

Solutions Manual for Enderton *Elements of Set
Theory*

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Chapter 1

Chapter 1 — Introduction

1.1 Baby Set Theory

Exercise 1

- $\{\emptyset\} \in \{\emptyset, \{\emptyset\}\}$ — true
- $\{\emptyset\} \subseteq \{\emptyset, \{\emptyset\}\}$ — true
- $\{\emptyset\} \in \{\emptyset, \{\{\emptyset\}\}\}$ — false
- $\{\emptyset\} \subseteq \{\emptyset, \{\{\emptyset\}\}\}$ — true
- $\{\{\emptyset\}\} \in \{\emptyset, \{\emptyset\}\}$ — false
- $\{\{\emptyset\}\} \subseteq \{\emptyset, \{\emptyset\}\}$ — true
- $\{\{\emptyset\}\} \in \{\emptyset, \{\{\emptyset\}\}\}$ — true
- $\{\{\emptyset\}\} \subseteq \{\emptyset, \{\{\emptyset\}\}\}$ — false
- $\{\{\emptyset\}\} \in \{\emptyset, \{\emptyset, \{\emptyset\}\}\}$ — false
- $\{\{\emptyset\}\} \subseteq \{\emptyset, \{\emptyset, \{\emptyset\}\}\}$ — false

Exercise 2 We have $\emptyset \neq \{\emptyset\}$ because $\{\emptyset\}$ has an element (namely \emptyset) while \emptyset has no elements.

We have $\emptyset \neq \{\{\emptyset\}\}$ because $\{\{\emptyset\}\}$ has an element (namely $\{\emptyset\}$) while \emptyset has no elements.

We have $\{\emptyset\} \neq \{\{\emptyset\}\}$ because $\emptyset \in \{\emptyset\}$ but $\emptyset \notin \{\{\emptyset\}\}$. This last fact is true because $\emptyset \neq \{\emptyset\}$ as we proved in the first paragraph.

Exercise 3 Assume $B \subseteq C$. Let $A \in \mathcal{P}B$; we must show that $A \in \mathcal{P}C$.

We have $A \subseteq B$ (since $A \in \mathcal{P}B$) and $B \subseteq C$. From this it follows that $A \subseteq C$ (every element of A is an element of B ; every element of B is an element of C ; therefore every element of A is an element of C). Hence $A \in \mathcal{P}C$ as required.

Exercise 4 Since $x \in B$, we have $\{x\} \subseteq B$ and so $\{x\} \in \mathcal{P}B$.

Since $x \in B$ and $y \in B$, we have $\{x, y\} \subseteq B$ and so $\{x, y\} \in \mathcal{P}B$.

From these two facts, it follows that $\{\{x\}, \{x, y\}\} \subseteq \mathcal{P}B$ and so $\{\{x\}, \{x, y\}\} \in \mathcal{P}\mathcal{P}B$.

1.2 Sets — An Informal View

Exercise 5 We have

$$\begin{aligned} V_0 &= A \\ V_1 &= V_0 \cup \mathcal{P}V_0 \\ &= A \cup \mathcal{P}A \\ V_2 &= V_1 \cup \mathcal{P}V_1 \\ &= \{\emptyset, \{\emptyset\}\} \\ V_3 &= \mathcal{P}V_2 \\ &= \{\emptyset, \{\emptyset\}, \{\{\emptyset\}\}, \{\emptyset, \{\emptyset\}\}\} \end{aligned}$$

We have $\emptyset \subseteq V_0$ and so $\emptyset \in V_1$. Therefore $\{\emptyset\} \subseteq V_1$ and so $\{\emptyset\} \in V_2$. Hence $\{\{\emptyset\}\} \subseteq V_2$.

We also have $\{\{\emptyset\}\} \not\subseteq V_0$ because $\{\emptyset\}$ is not an atom, and $\{\{\emptyset\}\} \not\subseteq V_1$ since $\{\emptyset\} \notin V_1$ because \emptyset is not an atom.

Thus the rank of $\{\{\emptyset\}\}$ is 2.

Likewise we have \emptyset and $\{\emptyset\}$ are both subsets of V_1 , hence

$$\emptyset \in V_2, \quad \{\emptyset\} \in V_2$$

Thus $\emptyset, \{\emptyset\}, \{\emptyset, \{\emptyset\}\}$ are all subsets of V_2 , hence elements of V_3 . Therefore,

$$\{\emptyset, \{\emptyset\}, \{\emptyset, \{\emptyset\}\}\} \subseteq V_3$$

Now, $\{\emptyset, \{\emptyset\}, \{\emptyset, \{\emptyset\}\}\}$ is not a subset of V_0 (because \emptyset is not an atom.) It is not a subset of V_1 ($\{\emptyset\} \notin V_1$ because \emptyset is not an atom.) It is not a subset of V_2 (we have $\{\emptyset, \{\emptyset\}\} \notin V_2$ since $\{\emptyset\} \notin V_1$).

