be a partition of  $X$ . The relation *induced* by  $P$  is  $X/P$  where  $x(X/P)y$  iff there exists  $X \in P$  such that  $x \in X$  and  $y \in X$ .

**Theorem 3.28.** Let  $R$  be an equivalence relation on  $X$ . Then  $X/R$  is a partition of  $X$  that induces the relation  $R$ .

PROOF: Easy.  $\square$

**Theorem 3.29.** Let  $P$  be a partition of  $X$ . Then  $X/P$  is an equivalence relation on  $X$ , and  $P = X/(X/P)$ .

PROOF: Easy.  $\square$

## 3.6 Functions

**Definition 3.30** (Injective). A function  $f : X \rightarrow Y$  is *one-to-one* or *injective* or an *injection* iff, for all  $x, y \in X$ , if  $f(x) = f(y)$  then  $x = y$ . In this case, we write  $f : X \rightarrowtail Y$ .

**Definition 3.31** (Surjective). Let  $f : X \rightarrow Y$ . We say  $f$  is *surjective*, or a *surjection*, or  $f$  maps  $X$  *onto*  $Y$  iff  $\text{ran } f = Y$ . In this case, we write  $f : X \twoheadrightarrow Y$ .

**Definition 3.32** (Bijective). Let  $f : X \rightarrow Y$ . Then  $f$  is *bijective*, or a *bijection*, iff it is injective and surjective.

**Definition 3.33** (Image). Let  $f : X \rightarrow Y$  and  $A \subseteq X$ . The *image* of  $A$  under  $f$  is

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

**Proposition 3.34.** Let  $f : X \rightarrow Y$  and  $A \subseteq B \subseteq X$ . Then  $f(A) \subseteq f(B)$ .

PROOF:

$\langle 1 \rangle 1$ . LET:  $X$  and  $Y$  be sets.

$\langle 1 \rangle 2$ . LET:  $f : X \rightarrow Y$

$\langle 1 \rangle 3$ . LET:  $A, B \in \mathcal{P}X$  with  $A \subseteq B$ .

$\langle 1 \rangle 4$ . LET:  $y \in f(A)$

$\langle 1 \rangle 5$ . PICK  $x \in A$  such that  $f(x) = y$

PROOF:  $\langle 1 \rangle 4$

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

PROOF:  $\langle 1 \rangle 3, \langle 1 \rangle 5$

$\langle 1 \rangle 7$ .  $y \in f(B)$

PROOF:  $\langle 1 \rangle 5, \langle 1 \rangle 6$

□

**Proposition 3.35.** *Let  $f : X \rightarrow Y$ . Let  $\mathcal{A} \subseteq \mathcal{P}X$ . Then  $f(\bigcup \mathcal{A}) = \bigcup_{A \in \mathcal{A}} f(A)$ .*

PROOF:

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

**Proposition 3.36.** *Let  $f : X \rightarrow Y$ . Let  $\mathcal{A}$  be a nonempty subset of  $\mathcal{P}X$ . Then  $f(\bigcap \mathcal{A}) \subseteq \bigcap_{A \in \mathcal{A}} f(A)$ . Equality holds if  $f$  is injective.*

PROOF:

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

PROOF:  $\langle 3 \rangle 3, \langle 3 \rangle 4$   
 $\langle 2 \rangle 7. y \in f(\bigcap \mathcal{A})$   
 PROOF:  $\langle 2 \rangle 5, \langle 2 \rangle 6$

□

**Proposition 3.37.** *Let  $X$  and  $Y$  be sets. Let  $f : X \rightarrow Y$ . Let  $A, B \in \mathcal{P}X$ . Then  $f(A) - f(B) \subseteq f(A - B)$ . Equality holds if  $f$  is injective.*

PROOF:  
 $\langle 1 \rangle 1$ . LET:  $X$  and  $Y$  be sets.  
 $\langle 1 \rangle 2$ . LET:  $f : X \rightarrow Y$   
 $\langle 1 \rangle 3$ . LET:  $A, B \in \mathcal{P}X$   
 $\langle 1 \rangle 4$ .  $f(A) - f(B) \subseteq f(A - B)$   
 $\langle 2 \rangle 1$ . LET:  $y \in f(A) - f(B)$   
 $\langle 2 \rangle 2$ .  $y \in f(A)$   
 PROOF:  $\langle 2 \rangle 1$   
 $\langle 2 \rangle 3$ . PICK  $x \in A$  such that  $y = f(x)$ .  
 PROOF:  $\langle 2 \rangle 2$   
 $\langle 2 \rangle 4$ .  $x \notin B$   
 $\langle 3 \rangle 1$ . ASSUME: for a contradiction  $x \in B$   
 $\langle 3 \rangle 2$ .  $y \in f(B)$   
 PROOF:  $\langle 2 \rangle 3, \langle 3 \rangle 1$   
 $\langle 3 \rangle 3$ . Q.E.D.  
 PROOF:  $\langle 2 \rangle 1$  and  $\langle 3 \rangle 2$  form a contradiction.  
 $\langle 2 \rangle 5$ .  $x \in A - B$   
 PROOF:  $\langle 2 \rangle 3, \langle 2 \rangle 4$   
 $\langle 2 \rangle 6$ .  $y \in f(A - B)$   
 PROOF:  $\langle 2 \rangle 3, \langle 2 \rangle 5$   
 $\langle 1 \rangle 5$ . If  $f$  is injective then  $f(A - B) = f(A) - f(B)$ .  
 $\langle 2 \rangle 1$ . ASSUME:  $f$  is injective.  
 $\langle 2 \rangle 2$ . LET:  $y \in f(A - B)$   
 $\langle 2 \rangle 3$ . PICK  $x \in A - B$  such that  $y = f(x)$   
 PROOF:  $\langle 2 \rangle 2$   
 $\langle 2 \rangle 4$ .  $x \in A$   
 PROOF:  $\langle 2 \rangle 3$   
 $\langle 2 \rangle 5$ .  $y \in f(A)$   
 PROOF:  $\langle 2 \rangle 3, \langle 2 \rangle 4$   
 $\langle 2 \rangle 6$ .  $y \notin f(B)$   
 $\langle 3 \rangle 1$ . ASSUME:  $y \in f(B)$   
 $\langle 3 \rangle 2$ . PICK  $x' \in B$  such that  $y = f(x')$   
 PROOF:  $\langle 3 \rangle 1$   
 $\langle 3 \rangle 3$ .  $x = x'$   
 PROOF:  $\langle 2 \rangle 1, \langle 2 \rangle 3, \langle 3 \rangle 2$   
 $\langle 3 \rangle 4$ .  $x \in B$   
 PROOF:  $\langle 3 \rangle 2, \langle 3 \rangle 3$   
 $\langle 3 \rangle 5$ . Q.E.D.  
 PROOF:  $\langle 2 \rangle 3$  and  $\langle 3 \rangle 4$  form a contradiction.

$\langle 2 \rangle 7. y \in f(A) - f(B)$

PROOF:  $\langle 2 \rangle 5, \langle 2 \rangle 6$

□

**Definition 3.38** (Inclusion Map). Let  $Y$  be a set and  $X \subseteq Y$ . Then the *inclusion map*  $i : X \hookrightarrow Y$  is the function defined by  $i(x) = x$  for all  $x \in X$ .

**Proposition 3.39.** For any set  $X$ , the identity relation  $I_X$  is a function  $X \rightarrow X$ .

PROOF: Easy. □

**Definition 3.40** (Restriction). Let  $f : Y \rightarrow Z$  and  $X \subseteq Y$ . The *restriction* of  $f$  to  $X$  is the function  $f \upharpoonright X : X \rightarrow Z$  defined by

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

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

**Definition 3.41** (Projection). Given sets  $X$  and  $Y$ , the *projection* maps  $\pi_1 : X \times Y \rightarrow X$  and  $\pi_2 : X \times Y \rightarrow Y$  are defined by

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

**Definition 3.42** (Canonical Map). Let  $X$  be a set and  $R$  an equivalence relation on  $X$ . The *canonical map*  $\pi : X \rightarrow X/R$  is the map defined by  $\pi(x) = x/R$ .

**Proposition 3.43.** Let  $f : X \rightarrow Y$ . Then the following are equivalent:

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

PROOF: Easy. □

**Proposition 3.44.** Let  $f : X \rightarrow Y$ . Then  $f$  maps  $X$  onto  $Y$  if and only if, for all  $A \subseteq X$ , we have  $Y - f(A) \subseteq f(X - A)$ .

PROOF: Easy. □

## 3.7 Families

**Proposition 3.45** (Generalized Associative Law for Unions). Let  $\{I_j\}_{j \in J}$  be a family of sets. Let  $K = \bigcup_{j \in J} I_j$ . Let  $\{A_k\}_{k \in K}$  be a family of sets indexed by  $K$ . Then

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

PROOF: Easy.  $\square$

**Proposition 3.46** (Generalized Commutative Law for Unions). *Let  $\{I_j\}_{j \in J}$  be a family of sets. Let  $f : J \rightarrow J$  be a one-to-one correspondence from  $J$  onto  $J$ . Then*

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

PROOF: Easy.  $\square$

**Proposition 3.47** (Generalized Associative Law for Intersections). *Let  $\{I_j\}_{j \in J}$  be a nonempty family of nonempty sets. Let  $K = \bigcup_{j \in J} I_j$ . Let  $\{A_k\}_{k \in K}$  be a family of sets indexed by  $K$ . Then*

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

PROOF: Easy.  $\square$

**Proposition 3.48** (Generalized Commutative Law for Intersections). *Let  $\{I_j\}_{j \in J}$  be a nonempty family of sets. Let  $f : J \rightarrow J$  be a one-to-one correspondence from  $J$  onto  $J$ . Then*

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

PROOF: Easy.  $\square$

**Proposition 3.49.** *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.  $\square$

**Proposition 3.50.** *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.  $\square$

**Definition 3.51** (Projection). *Let  $\{A_i\}_{i \in I}$  be a family of sets and  $i \in I$ . The projection function  $\pi_i : \times_{i \in I} A_i \rightarrow A_i$  is defined by  $\pi_i(a) = a_i$ .*

**Proposition 3.52.** *Let  $\{A_i\}_{i \in I}$  and  $\{B_j\}_{j \in J}$  be families of sets. Then*

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

PROOF: Easy.  $\square$

**Proposition 3.53.** Let  $\{A_i\}_{i \in I}$  and  $\{B_j\}_{j \in J}$  be nonempty families of sets. Then

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

PROOF: Easy.  $\square$

**Proposition 3.54.** Let  $f : X \rightarrow Y$ . Let  $\{A_i\}_{i \in I}$  be a family of subsets of  $X$ . Then

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

PROOF: Easy.  $\square$

**Example 3.55.** It is not true in general that, if  $f : X \rightarrow Y$  and  $\{A_i\}_{i \in I}$  is a nonempty family of subsets of  $X$ , then  $f(\bigcap_{i \in I} A_i) = \bigcap_{i \in I} f(A_i)$ .

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  $X \rightarrow Y$ . Then  $f(\bigcap_{i \in I} A_i) = f(\emptyset) = \emptyset$  but  $\bigcap_{i \in I} f(A_i) = \{c\}$ .

## 3.8 Inverses and Composites of Functions

### 3.8.1 Inverse Image

**Definition 3.56** (Inverse Image). Let  $f : X \rightarrow Y$ . Let  $B$  be a subset of  $Y$ . Then the *inverse image* of  $B$  under  $f$  is

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

**Proposition 3.57.** Let  $f : X \rightarrow Y$ . Let  $B \subseteq Y$ . Then

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

*Equality holds if  $f$  is surjective.*

PROOF:

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



$\langle 2 \rangle 3$ . PICK  $x \in X$  such that  $f(x) = y$

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

$\langle 2 \rangle 4$ .  $x \in f^{-1}(B)$

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

$\langle 2 \rangle 5$ .  $y \in f(f^{-1}(B))$

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

□

**Proposition 3.58.** *Let  $f : X \rightarrow Y$ . Let  $A \subseteq X$ . Then*

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

*Equality holds if  $f$  is one-to-one.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $X$  and  $Y$  be sets.

$\langle 1 \rangle 2$ . LET:  $f : X \rightarrow Y$

$\langle 1 \rangle 3$ . LET:  $A \subseteq X$

$\langle 1 \rangle 4$ .  $A \subseteq f^{-1}(f(A))$

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

$\langle 2 \rangle 2$ .  $f(x) \in f(A)$

$\langle 2 \rangle 3$ .  $x \in f^{-1}(f(x))$

$\langle 1 \rangle 5$ . If  $f$  is injective then  $f^{-1}(f(A)) = A$

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

$\langle 2 \rangle 2$ . LET:  $x \in f^{-1}(f(A))$

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

PROOF:  $\langle 2 \rangle 2$

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

PROOF:  $\langle 2 \rangle 3$

$\langle 2 \rangle 5$ .  $x' = x$

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

$\langle 2 \rangle 6$ .  $x \in A$

PROOF:  $\langle 2 \rangle 4, \langle 2 \rangle 5$

□

**Proposition 3.59.** *Let  $f : X \rightarrow Y$ . Let  $A \subseteq B \subseteq Y$ . Then  $f^{-1}(A) \subseteq f^{-1}(B)$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $X$  and  $Y$  be sets.

$\langle 1 \rangle 2$ . LET:  $f : X \rightarrow Y$

$\langle 1 \rangle 3$ . LET:  $A \subseteq B \subseteq Y$

$\langle 1 \rangle 4$ . LET:  $x \in f^{-1}(A)$

$\langle 1 \rangle 5$ .  $f(x) \in A$

$\langle 1 \rangle 6$ .  $f(x) \in B$

$\langle 1 \rangle 7$ .  $x \in f^{-1}(B)$

□

**Proposition 3.60.** *Let  $f : X \rightarrow Y$ . Let  $\mathcal{B} \subseteq Y$ . Then*

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

PROOF:

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

**Proposition 3.61.** *Let  $f : X \rightarrow Y$ . Let  $\{B_i\}_{i \in I}$  be a nonempty family of subsets of  $Y$ . Then*

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

PROOF: Easy.  $\square$

**Proposition 3.62.** *Let  $f : X \rightarrow Y$  and  $B \subseteq Y$ . Then  $f^{-1}(Y - B) = X - f^{-1}(B)$ .*

PROOF: Easy.  $\square$

### 3.8.2 Inverse of a Function

**Proposition 3.63.** *Let  $f : X \approx Y$ . Then  $f^{-1}$  is a function, and is a bijection  $f^{-1} : Y \approx X$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $X$  and  $Y$  be sets.

$\langle 1 \rangle 2$ . LET:  $f : X \approx Y$

$\langle 1 \rangle 3$ .  $f^{-1}$  is a function.

$\langle 2 \rangle 1$ . LET:  $(x, y), (x, z) \in f^{-1}$

$\langle 2 \rangle 2$ .  $(y, x), (z, x) \in f$

$\langle 2 \rangle 3$ .  $y = z$

PROOF:  $f$  is injective.

$\langle 1 \rangle 4$ .  $\text{dom } f^{-1} = Y$

PROOF: Proposition 3.17,  $\langle 1 \rangle 2$

$\langle 1 \rangle 5$ .  $\text{ran } f^{-1} = X$

PROOF:

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

$\langle 1 \rangle 6$ .  $f^{-1}$  is injective.

$\langle 2 \rangle 1$ . LET:  $y, y' \in Y$

$\langle 2 \rangle 2$ . ASSUME:  $f^{-1}(y) = f^{-1}(y')$

$\langle 2 \rangle 3$ .  $y = y'$

PROOF:  $y = f(f^{-1}(y)) = f(f^{-1}(y')) = y'$ .

□

**Proposition 3.64.** *Let  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$ . Then  $gf : X \rightarrow Z$  and, for all  $x \in X$ , we have*

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

PROOF: Easy. □

**Example 3.65.** Example 3.14 shows that function composition is not commutative in general.

**Proposition 3.66.** *The composite of two injective functions is injective.*

PROOF:

⟨1⟩1. LET:  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$

⟨1⟩2. LET:  $x, y \in X$

⟨1⟩3. ASSUME:  $(g \circ f)(x) = (g \circ f)(y)$

⟨1⟩4.  $g(f(x)) = g(f(y))$

⟨1⟩5.  $f(x) = f(y)$

PROOF:  $g$  is injective.

⟨1⟩6.  $x = y$

PROOF:  $f$  is injective.

□

**Proposition 3.67.** *Let  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$ . If  $g \circ f$  is injective then  $f$  is injective.*

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

**Proposition 3.68.** *The composite of two surjective functions is surjective.*

PROOF:

⟨1⟩1. LET:  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$

⟨1⟩2. LET:  $z \in Z$

⟨1⟩3. PICK  $y \in Y$  such that  $g(y) = z$

PROOF: Since  $g$  is surjective.

⟨1⟩4. PICK  $x \in X$  such that  $f(x) = y$

PROOF: Since  $f$  is surjective.

⟨1⟩5.  $(g \circ f)(x) = z$

□

**Proposition 3.69.** *Let  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$ . If  $g \circ f$  is surjective then  $g$  is surjective.*

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

**Proposition 3.70.** *The composite of two bijective functions is bijective.*

PROOF: Propositions 3.66 and 3.68. □

**Proposition 3.71.** *Let  $X, Y$  and  $Z$  be sets. Let  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$ . Let  $A \subseteq Z$ . Then*

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

PROOF:

$\langle 1 \rangle 1$ . LET:  $X, Y$  and  $Z$  be sets.

$\langle 1 \rangle 2$ . LET:  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$

$\langle 1 \rangle 3$ . LET:  $A \subseteq Z$

$\langle 1 \rangle 4$ .  $(g \circ f)^{-1}(A) = f^{-1}(g^{-1}(A))$

PROOF:

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

$\langle 2 \rangle 2$ .  $x \in (g \circ f)^{-1}(A) \Leftrightarrow x \in f^{-1}(g^{-1}(A))$

PROOF:

$$\begin{aligned} x \in (g \circ f)^{-1}(A) &\Leftrightarrow (g \circ f)(x) \in A \\ &\Leftrightarrow g(f(x)) \in A && \text{(Proposition 3.64, } \langle 1 \rangle 2, \langle 2 \rangle 1) \\ &\Leftrightarrow f(x) \in g^{-1}(A) \\ &\Leftrightarrow x \in f^{-1}(g^{-1}(A)) \end{aligned}$$

□

**Proposition 3.72.** *Let  $f : X \approx Y$  and  $g : Y \approx Z$ . Then*

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

PROOF: Easy. □

**Definition 3.73** (Left Inverse, Right Inverse). Let  $f : X \rightarrow Y$  and  $g : Y \rightarrow X$ . Then  $g$  is a *left inverse* of  $f$ , and  $f$  is a *right inverse* of  $g$ , iff  $g \circ f = I_X$ .

**Proposition 3.74.** *Let  $f : X \rightarrow Y$  and  $g : Y \rightarrow X$ . If  $gf = I_X$  then  $f$  is one-to-one and  $g$  maps  $Y$  onto  $X$ .*

PROOF: Easy. □

**Lemma 3.75.** *Let  $f : A \rightarrow B$ . If there are functions  $g : B \rightarrow A$  and  $h : B \rightarrow A$  such that  $\forall a \in A. g(f(a)) = a$  and  $\forall b \in B. f(h(b)) = b$ , then  $f$  is bijective and  $g = h = f^{-1}$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $A$  and  $B$  be sets.

$\langle 1 \rangle 2$ . LET:  $f : A \rightarrow B$  and  $g, h : B \rightarrow A$

$\langle 1 \rangle 3$ . ASSUME:  $\forall a \in A. g(f(a)) = a$

$\langle 1 \rangle 4$ . ASSUME:  $\forall b \in B. f(h(b)) = b$

$\langle 1 \rangle 5$ .  $f$  is injective.

PROOF: Proposition 3.74,  $\langle 1 \rangle 2, \langle 1 \rangle 3$ .

$\langle 1 \rangle 6$ .  $f$  is surjective.

PROOF: Proposition 3.74,  $\langle 1 \rangle 2, \langle 1 \rangle 4$ .

$\langle 1 \rangle 7$ .  $g = h$

$\langle 2 \rangle 1$ . LET:  $b \in B$   
 $\langle 2 \rangle 2$ .  $g(b) = h(b)$   
 PROOF:  

$$\begin{aligned} g(b) &= g(f(h(b))) && (\langle 1 \rangle 4, \langle 2 \rangle 1) \\ &= h(b) && (\langle 1 \rangle 3, \langle 1 \rangle 2, \langle 2 \rangle 1) \end{aligned}$$
 $\langle 1 \rangle 8$ .  $h = f^{-1}$   
 $\langle 2 \rangle 1$ . LET:  $b \in B$   
 $\langle 2 \rangle 2$ .  $f(h(b)) = b$   
 PROOF:  $\langle 1 \rangle 4, \langle 2 \rangle 1$   
 $\langle 2 \rangle 3$ .  $h(b) = f^{-1}(b)$   
 $\square$

### 3.9 Choice Functions

**Definition 3.76** (Choice Function). A *choice function* for a set  $X$  is a function  $f : \mathcal{P}X - \{\emptyset\} \rightarrow X$  such that  $f(S) \in S$  for all  $S$ .

**Proposition 3.77.** *Every set has a choice function.*

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

**Proposition 3.78.** *For any relation  $R$ , there exists a function  $f \subseteq R$  such that  $\text{dom } f = \text{dom } R$ .*

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

**Proposition 3.79.** *If  $\mathcal{C}$  is a set of pairwise disjoint nonempty sets, then there exists a set  $A$  such that, for all  $C \in \mathcal{C}$ , we have  $A \cap C$  is a singleton.*

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

## Chapter 4

# Equivalence

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

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

PROOF: Easy.

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

PROOF:

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

15.  $h : X \sim Y$   
 $\square$

**Theorem 4.4** (Cantor). *For any set  $X$  we have  $X \not\sim \mathcal{P}X$ .*

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

# Chapter 5

## Order

### 5.1 Partial Orders

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

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

Given a partial order  $\leq$ , we write  $\geq$  for the inverse of  $\leq$ .

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

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

PROOF: From Theorems 2.16, 2.17 and 2.18.  $\square$

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

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

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

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

PROOF:

$\langle 1 \rangle 1$ . LET:  $X$  be a set.

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

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

PROOF: Trivial.

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

$\langle 2 \rangle 1$ . LET:  $\leq$  be a partial order on  $X$ .