Therefore the rank of $\{\emptyset, \{\emptyset\}, \{\emptyset, \{\emptyset\}\}\}$ is 3.

Exercise 6

$$\begin{aligned}
V_1 &= V_0 \cup \mathcal{P}V_0 \\
&= A \cup \mathcal{P}V_0 && (\text{since } V_0 = A) \\
V_2 &= V_1 \cup \mathcal{P}V_1 \\
&= A \cup \mathcal{P}V_0 \cup \mathcal{P}V_1 \\
&= A \cup \mathcal{P}V_1 && (\text{since } \mathcal{P}V_0 \subseteq \mathcal{P}V_1 \text{ by Exercise 3}) \\
V_3 &= V_2 \cup \mathcal{P}V_2 \\
&= A \cup \mathcal{P}V_1 \cup \mathcal{P}V_2 \\
&= A \cup \mathcal{P}V_2 && (\text{since } \mathcal{P}V_1 \subseteq \mathcal{P}V_2 \text{ by Exercise 3}) \\
V_4 &= V_3 \cup \mathcal{P}V_3 \\
&= A \cup \mathcal{P}V_2 \cup \mathcal{P}V_3 \\
&= A \cup \mathcal{P}V_3 && (\text{since } \mathcal{P}V_2 \subseteq \mathcal{P}V_3 \text{ by Exercise 3})
\end{aligned}$$

Exercise 7 In Exercise 5 we calculated $V_3 = \{\emptyset, \{\emptyset\}, \{\{\emptyset\}\}, \{\emptyset, \{\emptyset\}\}\}$
Hence

$$\begin{aligned}
V_4 &= \mathcal{P}V_3 \\
&= \{\emptyset, \\
&\quad \{\emptyset\}, \\
&\quad \{\{\emptyset\}\}, \\
&\quad \{\{\{\emptyset\}\}\}, \\
&\quad \{\{\emptyset, \{\emptyset\}\}\}, \\
&\quad \{\emptyset, \{\emptyset\}\}, \\
&\quad \{\emptyset, \{\{\emptyset\}\}\}, \\
&\quad \{\emptyset, \{\emptyset, \{\emptyset\}\}\}, \\
&\quad \{\{\emptyset\}, \{\{\emptyset\}\}\}, \\
&\quad \{\{\emptyset\}, \{\emptyset, \{\emptyset\}\}\}, \\
&\quad \{\{\{\emptyset\}\}, \{\emptyset, \{\emptyset\}\}\}, \\
&\quad \{\emptyset, \{\emptyset\}, \{\{\emptyset\}\}\}, \\
&\quad \{\emptyset, \{\emptyset\}, \{\emptyset, \{\emptyset\}\}\}, \\
&\quad \{\emptyset, \{\{\emptyset\}\}, \{\emptyset, \{\emptyset\}\}\}, \\
&\quad \{\{\emptyset\}, \{\{\emptyset\}\}, \{\emptyset, \{\emptyset\}\}\}, \\
&\quad \{\emptyset, \{\emptyset\}, \{\{\emptyset\}\}, \{\emptyset, \{\emptyset\}\}\} \\
&\quad \}
\end{aligned}$$

Chapter 2

Chapter 2 — Axioms and Operations

2.1 Arbitrary Unions and Intersections

Exercise 1 $A \cap B \cap C$ is the set of all integers that are divisible by 4, 9 and 10, which is the same as the set of all integers that are divisible by 180.

Exercise 2 Take $A = \emptyset$ and $B = \{\emptyset\}$. Then $\bigcup A = \bigcup B = \emptyset$ but $A \neq B$. (There are many other possible answers.)

Exercise 3 Let $b \in A$. We must show that $b \subseteq \bigcup A$.

Let x be any element of b . We must show that $x \in \bigcup A$. We know that $x \in b$ and $b \in A$, and so $x \in \bigcup A$ by the definition of $\bigcup A$.

Exercise 4 Suppose $A \subseteq B$. Let $x \in \bigcup A$. We must show that $x \in \bigcup B$.