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



$\langle 2 \rangle 3$ . LET:  $x < y$  and  $y < z$   
 $\langle 2 \rangle 4$ .  $x \leq y$   
 PROOF:  $\langle 2 \rangle 3$   
 $\langle 2 \rangle 5$ .  $x \neq y$   
 PROOF:  $\langle 2 \rangle 3$   
 $\langle 2 \rangle 6$ .  $y \leq z$   
 PROOF:  $\langle 2 \rangle 3$   
 $\langle 2 \rangle 7$ .  $y \neq z$   
 PROOF:  $\langle 2 \rangle 3$   
 $\langle 2 \rangle 8$ .  $x \leq z$   
 PROOF: From  $\langle 2 \rangle 4$  and  $\langle 2 \rangle 6$  since  $\leq$  is transitive by  $\langle 2 \rangle 1$ .  
 $\langle 2 \rangle 9$ .  $x \neq z$   
 $\langle 3 \rangle 1$ . ASSUME: for a contradiction  $x = z$   
 $\langle 3 \rangle 2$ .  $y \leq x$   
 PROOF:  $\langle 2 \rangle 6$ ,  $\langle 3 \rangle 1$   
 $\langle 3 \rangle 3$ .  $x = y$   
 PROOF: From  $\langle 2 \rangle 4$  and  $\langle 3 \rangle 2$  since  $\leq$  is antisymmetric by  $\langle 2 \rangle 1$ .  
 $\langle 3 \rangle 4$ . Q.E.D.  
 PROOF:  $\langle 2 \rangle 5$  and  $\langle 3 \rangle 3$  form a contradiction.  
 $\langle 2 \rangle 10$ .  $x < z$   
 PROOF:  $\langle 2 \rangle 8$ ,  $\langle 2 \rangle 9$   
 $\langle 1 \rangle 5$ . If there exists a partial order  $\leq$  on  $X$  such that  $\forall x, y \in X (x < y \Leftrightarrow x \leq y \wedge x \neq y)$ , then  $\forall x, y \in X (x \leq y \Leftrightarrow x < y \vee x = y)$ .  
 PROOF: Trivial.  
 $\langle 1 \rangle 6$ . If  $<$  is irreflexive and transitive, then the relation  $\leq$  defined by  $\forall x, y \in X (x \leq y \Leftrightarrow x < y \vee x = y)$  is a partial order on  $X$ .  
 $\langle 2 \rangle 1$ . ASSUME:  $<$  is irreflexive.  
 $\langle 2 \rangle 2$ . ASSUME:  $<$  is transitive.  
 $\langle 2 \rangle 3$ . LET:  $\leq$  be the relation defined by  $\forall x, y \in X (x \leq y \Leftrightarrow x < y \vee x = y)$   
 $\langle 2 \rangle 4$ .  $\leq$  is reflexive.  
 PROOF: Immediate from  $\langle 2 \rangle 3$ .  
 $\langle 2 \rangle 5$ .  $\leq$  is transitive.  
 $\langle 3 \rangle 1$ . LET:  $x, y, z \in X$   
 $\langle 3 \rangle 2$ . ASSUME:  $x \leq y$  and  $y \leq z$   
 $\langle 3 \rangle 3$ .  $x < y$  or  $x = y$   
 PROOF:  $\langle 2 \rangle 4$ ,  $\langle 3 \rangle 2$   
 $\langle 3 \rangle 4$ .  $y < z$  or  $y = z$   
 PROOF:  $\langle 2 \rangle 4$ ,  $\langle 3 \rangle 2$   
 $\langle 3 \rangle 5$ . CASE:  $x < y$  and  $y < z$   
 $\langle 4 \rangle 1$ .  $x < z$   
 PROOF:  $\langle 2 \rangle 2$   
 $\langle 4 \rangle 2$ .  $x \leq z$   
 PROOF:  $\langle 2 \rangle 4$ ,  $\langle 4 \rangle 1$   
 $\langle 3 \rangle 6$ . CASE:  $x = y$   
 PROOF: Then  $x \leq z$  from  $\langle 3 \rangle 2$   
 $\langle 3 \rangle 7$ . CASE:  $y = z$

PROOF: Then  $x \leq z$  from  $\langle 3 \rangle 2$   
 $\langle 2 \rangle 6$ .  $\leq$  is antisymmetric.  
 $\langle 3 \rangle 1$ . LET:  $x, y \in X$   
 $\langle 3 \rangle 2$ . ASSUME:  $x \leq y$   
 $\langle 3 \rangle 3$ . ASSUME:  $y \leq x$   
 $\langle 3 \rangle 4$ .  $x < y$  or  $x = y$   
PROOF:  $\langle 2 \rangle 4, \langle 3 \rangle 2$   
 $\langle 3 \rangle 5$ .  $y < x$  or  $y = x$   
PROOF:  $\langle 2 \rangle 4, \langle 3 \rangle 2$   
 $\langle 3 \rangle 6$ .  $\neg(x < y \wedge y < x)$   
 $\langle 4 \rangle 1$ . ASSUME: for a contradiction  $x < y$  and  $y < x$   
 $\langle 4 \rangle 2$ .  $x < x$   
PROOF:  $\langle 2 \rangle 2, \langle 4 \rangle 1$   
 $\langle 4 \rangle 3$ . Q.E.D.  
PROOF:  $\langle 2 \rangle 1$  and  $\langle 4 \rangle 2$  form a contradiction.  
 $\langle 3 \rangle 7$ .  $x = y$   
PROOF:  $\langle 3 \rangle 4, \langle 3 \rangle 5, \langle 3 \rangle 6$   
 $\langle 1 \rangle 7$ . If  $<$  is irreflexive, then the relation  $\leq$  defined by  $\forall x, y \in X (x \leq y \Leftrightarrow x < y \vee x = y)$  satisfies  $\forall x, y \in X (x < y \Leftrightarrow x \leq y \wedge x \neq y)$ .  
PROOF: Trivial.  
 $\square$

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

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

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

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

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

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

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

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

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

PROOF: If  $a$  and  $b$  are least then  $a \leq b$  and  $b \leq a$ , hence  $a = b$ .  $\square$

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

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

PROOF: If  $a$  and  $b$  are greatest then  $a \leq b$  and  $b \leq a$ , hence  $a = b$ .  $\square$

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

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

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

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

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

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

## 5.2 Linear Orders

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

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

PROOF: Easy.  $\square$

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

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

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

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

*In this case,  $\leq$  is unique and is defined by*

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

PROOF:

$\langle 1 \rangle$ 1. LET:  $X$  be a set.

- $\langle 1 \rangle 2$ . LET:  $<$  be a relation on  $X$   
 $\langle 1 \rangle 3$ . If there exists a linear order  $\leq$  on  $X$  such that  $\forall x, y \in X (x < y \Leftrightarrow x \leq y \wedge x \neq y)$ , then  $<$  is irreflexive.  
 PROOF: Trivial.  
 $\langle 1 \rangle 4$ . If there exists a linear order  $\leq$  on  $X$  such that  $\forall x, y \in X (x < y \Leftrightarrow x \leq y \wedge x \neq y)$ , then  $<$  is transitive.  
 $\langle 2 \rangle 1$ . LET:  $\leq$  be a linear order on  $X$ .  
 $\langle 2 \rangle 2$ . ASSUME:  $\forall x, y \in X (x < y \Leftrightarrow x \leq y \wedge x \neq y)$   
 $\langle 2 \rangle 3$ . LET:  $x < y$  and  $y < z$   
 $\langle 2 \rangle 4$ .  $x \leq y$   
 PROOF:  $\langle 2 \rangle 3$   
 $\langle 2 \rangle 5$ .  $x \neq y$   
 PROOF:  $\langle 2 \rangle 3$   
 $\langle 2 \rangle 6$ .  $y \leq z$   
 PROOF:  $\langle 2 \rangle 3$   
 $\langle 2 \rangle 7$ .  $y \neq z$   
 PROOF:  $\langle 2 \rangle 3$   
 $\langle 2 \rangle 8$ .  $x \leq z$   
 PROOF: From  $\langle 2 \rangle 4$  and  $\langle 2 \rangle 6$  since  $\leq$  is transitive.  
 $\langle 2 \rangle 9$ .  $x \neq z$   
 $\langle 3 \rangle 1$ . ASSUME: for a contradiction  $x = z$   
 $\langle 3 \rangle 2$ .  $y \leq x$   
 PROOF:  $\langle 2 \rangle 6$ ,  $\langle 3 \rangle 1$   
 $\langle 3 \rangle 3$ .  $x = y$   
 PROOF: From  $\langle 2 \rangle 4$  and  $\langle 3 \rangle 2$  since  $\leq$  is antisymmetric.  
 $\langle 3 \rangle 4$ . Q.E.D.  
 PROOF:  $\langle 2 \rangle 5$  and  $\langle 3 \rangle 3$  form a contradiction.  
 $\langle 2 \rangle 10$ .  $x < z$   
 PROOF:  $\langle 2 \rangle 8$ ,  $\langle 2 \rangle 9$   
 $\langle 1 \rangle 5$ . If there exists a linear order  $\leq$  on  $X$  such that  $\forall x, y \in X (x < y \Leftrightarrow x \leq y \wedge x \neq y)$ , then  $\forall x, y \in X (x < y \vee x = y \vee y < x)$ .  
 $\langle 2 \rangle 1$ . LET:  $\leq$  be a linear order on  $X$ .  
 $\langle 2 \rangle 2$ . ASSUME:  $\forall x, y \in X (x < y \Leftrightarrow x \leq y \wedge x \neq y)$   
 $\langle 2 \rangle 3$ . LET:  $x, y \in X$   
 $\langle 2 \rangle 4$ .  $x \leq y$  or  $y \leq x$   
 $\langle 2 \rangle 5$ . CASE:  $x \leq y$   
 PROOF: Then  $x < y$  or  $x = y$  using  $\langle 2 \rangle 2$ .  
 $\langle 2 \rangle 6$ . CASE:  $y \leq x$   
 PROOF: Then  $y < x$  or  $x = y$  using  $\langle 2 \rangle 2$ .  
 $\langle 1 \rangle 6$ . If there exists a linear order  $\leq$  on  $X$  such that  $\forall x, y \in X (x < y \Leftrightarrow x \leq y \wedge x \neq y)$ , then  $\forall x, y \in X (x \leq y \Leftrightarrow x < y \vee x = y)$ .  
 PROOF: Trivial.  
 $\langle 1 \rangle 7$ . If  $<$  is irreflexive, transitive and satisfies  $\forall x, y \in X (x < y \vee x = y \vee y < x)$ , then the relation  $\leq$  defined by  $\forall x, y \in X (x \leq y \Leftrightarrow x < y \vee x = y)$  is a linear order on  $X$ .  
 $\langle 2 \rangle 1$ . ASSUME:  $<$  is irreflexive.

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

□

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

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

PROOF:

⟨1⟩1. PICK a choice function  $f$  for  $X$ .

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

⟨1⟩3. For all  $A \in \mathcal{X}$ ,

LET:  $\hat{A} = \{x \in X : A \cup \{x\} \in \mathcal{X}\}$

⟨1⟩4. LET:  $g : \mathcal{X} \rightarrow \mathcal{X}$  be the function

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

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

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

⟨1⟩6. LET:  $\mathcal{T}_0$  be the intersection of the set of all towers.

PROOF: The set of all towers is nonempty since  $\mathcal{X}$  is a tower.

⟨1⟩7. LET:  $A = \bigcup \mathcal{T}_0$

⟨1⟩8.  $A$  is a chain in  $X$ .

⟨2⟩1.  $\mathcal{T}_0$  is a chain under  $\subseteq$

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

⟨3⟩2. For all  $A, C \in \mathcal{T}_0$ , if  $C$  is comparable and  $A \subsetneq C$  then  $g(A) \subseteq C$ .

PROOF: Since  $g(A) - A$  has at most one element, so if  $A \subsetneq C \subseteq g(A)$  then  $C = g(A)$ .

⟨3⟩3. For  $C \in \mathcal{T}_0$  comparable,

LET:  $\mathcal{U}_C = \{A \in \mathcal{T}_0 : A \subseteq C \vee g(C) \subseteq A\}$

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

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

⟨4⟩2.  $\emptyset \in \mathcal{U}_C$

PROOF: Since  $\emptyset \subseteq C$ .

⟨4⟩3.  $\forall A \in \mathcal{U}_C. g(A) \in \mathcal{U}_C$

PROOF: By ⟨1⟩8.

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

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

⟨5⟩2. CASE:  $\exists A \in \mathcal{C}. g(C) \subseteq A$

PROOF: Then  $g(C) \subseteq \bigcup \mathcal{C}$

⟨5⟩3. CASE:  $\forall A \in \mathcal{C}. A \subseteq C$

PROOF: Then  $\bigcup \mathcal{C} \subseteq C$ .

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

⟨3⟩6. For  $C \in \mathcal{T}_0$  comparable we have  $g(C)$  is comparable.

PROOF: Since for all  $A \in \mathcal{T}_0$  either  $A \subseteq C \subseteq g(C)$  or  $g(C) \subseteq A$ .

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

⟨4⟩1.  $\emptyset$  is comparable.

PROOF:  $\forall A \in \mathcal{T}_0. \emptyset \subseteq A$

$\langle 4 \rangle 2$ . For all  $C \in \mathcal{T}_0$ , if  $A$  is comparable then  $g(C)$  is comparable.  
 PROOF:  $\langle 3 \rangle 6$   
 $\langle 4 \rangle 3$ . For every chain  $\mathcal{C} \subseteq \mathcal{T}_0$  of comparable sets, we have  $\bigcup \mathcal{C}$  is comparable.  
 $\langle 5 \rangle 1$ . LET:  $\mathcal{C} \subseteq \mathcal{T}_0$  be a chain of comparable sets.  
 $\langle 5 \rangle 2$ . LET:  $A \in \mathcal{T}_0$   
 $\langle 5 \rangle 3$ . CASE: there exists  $C \in \mathcal{C}$  such that  $A \subseteq C$   
 PROOF: Then  $A \subseteq \bigcup \mathcal{C}$ .  
 $\langle 5 \rangle 4$ . CASE: for all  $C \in \mathcal{C}$  we have  $C \subseteq A$   
 PROOF: Then  $\bigcup \mathcal{C} \subseteq A$ .  
 $\langle 3 \rangle 8$ . Every set in  $\mathcal{T}_0$  is comparable.  
 $\langle 2 \rangle 2$ . LET:  $x, y \in A$   
 $\langle 2 \rangle 3$ . PICK  $A, C \in \mathcal{T}_0$  such that  $x \in A$  and  $y \in C$   
 $\langle 2 \rangle 4$ . ASSUME: w.l.o.g.  $A \subseteq C$   
 $\langle 2 \rangle 5$ .  $x, y \in C$   
 $\langle 2 \rangle 6$ .  $x \leq y$  or  $y \leq x$   
 PROOF: Since  $C \in \mathcal{X}$  so  $C$  is a chain.  
 $\langle 1 \rangle 9$ . PICK an upper bound  $u$  for  $A$ .  
 $\langle 1 \rangle 10$ .  $A \in \mathcal{T}_0$   
 PROOF: Since  $\mathcal{T}_0$  is a chain in  $\mathcal{T}_0$  so  $\bigcup \mathcal{T}_0 \in \mathcal{T}_0$ .  
 $\langle 1 \rangle 11$ .  $g(A) \in \mathcal{T}_0$   
 $\langle 1 \rangle 12$ .  $g(A) \subseteq A$   
 $\langle 1 \rangle 13$ .  $g(A) = A$   
 $\langle 1 \rangle 14$ .  $\hat{A} - A = \emptyset$   
 $\langle 1 \rangle 15$ .  $u \in A$   
 PROOF: Since  $A \cup \{u\}$  is a chain so  $u \in \hat{A}$  and therefore  $u \in A$ .  
 $\langle 1 \rangle 16$ .  $u$  is maximal in  $X$ .  
 $\langle 2 \rangle 1$ . LET:  $x \in X$   
 $\langle 2 \rangle 2$ . ASSUME:  $u \leq x$   
 $\langle 2 \rangle 3$ .  $A \cup \{x\}$  is a chain.  
 $\langle 2 \rangle 4$ .  $x \in A$   
 $\langle 2 \rangle 5$ .  $x \leq u$   
 $\langle 2 \rangle 6$ .  $x = u$

□

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

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

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

PROOF: Easy. □

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

PROOF: Easy.  $\square$

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

PROOF: Easy.  $\square$

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

PROOF: Easy.  $\square$

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

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

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

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

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

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

PROOF:

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

$\langle 2 \rangle 1$ . LET:  $A$  be a linearly ordered set.

$\langle 2 \rangle 2$ . ASSUME:  $A$  has the least upper bound property.

$\langle 2 \rangle 3$ . LET:  $S$  be a nonempty subset of  $A$  bounded below.

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

$\langle 2 \rangle 5$ .  $S \downarrow \neq \emptyset$

PROOF: Since  $S$  is bounded below by  $\langle 2 \rangle 3$ .

$\langle 2 \rangle 6$ .  $S \downarrow$  is bounded above.

$\langle 3 \rangle 1$ . PICK  $s \in S$

PROOF:  $S$  is nonempty by  $\langle 2 \rangle 3$ .

$\langle 3 \rangle 2$ .  $s$  is an upper bound for  $S \downarrow$ .

$\langle 2 \rangle 7$ . LET:  $l$  be the supremum of  $S \downarrow$ .

PROOF:  $\langle 2 \rangle 2, \langle 2 \rangle 5, \langle 2 \rangle 6$

$\langle 2 \rangle 8$ .  $l$  is a lower bound for  $S$ .

$\langle 3 \rangle 1$ . LET:  $s \in S$



$\langle 3 \rangle 2$ .  $s$  is an upper bound for  $S \downarrow$

$\langle 3 \rangle 3$ .  $l \leq s$

PROOF:  $\langle 2 \rangle 7$ ,  $\langle 3 \rangle 2$

$\langle 2 \rangle 9$ . For any lower bound  $l'$  for  $S$  we have  $l' \leq l$ .

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

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

$\langle 2 \rangle 1$ . LET:  $(A, \leq)$  be a linearly ordered set.

$\langle 2 \rangle 2$ . ASSUME: Every nonempty subset of  $A$  bounded below has a greatest lower bound.

$\langle 2 \rangle 3$ .  $(A, \geq)$  has the least upper bound property.

$\langle 2 \rangle 4$ . Every nonempty subset of  $A$  bounded below with respect to  $\geq$  has a greatest lower bound with respect to  $\geq$ .

$\langle 2 \rangle 5$ . Every nonempty subset of  $A$  bounded above with respect to  $\leq$  has a least upper bound with respect to  $\leq$ .

□

### 5.3 Linear Continua

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

### 5.4 Well Orderings

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

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

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

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

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

Then  $S = X$ .

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

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

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

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

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

PROOF:

- $\langle 1 \rangle 1$ . LET:  $X$  be a totally ordered set.
- $\langle 1 \rangle 2$ . LET:  $\mathcal{C}$  be the poset of all well ordered subsets of  $X$  under continuation.
- $\langle 1 \rangle 3$ . Every chain in  $\mathcal{C}$  has an upper bound.

PROOF: Proposition 5.37.

- $\langle 1 \rangle 4$ . PICK a maximal element  $C$  of  $\mathcal{C}$

PROVE:  $C$  is cofinal

PROOF: Zorn's Lemma

- $\langle 1 \rangle 5$ . LET:  $x \in X$
- $\langle 1 \rangle 6$ . We cannot have  $\forall c \in C. c < x$
- PROOF: Then  $C \cup \{x\}$  would be a larger chain.
- $\langle 1 \rangle 7$ .  $\exists c \in C. x \leq c$

$\square$

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

PROOF:

- $\langle 1 \rangle 1$ . LET:  $X$  be a set.
- $\langle 1 \rangle 2$ . LET:  $\mathcal{W}$  be the poset of all well ordered subsets of  $X$  under continuation.
- $\langle 1 \rangle 3$ . Every chain in  $\mathcal{W}$  has an upper bound.

PROOF: Proposition 5.37.

- $\langle 1 \rangle 4$ . PICK a maximal  $M \in \mathcal{W}$

PROOF: Zorn's Lemma

- $\langle 1 \rangle 5$ .  $M = X$

PROOF: If  $x \in X - M$  then  $M \cup \{x\}$  with  $x$  as the greatest element is a continuation of  $M$ .

$\square$

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

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

PROOF:

- $\langle 1 \rangle 1$ . Let us say that a subset  $A \subseteq W \times X$  is *f-closed* iff, whenever  $a \in W$  and  $t : s(a) \rightarrow X$  satisfies  $\forall c < a. (c, t(c)) \in A$ , then  $(a, f(t)) \in A$ .
- $\langle 1 \rangle 2$ . LET:  $U$  be the intersection of the set of *f-closed* subsets of  $W \times X$
- PROOF: This set is nonempty since  $W \times X$  is *f-closed*.
- $\langle 1 \rangle 3$ .  $U$  is *f-closed*.
- $\langle 1 \rangle 4$ .  $U$  is a function.

- $\langle 2 \rangle 1$ . LET:  $P(a)$  be the property: there is at most one  $x \in X$  such that  $(a, x) \in U$

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

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

PROOF:  
 $\langle 1 \rangle 1$ . LET:  $a \in X$   
 $\langle 1 \rangle 2$ . ASSUME: as transfinite induction hypothesis  $\forall c < a. c \leq f(c)$   
 $\langle 1 \rangle 3$ . ASSUME: for a contradiction  $f(a) < a$   
 $\langle 1 \rangle 4$ .  $f(a) \leq f(f(a))$   
 PROOF:  $\langle 1 \rangle 2$   
 $\langle 1 \rangle 5$ .  $f(f(a)) < f(a)$   
 PROOF: From  $\langle 1 \rangle 3$  since  $f$  is a similarity.  
 $\langle 1 \rangle 6$ . Q.E.D.  
 PROOF: This is a contradiction.  
 $\square$

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

PROOF:  
 $\langle 1 \rangle 1$ . LET:  $f, g : X \cong Y$   
 PROVE:  $\forall a \in X. f(a) = g(a)$   
 $\langle 1 \rangle 2$ . LET:  $a \in X$   
 $\langle 1 \rangle 3$ . ASSUME: as transfinite induction hypothesis  $\forall c < a. f(c) = g(c)$   
 $\langle 1 \rangle 4$ .  $f(a)$  is the least element of  $Y - \{f(c) : c < a\}$   
 $\langle 1 \rangle 5$ .  $g(a)$  is the least element of  $Y - \{g(c) : c < a\}$   
 $\langle 1 \rangle 6$ .  $f(a) = g(a)$   
 $\square$

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

PROOF:  
 $\langle 1 \rangle 1$ . LET:  $X$  be a well ordered set.

⟨1⟩2. ASSUME: for a contradiction  $f : X \cong s(a)$  for some  $a \in X$

⟨1⟩3.  $f(a) < a$

⟨1⟩4. Q.E.D.

PROOF: This contradicts Proposition 5.41.

□

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

PROOF:

⟨1⟩1. LET:  $X_0 = \{a \in X : \exists b \in Y. s(a) \cong s(b)\}$

⟨1⟩2. LET:  $U : X_0 \rightarrow Y$  be the function: for  $a \in X_0$ , we have  $U(a)$  is the unique element in  $Y$  such that  $s(a) \cong s(U(a))$

⟨1⟩3. LET:  $Y_0 = \text{ran } U$

⟨1⟩4. Either  $X_0 = X$  or there exists  $a \in X$  such that  $X_0 = s(a)$

⟨2⟩1. ASSUME:  $X_0 \neq X$

⟨2⟩2. LET:  $a$  be the least element of  $X - X_0$

⟨2⟩3. LET:  $x \in X_0$

PROVE:  $x < a$

⟨2⟩4. PICK  $f : s(x) \cong s(U(x))$

⟨2⟩5. ASSUME: for a contradiction  $a < x$

⟨2⟩6.  $f \upharpoonright s(a) : s(a) \cong s(f(a))$

⟨2⟩7.  $a \in X_0$

⟨2⟩8. Q.E.D.

PROOF: This is a contradiction.

⟨1⟩5. Either  $Y_0 = Y$  or there exists  $b \in Y$  such that  $Y_0 = s(b)$

PROOF: Similar.

⟨1⟩6. CASE:  $X_0 = X$  and  $Y_0 = Y$

PROOF: Then  $U : X \cong Y$ .

⟨1⟩7. CASE:  $X_0 = X$  and  $Y_0 \neq Y$

PROOF: Then  $U : X \cong s(b)$  where  $Y_0 = s(b)$ .

⟨1⟩8. CASE:  $X_0 \neq X$  and  $Y_0 = Y$

PROOF: Then  $U : s(a) \cong Y$  where  $X_0 = s(a)$ .

⟨1⟩9. CASE:  $X_0 \neq X$  and  $Y_0 \neq Y$

⟨2⟩1. LET:  $X_0 = s(a)$  and  $Y_0 = s(b)$

⟨2⟩2.  $U : s(a) \cong s(b)$

⟨2⟩3.  $a \in X_0$

⟨2⟩4. Q.E.D.

PROOF: This is a contradiction.

□

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

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

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

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

# Chapter 6

## Natural Numbers

### 6.1 Natural Numbers

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

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

**Definition 6.2.** We define

$$0 = \emptyset$$

$$1 = 0^+$$

$$2 = 1^+$$

etc.