Pick an element $a \in A$ such that $x \in a$. Then $a \in B$ because $A \subseteq B$. Since we know $x \in a$ and $a \in B$, we know that $x \in \bigcup B$.

Exercise 5 Assume that every member of \mathcal{A} is a subset of B . Let $x \in \bigcup \mathcal{A}$. We must show that $x \in B$.

Pick $A \in \mathcal{A}$ such that $x \in A$. By our assumption, we have $A \subseteq B$. Since $x \in A$ and $A \subseteq B$, we have $x \in B$ as required.

Exercise 6

(a) We will show that $\bigcup \mathcal{P}A \subseteq A$ and $A \subseteq \bigcup \mathcal{P}A$.

To show $\bigcup \mathcal{P}A \subseteq A$: This follows from Exercise 5, since every member of $\mathcal{P}A$ is a subset of A .

To show $A \subseteq \bigcup \mathcal{P}A$: Let $a \in A$. Then we have $a \in \{a\}$ and $\{a\} \in \mathcal{P}A$ so $a \in \bigcup \mathcal{P}A$.

(b) To show $A \subseteq \mathcal{P} \bigcup A$: This holds because every element of A is a subset of $\bigcup A$, as we proved in Exercise 3.

Equality holds if and only if $A = \mathcal{P}X$ for some set X .

Proof: If $A = \mathcal{P} \bigcup A$ then of course $A = \mathcal{P}X$ for some X .

Conversely, if $A = \mathcal{P}X$, then we have

$$\begin{aligned} \mathcal{P} \bigcup A &= \mathcal{P} \bigcup \mathcal{P}X \\ &= \mathcal{P}X && \text{(by part (a))} \\ &= A \end{aligned}$$

Exercise 7

(a) For any set X ,

$$\begin{aligned} X &\in \mathcal{P}A \cap \mathcal{P}B \\ \Leftrightarrow X &\subseteq A \text{ and } X \subseteq B \\ \Leftrightarrow \text{Every member of } X &\text{ is a member of } A \text{ and a member of } B \\ \Leftrightarrow X &\subseteq A \cap B \\ \Leftrightarrow X &\in \mathcal{P}(A \cap B) \end{aligned}$$

(b) Let $X \in \mathcal{P}A \cup \mathcal{P}B$. Then either $X \in \mathcal{P}A$ or $X \in \mathcal{P}B$ (or both). If $X \in \mathcal{P}A$, then we have $X \subseteq A$ and so $X \subseteq A \cup B$ (because $A \subseteq A \cup B$). Similarly if $X \in \mathcal{P}B$ then we have $X \subseteq A \cup B$. So in either case $X \subseteq A \cup B$, hence $X \in \mathcal{P}(A \cup B)$.

Equality holds if and only if either $A \subseteq B$ or $B \subseteq A$.

Proof: Suppose $A \subseteq B$. Then $\mathcal{P}A \subseteq \mathcal{P}B$ (Chapter 1 Exercise 3) and so $\mathcal{P}A \cup \mathcal{P}B = \mathcal{P}B$. Also $A \cup B = B$ so $\mathcal{P}(A \cup B) = \mathcal{P}B$. Thus $\mathcal{P}A \cup \mathcal{P}B$ and $\mathcal{P}(A \cup B)$ are equal.

Similarly if $B \subseteq A$ then $\mathcal{P}A \cup \mathcal{P}B = \mathcal{P}(A \cup B)$.

Conversely, suppose $\mathcal{P}A \cup \mathcal{P}B = \mathcal{P}(A \cup B)$. We have $A \cup B \in \mathcal{P}(A \cup B)$, so $A \cup B \in \mathcal{P}A \cup \mathcal{P}B$. If $A \cup B \in \mathcal{P}A$, then we have $B \subseteq A \cup B \subseteq A$. And if $A \cup B \in \mathcal{P}B$, then we have $A \subseteq A \cup B \subseteq B$.

Exercise 8 If A is a set such that every singleton belongs to A , then every set belongs to $\bigcup A$, contradicting Theorem 2A.

Exercise 9 Let $a = \{\emptyset\}$ and $B = \{\{\emptyset\}\}$. Then $a \in B$ but $\mathcal{P}a$ is not a subset of B because $\emptyset \in \mathcal{P}a$ and $\emptyset \notin B$.

Exercise 10 We must show that $\mathcal{P}a \subseteq \mathcal{P} \bigcup B$. So let $X \in \mathcal{P}a$. Then $X \subseteq a$; we must show that $X \subseteq \bigcup B$.