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

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

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

PROOF: Easy.  $\square$

**Definition 6.5.** The set  $\omega$  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  $\omega = \bigcap \{X \in \mathcal{P}A : 0 \in X \wedge \forall n \in X. n^+ \in X\}$ .  
 $\square$

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

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

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

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

PROOF:

$\langle 1 \rangle 1$ . LET:  $P(n)$  be the property  $\forall m \in n. m^+ \in n^+$

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

PROOF: Vacuous.

$\langle 1 \rangle 3$ . For any natural number  $n$ , if  $P(n)$  then  $P(n^+)$ .

$\langle 2 \rangle 1$ . LET:  $n$  be a natural number.

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

$\langle 2 \rangle 3$ . LET:  $m \in n^+$

$\langle 2 \rangle 4$ .  $m \in n$  or  $m = n$

$\langle 2 \rangle 5$ .  $m^+ \in n^+$  or  $m^+ = n^+$

PROOF:  $\langle 2 \rangle 2$

$\langle 2 \rangle 6$ . CASE:  $m^+ \in n^{++}$

$\square$

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

PROOF: From the definition of  $\omega$ .  $\square$

**Proposition 6.9.**

$$\forall n \in \omega. \forall x \in n. n \not\subseteq x$$

PROOF:

$\langle 1 \rangle 1$ .  $\forall x \in 0. 0 \not\subseteq x$

PROOF: Vacuous.

$\langle 1 \rangle 2$ . For any natural number  $n$ , if  $\forall x \in n. n \not\subseteq x$  then  $\forall x \in n^+. n^+ \not\subseteq x$ .

$\langle 2 \rangle 1$ . LET:  $n$  be a natural number.

$\langle 2 \rangle 2$ . ASSUME:  $\forall x \in n. n \not\subseteq x$

$\langle 2 \rangle 3$ . LET:  $x \in n^+$

$\langle 2 \rangle 4$ . ASSUME: for a contradiction  $n^+ \subseteq x$

$\langle 2 \rangle 5$ .  $x \in n$  or  $x = n$

$\langle 2 \rangle 6$ . CASE:  $x \in n$

PROOF: Then we have  $n \subseteq n^+ \subseteq x$  contradicting  $\langle 2 \rangle 2$ .

$\langle 2 \rangle 7$ . CASE:  $x = n$

PROOF: Then we have  $n \in n^+ \subseteq x = n$  and  $n \subseteq n$  contradicting  $\langle 2 \rangle 2$ .

$\square$

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

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

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

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

PROOF:

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

$\langle 3 \rangle 2$ .  $x \in n^+$

□

**Proposition 6.12.** *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 6.11).

$\langle 2 \rangle 3$ . Q.E.D.

PROOF: This contradicts Proposition 6.9.

$\langle 1 \rangle 8$ .  $m = n$

□

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



PROOF:

$\langle 1 \rangle 1$ . LET:  $\mathcal{C} = \{A \in \mathcal{P}(\omega \times X) : (0, a) \in A \wedge \forall n \in \omega. \forall x \in X. (n, x) \in A \Rightarrow (n^+, f(x)) \in A\}$

$\langle 1 \rangle 2$ .  $\mathcal{C} \neq \emptyset$

PROOF:  $\omega \times X \in \mathcal{C}$

$\langle 1 \rangle 3$ . LET:  $u = \bigcap \mathcal{C}$

$\langle 1 \rangle 4$ .  $u \in \mathcal{C}$

$\langle 1 \rangle 5$ .  $u$  is a function.

$\langle 2 \rangle 1$ . LET:  $P(n)$  be the property:  $\forall x, y \in X. (n, x) \in u \wedge (n, y) \in u \Rightarrow x = y$

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

$\langle 3 \rangle 1$ .  $\forall x \in X. (0, x) \in u \Rightarrow x = a$

PROOF: If  $(0, x) \in u$  and  $x \neq a$  then  $u - \{(0, x)\} \in \mathcal{C}$  and so  $u - \{(0, x)\} \subseteq u$ , which is impossible.

$\langle 2 \rangle 3$ . For every natural number  $n$ , if  $P(n)$  then  $P(n^+)$ .

$\langle 3 \rangle 1$ . LET:  $n$  be a natural number.

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

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

$\langle 3 \rangle 4$ . ASSUME:  $(n^+, x), (n^+, y) \in u$

$\langle 3 \rangle 5$ . PICK  $x', y' \in X$  such that  $(n, x') \in u$ ,  $(n, y') \in u$  and  $f(x') = x$  and  $f(y') = y$

PROOF: If no such  $x'$  exists then  $u - \{(n^+, x)\} \in \mathcal{C}$  and so  $u - \{(n^+, x)\} \subseteq u$  which is impossible. Similarly for  $y'$ .

$\langle 3 \rangle 6$ .  $x' = y'$

PROOF:  $\langle 3 \rangle 2$

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

□

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

PROOF: Easy induction on  $n$ . □

**Proposition 6.15.**  *$\omega$  is a transitive set.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $P(n)$  be the property  $\forall x \in n. x \in \omega$

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

PROOF: Vacuous.

$\langle 1 \rangle 3$ . For any natural number  $n$ , if  $P(n)$  then  $P(n^+)$ .

$\langle 2 \rangle 1$ . LET:  $n$  be a natural number.

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

$\langle 2 \rangle 3$ . LET:  $x \in n^+$

$\langle 2 \rangle 4$ .  $x \in n$  or  $x = n$

$\langle 2 \rangle 5$ . CASE:  $x \in n$

PROOF: Then  $x \in \omega$  by  $\langle 2 \rangle 2$ .

$\langle 2 \rangle 6$ . CASE:  $x = n$

PROOF: Then  $x \in \omega$  by  $\langle 2 \rangle 1$ .

□

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

PROOF:

⟨1⟩1. LET:  $P(n)$  be the property: for any nonempty subset  $E \subseteq n$ , there exists  $k \in E$  such that  $\forall m \in E. k = m \vee k \in m$

⟨1⟩2.  $P(0)$

PROOF: Vacuous as there is no nonempty subset of 0.

⟨1⟩3. For any natural number  $n$ , if  $P(n)$  then  $P(n^+)$ .

⟨2⟩1. LET:  $n$  be a natural number.

⟨2⟩2. ASSUME:  $P(n)$

⟨2⟩3. LET:  $E$  be a nonempty subset of  $n^+$

⟨2⟩4. CASE:  $E - \{n\} = \emptyset$

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

⟨2⟩5. CASE:  $E - \{n\} \neq \emptyset$

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

PROOF: By ⟨2⟩2.

⟨3⟩2.  $\forall m \in E. k = m \vee k \in m$

PROOF: Since  $k \in n$ .

□

## Chapter 7

# Ordinal Numbers

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

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

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

PROOF: Easy.  $\square$

**Proposition 7.3.**  $\omega$  is an ordinal.

PROOF: Easy.  $\square$

**Proposition 7.4.** If  $\alpha$  is an ordinal number then so is  $\alpha^+$ .

PROOF: Easy.  $\square$

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

PROOF: Easy.  $\square$

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

PROOF: Easy.  $\square$

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

PROOF: Easy.  $\square$

**Proposition 7.8.** Similar ordinals are equal.

PROOF:

$\langle 1 \rangle 1$ . LET:  $\alpha, \beta$  be ordinals.

$\langle 1 \rangle 2$ . LET:  $f : \alpha \cong \beta$  be a similarity.

PROVE:  $\forall \xi \in \alpha. f(\xi) = \xi$

$\langle 1 \rangle 3$ . LET:  $\xi \in \alpha$

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

**Proposition 7.9.** *Let  $\alpha$  and  $\beta$  be ordinals. Then the following are equivalent.*

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

PROOF:

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

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

PROOF:

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

□

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

PROOF:

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

□

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

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

PROOF: Proposition 5.37. □

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

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

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

PROOF:

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

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

## 7.1 Order on the Natural Numbers

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

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

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

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

PROOF:

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

□

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

PROOF:

⟨1⟩1. LET:  $P(n)$  be the property: for every proper subset  $X \subsetneq n$ , there exists  $m < n$  such that  $X \sim m$ .

⟨1⟩2.  $P(0)$

PROOF: Vacuous.

⟨1⟩3.  $\forall n \in \omega. P(n) \Rightarrow P(n+1)$

⟨2⟩1. LET:  $n \in \omega$

⟨2⟩2. ASSUME:  $P(n)$

⟨2⟩3. LET:  $X$  be a proper subset of  $n+1$

⟨2⟩4. CASE:  $X - \{n\} = n$

PROOF: Then  $X = n$  so  $X \sim n < n+1$ .

⟨2⟩5. CASE:  $X - \{n\} \subsetneq n$

⟨3⟩1. PICK  $m < n$  such that  $X - \{n\} \sim m$

⟨3⟩2.  $X \sim m$  or  $X \sim m+1$

PROOF: If  $n \in X$  then  $X \sim m+1$ . If  $n \notin X$  then  $X \sim m$ .

□

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

PROOF:

⟨1⟩1. LET:  $P(n)$  be the property: every one-to-one function  $n \rightarrow n$  is onto.

⟨1⟩2.  $P(0)$

PROOF: The only function  $0 \rightarrow 0$  is  $\emptyset$ .

⟨1⟩3.  $\forall n \in \omega. P(n) \Rightarrow P(n+1)$

⟨2⟩1. LET:  $n \in \omega$

⟨2⟩2. ASSUME:  $P(n)$

⟨2⟩3. ASSUME:  $f : n+1 \rightarrow n+1$  is one-to-one.

⟨2⟩4. LET:  $g : n \rightarrow n$  be the function

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

PROOF: If  $k < n$  and  $f(k) = n$  then  $f(n) < n$  since  $f$  is one-to-one.

⟨2⟩5.  $g$  is one-to-one.

⟨3⟩1. LET:  $k, l < n$

⟨3⟩2. ASSUME:  $g(k) = g(l)$

⟨3⟩3. CASE:  $f(k) < n$  and  $f(l) < n$

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

⟨3⟩4. CASE:  $f(k) < n$  and  $f(l) = n$   
PROOF: Then  $f(k) = g(k) = g(l) = f(n)$  contradicting the fact that  $f$  is one-to-one.

⟨3⟩5. CASE:  $f(k) = n$  and  $f(l) < n$   
PROOF: Similar.

⟨3⟩6. CASE:  $f(k) = n$  and  $f(l) = n$   
PROOF: Then  $k = l$  since  $f$  is one-to-one.

⟨2⟩6.  $g$  maps  $n$  onto  $n$ .  
PROOF: ⟨2⟩2

⟨2⟩7.  $f$  maps  $n + 1$  onto  $n + 1$ .  
⟨3⟩1. LET:  $l < n + 1$   
⟨3⟩2. CASE:  $l < n$   
⟨4⟩1. PICK  $k < n$  such that  $g(k) = l$   
⟨4⟩2.  $f(k) = l$  or  $f(n) = l$   
⟨3⟩3. CASE:  $l = n$   
⟨4⟩1. CASE:  $f(n) = n$   
PROOF: Then  $l \in \text{ran } f$  as required.  
⟨4⟩2. CASE:  $f(n) < n$   
⟨5⟩1. PICK  $k < n$  such that  $g(k) = f(n)$   
⟨5⟩2.  $f(k) = n$

□

**Corollary 7.19.1.** *Equivalent natural numbers are equal.*

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

PROOF: Easy. □

## 7.2 Finite Sets

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

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

PROOF: From Proposition 7.19. □

**Proposition 7.23.**  *$\omega$  is infinite.*

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

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

PROOF: Proposition 7.18. □

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



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

PROOF: Proposition 7.18.  $\square$

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

PROOF:

$\langle 1 \rangle 1$ . 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  $E \cup F \sim m + n$

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

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

$\langle 2 \rangle 2$ . LET:  $E \sim m$  and  $F \sim 0$

$\langle 2 \rangle 3$ .  $F = \emptyset$

$\langle 2 \rangle 4$ .  $E \cup F = E \sim m = m + 0$

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

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

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

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

$\langle 2 \rangle 4$ . LET:  $E \sim m$  and  $F \sim n + 1$

$\langle 2 \rangle 5$ . ASSUME:  $E \cap F = \emptyset$

$\langle 2 \rangle 6$ . PICK  $f \in F$

$\langle 2 \rangle 7$ .  $F - \{f\} \sim n$

$\langle 2 \rangle 8$ .  $E \cap (F - \{f\}) = \emptyset$

$\langle 2 \rangle 9$ .  $E \cup (F - \{f\}) \sim m + n$

PROOF:  $\langle 2 \rangle 2$

$\langle 2 \rangle 10$ .  $E \cup F \sim m + n + 1$

$\square$

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

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

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

PROOF:

$\langle 1 \rangle 1$ . LET:  $P(n)$  be the statement:  $n \in \omega$  and for all  $m \in \omega$ , if  $E \sim m$  and  $F \sim n$  then  $E \times F \sim mn$

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

PROOF: If  $F \sim 0$  then  $F = \emptyset$  so  $E \times F = \emptyset \sim 0$ .

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

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

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

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

$\langle 2 \rangle 4$ . ASSUME:  $E \sim m$  and  $F \sim n + 1$

$\langle 2 \rangle 5$ . PICK  $f \in F$

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

PROOF: Proposition 7.27.

□

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

PROOF:

- ⟨1⟩1. LET:  $P(n)$  be the property:  $n \in \omega$  and for all  $m \in \omega$ , if  $E \sim m$  and  $F \sim n$  then  $E^F \sim m^n$
- ⟨1⟩2.  $P(0)$   
PROOF: Since  $E^\emptyset = \{\emptyset\} \sim 1$
- ⟨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:  $\phi : E^F \rightarrow E^{F-\{f\}} \times E$  be the function  $\phi(g) = (g \upharpoonright (F - \{f\}), g(f))$
  - ⟨2⟩8.  $\phi$  is a one-to-one correspondence
  - ⟨2⟩9.  $\sharp(E^F) = m^{n+1}$

PROOF:

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

□

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

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

PROOF:

- ⟨1⟩1. LET:  $P(n)$  be the property: for any set  $E$ , if  $E \sim n$  and every element of  $E$  is finite, then  $\bigcup E$  is finite.
- ⟨1⟩2.  $P(0)$   
PROOF: Since  $\bigcup \emptyset = \emptyset$  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 7.27.1.

□

**Proposition 7.31.** *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.  $\forall n \geq 1. P(n) \Rightarrow P(n+1)$
- ⟨2⟩1. LET:  $n \geq 1$
- ⟨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  $E$ .

□

**Proposition 7.32.** *Every infinite set has a subset equivalent to  $\omega$ .*

PROOF:

- ⟨1⟩1. LET:  $X$  be an infinite set.
- ⟨1⟩2. PICK a choice function  $f$  for  $X$ .
- ⟨1⟩3. LET:  $\mathcal{C}$  be the set of all finite subsets of  $X$ .
- ⟨1⟩4. For all  $A \in \mathcal{C}$  we have  $X - A \in \text{dom } f$ .
- PROOF: For all  $A \in \mathcal{C}$  we have  $X - A \neq \emptyset$ .
- ⟨1⟩5. LET:  $U : \omega \rightarrow \mathcal{C}$  be the function defined recursively by  $U(0) = \emptyset$  and  $U(n+1) = U(n) \cup \{f(X - U(n))\}$  for all  $n \in \omega$ .
- ⟨1⟩6. LET:  $v : \omega \rightarrow X$  be the function  $v(n) = f(X - U(n))$
- PROVE:  $v$  is one-to-one.
- ⟨1⟩7.  $\forall n \in \omega. v(n) \notin U(n)$
- PROOF: Since  $v(n) = f(X - U(n)) \in X - U(n)$ .
- ⟨1⟩8.  $\forall n \in \omega. v(n) \in U(n+1)$
- ⟨1⟩9.  $\forall m, n \in \omega. n \leq m \Rightarrow U(n) \subseteq U(m)$
- PROOF: Since  $U(n) \subseteq U(n+1)$  for all  $n$ .
- ⟨1⟩10.  $\forall m, n \in \omega. n < m \Rightarrow v(n) \neq v(m)$
- PROOF: Since  $v(n) \in U(m)$  and  $v(m) \notin U(m)$ .

□

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

## 7.3 Ordinal Arithmetic

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

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

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

**Proposition 7.34.**

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

PROOF: Easy.  $\square$

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

PROOF: Easy.  $\square$

**Proposition 7.36.**

$$1 + \omega = \omega$$

PROOF: Easy.  $\square$

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

**Proposition 7.38.**

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

PROOF: Easy.  $\square$

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

PROOF: Easy.  $\square$

**Example 7.40.** The commutative law fails:

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

PROOF: Easy.  $\square$

**Example 7.41.** The right distributive law fails:

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

**Definition 7.42** (Exponentiation). Given ordinals  $\alpha$  and  $\beta$ , define the ordinal  $\alpha^\beta$  by

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

**Proposition 7.43.**

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

PROOF: Easy.  $\square$

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

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

## 7.4 Arithmetic on the Natural Numbers

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

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

PROOF:

$\langle 1 \rangle 1$ . 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:

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

□

**Proposition 7.46.** *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:

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

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

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

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

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

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

PROOF:  $\langle 1 \rangle 2$

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

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

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

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

PROOF:

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

□

## Chapter 8

# Countable Sets

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

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

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

PROOF: Easy.  $\square$

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

PROOF:

$\langle 1 \rangle 1$ . LET:  $f$  be a function from  $\omega$  onto  $X$ .

$\langle 1 \rangle 2$ . Choose a function  $g : X \rightarrow \omega$  such that, for all  $x \in X$ , we have  $f(g(x)) = x$ .

$\langle 1 \rangle 3$ .  $g$  is one-to-one.

$\square$

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

PROOF: The sequence

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

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

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

PROOF:

$\langle 1 \rangle 1$ . LET:  $A$  be a countable set of countable sets.

$\langle 1 \rangle 2$ . PICK a surjection  $f : \omega \rightarrow A$

$\langle 1 \rangle 3$ . For  $n \in \omega$ , PICK a surjection  $g_n : \omega \rightarrow f(n)$

$\langle 1 \rangle 4$ . PICK a surjection  $h : \omega \rightarrow \omega \times \omega$

$\langle 1 \rangle 5$ .  $\lambda n \in \omega. g_{\pi_1(h(n))}(\pi_2(h(n)))$  is a surjection  $\omega \rightarrow \bigcup A$

$\square$



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

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

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

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

PROOF: Cantor's Theorem.  $\square$

## Chapter 9

# Cardinal Numbers

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

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

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

PROOF: Easy.  $\square$

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

PROOF: Easy.  $\square$

**Proposition 9.5.** *Every natural number is a cardinal.  $\omega$  is a cardinal.*

PROOF: Easy.  $\square$

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

PROOF: For  $\alpha$  infinite we have  $f : \alpha^+ \sim \alpha$  where  $f(\alpha) = 0$  and  $f(\beta) = \beta^+$  for all other  $\beta$ .  $\square$

## 9.1 Cardinal Arithmetic

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

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

**Proposition 9.8.**

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

PROOF: Easy.  $\square$

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

PROOF: Easy induction.  $\square$

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

PROOF: Easy.  $\square$

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

PROOF:

$\langle 1 \rangle 1$ . LET:  $A$  be an infinite set.

PROVE:  $A \times 2 \sim A$

$\langle 1 \rangle 2$ . LET:  $\mathcal{F}$  be the set of all functions  $f$  such that there exists  $X \subseteq A$  such that  $f : X \times 2 \sim X$ .

$\langle 1 \rangle 3$ .  $\mathcal{F}$  is non-empty.

PROOF: Pick a subset  $X \subseteq A$  such that  $X \sim \omega$ , and a bijection  $X \times 2 \sim X$ .

$\langle 1 \rangle 4$ .  $\mathcal{F}$  is partially ordered by extension.

$\langle 1 \rangle 5$ . Every chain in  $\mathcal{F}$  has an upper bound.

PROOF: If  $\mathcal{C} \subseteq \mathcal{F}$  is a chain then  $\bigcup \mathcal{C} \in \mathcal{F}$ .

$\langle 1 \rangle 6$ . PICK  $f \in \mathcal{F}$  maximal.

$\langle 1 \rangle 7$ . PICK  $X \subseteq A$  such that  $f : X \times 2 \sim X$

$\langle 1 \rangle 8$ .  $X - A$  is finite.

$\langle 2 \rangle 1$ . ASSUME: for a contradiction  $X - A$  is infinite.

$\langle 2 \rangle 2$ . PICK  $Y \subseteq X - A$  such that  $Y \sim \omega$ .

$\langle 2 \rangle 3$ . PICK  $g : Y \times 2 \sim Y$

$\langle 2 \rangle 4$ .  $f \cup g : (X \cup Y) \times 2 \sim X \cup Y$

$\langle 2 \rangle 5$ . Q.E.D.

PROOF: This contradicts the maximality of  $f$ .

$\langle 1 \rangle 9$ .  $\text{card } A + \text{card } A = \text{card } A$

PROOF:

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

$\square$

**Corollary 9.11.1.** *For any cardinals  $\kappa$  and  $\lambda$  that are not both finite, we have*

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

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

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

**Proposition 9.13.**

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

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

PROOF: Easy induction.  $\square$

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

PROOF: Easy.  $\square$

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

PROOF:

$\langle 1 \rangle 1$ . Choose a one-to-one function  $f_i : \kappa_i \rightarrow \lambda_i$  for each  $i \in I$

$\langle 1 \rangle 2$ .  $\sum_{i \in I} \kappa_i \leq \prod_{i \in I} \lambda_i$

PROOF: Define  $g : \sum_{i \in I} \kappa_i \rightarrow \prod_{i \in I} \lambda_i$  by

$$g(i, \eta)(j) = \begin{cases} f_i(\eta) & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases}$$

$\langle 1 \rangle 3$ . There is no surjective function  $\sum_{i \in I} \kappa_i \rightarrow \prod_{i \in I} \lambda_i$

$\langle 2 \rangle 1$ . LET:  $h : \sum_i \kappa_i \rightarrow \prod_i \lambda_i$

$\langle 2 \rangle 2$ . Choose  $t(i) < \lambda_i$  for each  $i \in I$  such that, for all  $\eta < \kappa_i$ , we have  $t(i) \neq h(i, \eta)(i)$ .

PROOF: Since the function that maps  $\eta$  to  $h(i, \eta)(i)$  cannot be surjective  $\kappa_i \rightarrow \lambda_i$ .

$\langle 2 \rangle 3$ . For all  $i \in I$  and  $\eta < \kappa_i$  we have  $h \neq t(i, \eta)$ .

$\square$

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

PROOF:

$\langle 1 \rangle 1$ . LET:  $A$  be an infinite set.

$\langle 1 \rangle 2$ . LET:  $\mathcal{F}$  be the set of all functions  $f$  such that there exists  $X \subseteq A$  such that  $f : X \times X \sim X$

$\langle 1 \rangle 3$ .  $\mathcal{F}$  is nonempty.

PROOF: Pick a countably infinite  $X \subseteq A$ . Then  $X \times X \sim X$ .

$\langle 1 \rangle 4$ .  $\mathcal{F}$  is partially ordered by extension.

$\langle 1 \rangle 5$ . Every chain in  $\mathcal{F}$  has an upper bound.

$\langle 1 \rangle 6$ . PICK  $f \in \mathcal{F}$  maximal.

$\langle 1 \rangle 7$ . PICK  $X \subseteq A$  such that  $f : X \times X \sim X$ .

$\langle 1 \rangle 8$ .  $\text{card } X = \text{card } A$

$\langle 2 \rangle 1$ . ASSUME: for a contradiction  $\text{card } X < \text{card } A$

$\langle 2 \rangle 2$ .  $\text{card } A = \text{card}(A - X)$

PROOF: Corollary 9.11.1.

$\langle 2 \rangle 3$ .  $\text{card } X < \text{card}(A - X)$

$\langle 2 \rangle 4$ . PICK  $Y \subseteq A - X$  such that  $Y \sim X$

$\langle 2 \rangle 5$ . PICK  $g : (X \times Y) \cup (Y \times X) \cup (Y \times Y) \sim Y$

PROOF:

$$(X \times Y) \cup (Y \times X) \cup (Y \times Y) \sim 3 \times X \times X \quad (\langle 2 \rangle 4)$$

$$\sim 3 \times X \quad (\langle 1 \rangle 7)$$

$$\sim X \quad (\text{Corollary 9.11.1})$$

$$\sim Y \quad (\langle 2 \rangle 4)$$

$\langle 2 \rangle 6$ .  $f \cup g : (X \cup Y) \times (X \cup Y) \sim X \cup Y$

$\langle 2 \rangle 7$ . Q.E.D.

PROOF: This contradicts the maximality of  $f$ .

□

**Corollary 9.17.1.** *If  $\kappa$  and  $\lambda$  are non-zero cardinals that are not both finite, then*

$$\kappa\lambda = \max(\kappa, \lambda) \text{ .}$$

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

**Proposition 9.19.**

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

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

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

PROOF: Easy. □

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

PROOF: Easy. □

**Proposition 9.21.**

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

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

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

PROOF: Proposition 9.16. □

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

PROOF: Easy. □

## 9.2 Alephs

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

**Proposition 9.25.**

$$\aleph_0 = \omega$$

PROOF: Easy.  $\square$

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

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

## Chapter 10

# Field Theory

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

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

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

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

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

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

# Chapter 11

## Real Numbers

### 11.1 Axioms for Real Numbers

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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



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

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

**Axiom 11.11** (Distributive Law).

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

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

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

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

## 11.2 Consequences of the Axioms

### 11.2.1 Negation

**Theorem 11.15.** *For any real numbers  $x$  and  $y$ , if  $x + y = x$  then  $y = 0$ .*

PROOF:

$\langle 1 \rangle 1.$  LET:  $x, y \in \mathbb{R}$

$\langle 1 \rangle 2.$  ASSUME:  $x + y = x$

$\langle 1 \rangle 3.$   $y = 0$

PROOF:

$$\begin{aligned} y &= y + 0 && \text{(Definition of zero)} \\ &= y + (x + (-x)) && \text{(Definition of } -x) \\ &= (y + x) + (-x) && \text{(Associativity of Addition)} \\ &= (x + y) + (-x) && \text{(Commutativity of Addition)} \\ &= x + (-x) && (\langle 1 \rangle 2) \\ &= 0 && \text{(Definition of } -x) \end{aligned}$$

□

**Theorem 11.16.**

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

PROOF:

$\langle 1 \rangle 1.$  LET:  $x \in \mathbb{R}$

$\langle 1 \rangle 2.$   $xx + 0x = xx$

PROOF:

$$\begin{aligned} xx + 0x &= (x + 0)x && \text{(Distributive Law)} \\ &= xx && \text{(Definition of 0)} \end{aligned}$$

$\langle 1 \rangle 3. 0x = 0$

PROOF: Theorem 11.15,  $\langle 1 \rangle 2.$

□

**Theorem 11.17.**

$$-0 = 0$$

PROOF: Since  $0 + 0 = 0$ . □

**Theorem 11.18.**

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

PROOF: Since  $-x + x = 0$ . □

**Theorem 11.19.**

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

PROOF:

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

**Theorem 11.20.**

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

PROOF:

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

## 11.2.2 Subtraction

**Theorem 11.21.**

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

PROOF:

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

**Theorem 11.22.**

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

PROOF:

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

**Theorem 11.23.**

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

PROOF:

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

**Definition 11.24** (Reciprocal). Given  $x \in \mathbb{R}$  with  $x \neq 0$ , the *reciprocal* of  $x$ ,  $1/x$ , is the unique real number such that  $x \cdot 1/x = 1$ .

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

PROOF:

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

PROOF:

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

$\square$

**Definition 11.26** (Quotient). Given real numbers  $x$  and  $y$  with  $y \neq 0$ , the *quotient*  $x/y$  is defined by

$$x/y = x \cdot 1/y .$$

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

PROOF: Immediate from definitions.  $\square$

**Theorem 11.28.**

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

PROOF:

- $\langle 1 \rangle 1$ . LET:  $x \in \mathbb{R}$
- $\langle 1 \rangle 2$ .  $1/1 = 1$

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

- $\langle 1 \rangle 3$ .  $x/1 = x$

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

$\square$

**Theorem 11.29.** For any real numbers  $x$  and  $y$ , if  $x \neq 0$  and  $y \neq 0$  then  $xy \neq 0$ .

PROOF:

$\langle 1 \rangle 1$ . LET:  $x, y \in \mathbb{R}$

$\langle 1 \rangle 2$ . ASSUME:  $xy = 0$  and  $x \neq 0$

PROVE:  $y = 0$

$\langle 1 \rangle 3$ .  $y = 0$

PROOF:

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

□

**Theorem 11.30.** For any real numbers  $y$  and  $z$ , if  $y \neq 0$  and  $z \neq 0$  then  $(1/y)(1/z) = 1/(yz)$ .

PROOF: Since  $yz(1/y)(1/z) = 1 \cdot 1 = 1$ . □

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

**Theorem 11.31.** For any real numbers  $x, y, z, w$  with  $y \neq 0 \neq w$ , we have

$$\frac{x}{y} + \frac{z}{w} = \frac{xw + yz}{yw}$$

PROOF:

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

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

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

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

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

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

PROOF: Since  $ya(x/y) = ax$ . □

**Theorem 11.35.** For any real numbers  $x$  and  $y$ , if  $y \neq 0$  then  $(-x)/y = x/(-y) = -(x/y)$ .

PROOF:

⟨1⟩1.  $(-x)/y = -(x/y)$

PROOF: Take  $a = -1$  in Theorem 11.34.

⟨1⟩2.  $x/(-y) = -(x/y)$

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

□

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

PROOF: We have  $y + z < x + z < x + w$  by Monotonicity of Addition twice. □

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

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

PROOF:

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

**Theorem 11.38.** *For any real number  $x$ , we have  $x > 0$  iff  $-x < 0$ .*

PROOF:

⟨1⟩1. If  $0 < x$  then  $-x < 0$

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

⟨1⟩2. If  $-x < 0$  then  $0 < x$

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

□

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

PROOF:

⟨1⟩1. If  $y < x$  then  $-x < -y$ .

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

⟨1⟩2. If  $-x < -y$  then  $y < x$ .

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

□

**Theorem 11.40.** *For any real numbers  $x, y$  and  $z$ , if  $x > y$  and  $z < 0$  then  $xz < yz$ .*

PROOF:

⟨1⟩1. LET:  $x, y$  and  $z$  be real numbers.

⟨1⟩2. ASSUME:  $x > y$

⟨1⟩3. ASSUME:  $z < 0$

⟨1⟩4.  $-z > 0$

PROOF: Theorem 11.38, ⟨1⟩3.

⟨1⟩5.  $x(-z) > y(-z)$

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

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

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

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

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

□

**Theorem 11.41.** *For any real number  $x$ , if  $x \neq 0$  then  $xx > 0$ .*

PROOF:

$\langle 1 \rangle 1$ . If  $x > 0$  then  $xx > 0$

PROOF: By Monotonicity of Multiplication.

$\langle 1 \rangle 2$ . If  $x < 0$  then  $xx > 0$

PROOF: Theorem 11.40.

□

**Theorem 11.42.**

$$0 < 1$$

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

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

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

**Theorem 11.44.** *For any real numbers  $x$  and  $y$ , we have  $xy$  is positive if and only if  $x$  and  $y$  are both positive or both negative.*

PROOF: By the Monotonicity of Multiplication and Theorem 11.40. □

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

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

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

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

**Theorem 11.46.** *For any real numbers  $x$  and  $y$ , if  $x < y$  then  $x < (x+y)/2 < y$ .*

PROOF: We have  $2x < x+y$  and  $x+y < 2y$  by Monotonicity of Addition, hence  $x < (x+y)/2 < y$  by Monotonicity of Multiplication since  $1/2 > 0$ . □

**Corollary 11.46.1.**  $\mathbb{R}$  is a linear continuum.

**Definition 11.47** (Negative). A real number  $x$  is *negative* iff  $x < 0$ .

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

**Theorem 11.48.** *For every positive real number  $a$ , there exists a unique positive real  $\sqrt{a}$  such that  $\sqrt{a}^2 = a$ .*

PROOF:

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

⟨1⟩2. For any real numbers  $x$  and  $h$ , if  $0 \leq h < 1$ , then  

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

⟨2⟩1. LET:  $x$  and  $h$  be real numbers.

⟨2⟩2. ASSUME:  $0 \leq h < 1$

⟨2⟩3.  $(x+h)^2 < x^2 + h(2x+1)$

PROOF:

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

⟨1⟩3. For any real numbers  $x$  and  $h$ , if  $h > 0$  then

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

⟨2⟩1. LET:  $x$  and  $h$  be real numbers.

⟨2⟩2. ASSUME:  $h > 0$

⟨2⟩3.  $(x-h)^2 > x^2 - 2hx$

PROOF:

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

⟨1⟩4. For any positive real  $x$ , if  $x^2 < a$  then there exists  $h > 0$  such that  
 $(x+h)^2 < a.$

⟨2⟩1. LET:  $x$  be a positive real.

⟨2⟩2. ASSUME:  $x^2 < a$

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

⟨2⟩4.  $0 < h < 1$

⟨2⟩5.  $(x+h)^2 < a$

PROOF:

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

⟨1⟩5. For any positive real  $x$ , if  $x^2 > a$  then there exists  $h > 0$  such that  
 $(x-h)^2 > a.$

⟨2⟩1. LET:  $x$  be a positive real.

⟨2⟩2. ASSUME:  $x^2 > a$

⟨2⟩3. LET:  $h = (x^2 - a)/2x$

⟨2⟩4.  $h > 0$

⟨2⟩5.  $(x-h)^2 > a$

PROOF:

$$\begin{aligned} (x-h)^2 &> x^2 - 2hx \\ &= a & (\langle 2 \rangle 3) \end{aligned}$$

⟨1⟩6. LET:  $B = \{x \in \mathbb{R} : x^2 < a\}$

⟨1⟩7.  $B$  is bounded above.

PROOF: If  $a \geq 1$  then  $a$  is an upper bound. If  $a < 1$  then 1 is an upper bound.

⟨1⟩8.  $B$  contains at least one positive real.

PROOF: If  $a \geq 1$  then  $1 \in B$ . If  $a < 1$  then  $a \in B$ .

⟨1⟩9. LET:  $b = \sup B$

⟨1⟩10.  $b^2 = a$

$\langle 2 \rangle 1. b^2 \geq a$   
 $\langle 3 \rangle 1.$  ASSUME: for a contradiction  $b^2 < a$   
 $\langle 3 \rangle 2.$  PICK  $h > 0$  such that  $(b + h)^2 < a$   
PROOF:  $\langle 1 \rangle 4$   
 $\langle 3 \rangle 3. b + h \in B$   
 $\langle 3 \rangle 4.$  Q.E.D.  
PROOF: This contradicts  $\langle 1 \rangle 9$ .  
 $\langle 2 \rangle 2. b^2 \leq a$   
 $\langle 3 \rangle 1.$  ASSUME: for a contradiction  $b^2 > a$   
 $\langle 3 \rangle 2.$  PICK  $h > 0$  such that  $(b - h)^2 > a$   
PROOF:  $\langle 1 \rangle 5$   
 $\langle 3 \rangle 3.$  PICK  $x \in B$  such that  $b - h < x$   
PROOF:  $\langle 1 \rangle 9$   
 $\langle 3 \rangle 4. (b - h)^2 < x^2 < a$   
 $\langle 3 \rangle 5.$  Q.E.D.  
PROOF: This contradicts  $\langle 3 \rangle 2$   
 $\langle 1 \rangle 11.$  For any positive reals  $b$  and  $c$ , if  $b^2 = c^2$  then  $b = c$ .  
 $\langle 2 \rangle 1.$  LET:  $b$  and  $c$  be positive reals.  
 $\langle 2 \rangle 2.$  ASSUME:  $b^2 = c^2$   
 $\langle 2 \rangle 3. b^2 - c^2 = 0$   
 $\langle 2 \rangle 4. (b - c)(b + c) = 0$   
 $\langle 2 \rangle 5. b - c = 0$  or  $b + c = 0$   
 $\langle 2 \rangle 6. b + c \neq 0$   
PROOF: Since  $b + c > 0$   
 $\langle 2 \rangle 7. b - c = 0$   
 $\langle 2 \rangle 8. b = c$

□



## Chapter 12

# Integers and Rationals

### 12.1 Positive Integers

**Definition 12.1** (Inductive). A set of real numbers  $A$  is *inductive* iff  $1 \in A$  and  $\forall x \in A. x + 1 \in A$ .

**Definition 12.2** (Positive Integer). The set  $\mathbb{Z}_+$  of *positive integers* is the intersection of the set of inductive sets.

**Proposition 12.3.** *Every positive integer is positive.*

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

**Proposition 12.4.** *1 is the least element of  $\mathbb{Z}_+$ .*

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

**Proposition 12.5.**  *$\mathbb{Z}_+$  is inductive.*

PROOF: 1 is an element of every inductive set, and for all  $x \in \mathbb{R}$ , if  $x$  is an element of every inductive set then so is  $x + 1$ .  $\square$

**Theorem 12.6** (Principle of Induction). *If  $A$  is an inductive set of positive integers then  $A = \mathbb{Z}_+$ .*

PROOF: Immediate from definitions.  $\square$

**Theorem 12.7** (Well-Ordering Property).  *$\mathbb{Z}_+$  is well ordered.*

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

**Theorem 12.8** (Archimedean Ordering Property). *The set  $\mathbb{Z}_+$  is unbounded above.*

PROOF:

$\langle 1 \rangle 1$ . ASSUME: for a contradiction  $\mathbb{Z}_+$  is bounded above.

$\langle 1 \rangle 2$ . LET:  
 $s = \sup \mathbb{Z}_+$   
 $\langle 1 \rangle 3$ . PICK  $n \in \mathbb{Z}_+$  such that  $s - 1 < n$   
 $\langle 1 \rangle 4$ .  $s < n + 1$   
 $\langle 1 \rangle 5$ . Q.E.D.  
 PROOF:  $\langle 1 \rangle 2$  and  $\langle 1 \rangle 4$  form a contradiction.  
 $\square$

### 12.1.1 Exponentiation

**Definition 12.9.** For  $a$  a real number and  $n$  a positive integer, define the real number  $a^n$  recursively as follows:

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

**Theorem 12.10.** For all  $a \in \mathbb{R}$  and  $m, n \in \mathbb{Z}_+$ , we have

$$a^n a^m = a^{n+m}$$

PROOF:  
 $\langle 1 \rangle 1$ . LET:  $P(m)$  be the property  $\forall a \in \mathbb{R}. \forall n \in \mathbb{Z}_+. a^n a^m = a^{n+m}$   
 $\langle 1 \rangle 2$ .  $P(1)$   
 PROOF:  $a^n a^1 = a^n a = a^{n+1}$ .  
 $\langle 1 \rangle 3$ .  $\forall m \in \mathbb{Z}_+. P(m) \Rightarrow P(m+1)$   
 $\langle 2 \rangle 1$ . LET:  $m$  be a positive integer.  
 $\langle 2 \rangle 2$ . ASSUME:  $P(m)$   
 $\langle 2 \rangle 3$ . LET:  $a \in \mathbb{R}$   
 $\langle 2 \rangle 4$ . LET:  $n \in \mathbb{Z}_+$   
 $\langle 2 \rangle 5$ .  $a^n a^{m+1} = a^{n+m+1}$   
 PROOF:  

$$\begin{aligned}
 a^n a^{m+1} &= a^n a^m a \\
 &= a^{n+m} a && (\langle 2 \rangle 2) \\
 &= a^{n+m+1}
 \end{aligned}$$
 $\langle 1 \rangle 4$ . Q.E.D.  
 PROOF: By induction.  
 $\square$

**Theorem 12.11.** For all  $a \in \mathbb{R}$  and  $m, n \in \mathbb{Z}_+$ ,

$$(a^n)^m = a^{nm}.$$

PROOF:  
 $\langle 1 \rangle 1$ . LET:  $P(m)$  be the property  $\forall a \in \mathbb{R}. \forall n \in \mathbb{Z}_+. (a^n)^m = a^{nm}$ .  
 $\langle 1 \rangle 2$ .  $P(1)$   
 PROOF:  $(a^n)^1 = a^n = a^{n \cdot 1}$

⟨1⟩3.  $\forall m \in \mathbb{Z}_+. P(m) \Rightarrow P(m+1)$

PROOF:

$$\begin{aligned} (a^n)^{m+1} &= (a^n)^m a^n \\ &= a^{nm} a^n \\ &= a^{nm+n} && \text{(Theorem 12.10)} \\ &= a^{n(m+1)} \end{aligned}$$

□

**Theorem 12.12.** *For any real numbers  $a$  and  $b$  and positive integer  $m$ ,*

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

PROOF: Induction on  $m$ . □

## 12.2 Integers

**Definition 12.13** (Integer). The set  $\mathbb{Z}$  of *integers* is

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

**Proposition 12.14.** *The sum, difference and product of two integers is an integer.*

PROOF: Easy. □

**Example 12.15.**  $1/2$  is not an integer.

**Proposition 12.16.** *For any integer  $n$ , there is no integer  $a$  such that  $n < a < n+1$ .*

PROOF:

⟨1⟩1. For any positive integer  $n$ , there is no integer  $a$  such that  $n < a < n+1$ .

⟨2⟩1. There is no integer  $a$  such that  $1 < a < 2$ .

⟨3⟩1. There is no positive integer  $a$  such that  $1 < a < 2$ .

⟨4⟩1. We do not have  $1 < 1 < 2$ .

⟨4⟩2. For any positive integer  $n$ , we do not have  $1 < n+1 < 2$ .

PROOF: Since  $n \geq 1$  so  $n+1 \geq 2$ .

⟨3⟩2. We do not have  $1 < 0 < 2$ .

⟨3⟩3. For any positive integer  $a$ , we do not have  $1 < -a < 2$ .

PROOF: Since  $-a < 0 < 1$ .

⟨2⟩2. For any positive integer  $n$ , if there is no integer  $a$  such that  $n < a < n+1$ , then there is no integer  $a$  such that  $n+1 < a < n+2$ .

PROOF: If  $n+1 < a < n+2$  then  $n < a-1 < n+1$ .

⟨1⟩2. There is no integer  $a$  such that  $0 < a < 1$ .

PROOF: If  $0 < a < 1$  then  $1 < a+1 < 2$ .

⟨1⟩3. For any positive integer  $n$ , there is no integer  $a$  such that  $-n < a < -n+1$ .

PROOF: If  $-n < a < -n+1$  then  $n-1 < -a < n$ .

□

**Theorem 12.17.** *Every nonempty subset of  $\mathbb{Z}$  bounded above has a largest element.*

PROOF:

⟨1⟩1. LET:  $S$  be a nonempty subset of  $\mathbb{Z}$  bounded above.

⟨1⟩2. LET:  $u$  be an upper bound for  $S$ .

⟨1⟩3. PICK an integer  $n > u$

PROOF: Archimedean property.

⟨1⟩4. LET:  $k$  be the least positive integer such that  $n - k \in S$ .

⟨2⟩1. PICK  $m \in S$

⟨2⟩2.  $n - m$  is a positive integer.

⟨2⟩3. There exists a positive integer  $k$  such that  $n - k \in S$ .

⟨1⟩5.  $n - k$  is the greatest element in  $S$ .

⟨2⟩1. LET:  $m \in S$

⟨2⟩2.  $n - m \geq k$

⟨2⟩3.  $m \leq n - k$

□

**Theorem 12.18.** *For any real number  $x$ , if  $x$  is not an integer then there exists a unique integer  $n$  such that  $n < x < n + 1$ .*

PROOF:

⟨1⟩1.  $\{n \in \mathbb{Z} : n < x\}$  is a nonempty set of integers bounded above.

⟨2⟩1. PICK  $m > -x$

PROOF: Archimedean property.

⟨2⟩2.  $-m < x$

⟨2⟩3.  $\{n \in \mathbb{Z} : n < x\}$  is nonempty.

⟨1⟩2. LET:  $n$  be the greatest integer such that  $n < x$

⟨1⟩3.  $x < n + 1$

⟨1⟩4. If  $n'$  is an integer with  $n' < x < n' + 1$  then  $n' = n$ .

PROOF: We have  $n' < n + 1$  so  $n' \leq n$ , and  $n < n' + 1$  so  $n \leq n'$ .

□

**Definition 12.19** (Even). An integer  $n$  is *even* iff  $n/2$  is an integer; otherwise,  $n$  is *odd*.

**Theorem 12.20.** *If the integer  $m$  is odd then there exists an integer  $n$  such that  $m = 2n + 1$ .*

PROOF:

⟨1⟩1. LET:  $n$  be the integer such that  $n < m/2 < n + 1$

PROOF: Theorem 12.18.

⟨1⟩2.  $2n < m < 2n + 2$

⟨1⟩3.  $m = 2n + 1$

□

**Theorem 12.21.** *The product of two odd integers is odd.*

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

**Corollary 12.21.1.** *If  $p$  is an odd integer and  $n$  is a positive integer then  $p^n$  is an odd integer.*

**Definition 12.22** (Exponentiation). Extend the definition of exponentiation so  $a^n$  is defined for:

- all real numbers  $a$  and non-negative integers  $n$
- all non-zero real numbers  $a$  and integers  $n$

as follows:

$$\begin{aligned} a^0 &= 1 \\ a^{-n} &= 1/a^n \end{aligned} \quad (n \text{ a positive integer})$$

**Theorem 12.23** (Laws of Exponents). *For all non-zero reals  $a$  and  $b$  and integers  $m$  and  $n$ ,*

$$\begin{aligned} a^n a^m &= a^{n+m} \\ (a^n)^m &= a^{nm} \\ a^m b^m &= (ab)^m \end{aligned}$$

PROOF: Easy.  $\square$

## 12.3 Rational Numbers

**Definition 12.24** (Rational Number). The set  $\mathbb{Q}$  of *rational numbers* is the set of all real numbers that are the quotient of two integers. A real that is not rational is *irrational*.

**Theorem 12.25.**  $\sqrt{2}$  is irrational.

PROOF:

$\langle 1 \rangle 1$ . For any positive rational  $a$ , there exist positive integers  $m$  and  $n$  not both even such that  $a = m/n$ .

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

$\langle 2 \rangle 2$ . LET:  $n$  be the least positive integer such that  $na$  is a positive integer.

$\langle 2 \rangle 3$ . LET:  $m = na$

$\langle 2 \rangle 4$ . ASSUME: for a contradiction  $m$  and  $n$  are both even.

$\langle 2 \rangle 5$ .  $m/2 = (n/2)a$

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

PROOF: This contradicts the leastness of  $n$  ( $\langle 2 \rangle 2$ ).

$\langle 1 \rangle 2$ . ASSUME: for a contradiction  $\sqrt{2}$  is rational.

$\langle 1 \rangle 3$ . PICK positive integers  $m$  and  $n$  not both even such that  $\sqrt{2} = m/n$ .

$\langle 1 \rangle 4$ .  $m^2 = 2n^2$

$\langle 1 \rangle 5$ .  $m^2$  is even.

$\langle 1 \rangle 6$ .  $m$  is even.

PROOF: Theorem 12.21.

$\langle 1 \rangle 7$ . LET:  $k = m/2$

$\langle 1 \rangle 8$ .  $4k^2 = 2n^2$

$\langle 1 \rangle 9$ .  $n^2 = 2k^2$

$\langle 1 \rangle 10$ .  $n^2$  is even.

$\langle 1 \rangle 11$ .  $n$  is even.

PROOF: Theorem 12.21.

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

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

□