Let $x \in X$; we must show that $x \in \bigcup B$. We have $x \in a$ (because $x \in X$ and $X \subseteq a$) and $a \in B$, hence $x \in \bigcup B$ as required.

2.2 Algebra of Sets

Exercise 11 For any x we have

$$\begin{aligned} x \in (A \cap B) \cup (A - B) &\Leftrightarrow (x \in A \& x \in B) \text{ or } (x \in A \& x \notin B) \\ &\Leftrightarrow x \in A \& (x \in B \text{ or } x \notin B) \\ &\Leftrightarrow x \in A \end{aligned}$$

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

For any x we have

$$\begin{aligned} x \in A \cup (B - A) &\Leftrightarrow x \in A \text{ or } (x \in B \& x \notin A) \\ &\Leftrightarrow x \in A \text{ or } x \in B \\ &\Leftrightarrow x \in A \cup B \end{aligned}$$

Hence $A \cup (B - A) = A \cup B$.

Exercise 12 For any x ,

$$\begin{aligned} x \in C - (A \cap B) &\Leftrightarrow x \in C \& \neg(x \in A \& x \in B) \\ &\Leftrightarrow x \in C \& (x \notin A \text{ or } x \notin B) \\ &\Leftrightarrow (x \in C \& x \notin A) \text{ or } (x \in C \& x \notin B) \\ &\Leftrightarrow x \in (C - A) \cup (C - B) \end{aligned}$$

Exercise 13 Suppose $A \subseteq B$. Let $x \in C - B$; we must show $x \in C - A$. We have $x \in C$ and $x \notin B$. Therefore $x \notin A$, since every member of A is a member of B . And so we have $x \in C - A$ as required.

Exercise 14 Let $A = \{\emptyset\}$, $B = \emptyset$ and $C = \{\emptyset\}$. Then $A - (B - C) = A - \emptyset = \{\emptyset\}$ while $(A - B) - C = \{\emptyset\} - C = \emptyset$.

Exercise 15

(a) For any x we have the following eight possibilities:

| | | | | |
|--------------|--------------|--------------|---------------------------|------------------------------------|
| $x \in A$ | $x \in B$ | $x \in C$ | $x \notin A \cap (B + C)$ | $x \notin (A \cap B) + (A \cap C)$ |
| $x \in A$ | $x \in B$ | $x \notin C$ | $x \in A \cap (B + C)$ | $x \in (A \cap B) + (A \cap C)$ |
| $x \in A$ | $x \notin B$ | $x \in C$ | $x \in A \cap (B + C)$ | $x \in (A \cap B) + (A \cap C)$ |
| $x \in A$ | $x \notin B$ | $x \notin C$ | $x \notin A \cap (B + C)$ | $x \notin (A \cap B) + (A \cap C)$ |
| $x \notin A$ | $x \in B$ | $x \in C$ | $x \notin A \cap (B + C)$ | $x \notin (A \cap B) + (A \cap C)$ |
| $x \notin A$ | $x \in B$ | $x \notin C$ | $x \notin A \cap (B + C)$ | $x \notin (A \cap B) + (A \cap C)$ |
| $x \notin A$ | $x \notin B$ | $x \in C$ | $x \notin A \cap (B + C)$ | $x \notin (A \cap B) + (A \cap C)$ |
| $x \notin A$ | $x \notin B$ | $x \notin C$ | $x \notin A \cap (B + C)$ | $x \notin (A \cap B) + (A \cap C)$ |

In every case, we have $x \in A \cap (B + C) \Leftrightarrow x \in (A \cap B) + (A \cap C)$.

(b) For any x we have the following eight possibilities:

| | | | | |
|--------------|--------------|--------------|------------------------|------------------------|
| $x \in A$ | $x \in B$ | $x \in C$ | $x \in A + (B + C)$ | $x \in (A + B) + C$ |
| $x \in A$ | $x \in B$ | $x \notin C$ | $x \notin A + (B + C)$ | $x \notin (A + B) + C$ |
| $x \in A$ | $x \notin B$ | $x \in C$ | $x \notin A + (B + C)$ | $x \notin (A + B) + C$ |
| $x \in A$ | $x \notin B$ | $x \notin C$ | $x \in A + (B + C)$ | $x \in (A + B) + C$ |
| $x \notin A$ | $x \in B$ | $x \in C$ | $x \notin A + (B + C)$ | $x \notin (A + B) + C$ |
| $x \notin A$ | $x \in B$ | $x \notin C$ | $x \in A + (B + C)$ | $x \in (A + B) + C$ |
| $x \notin A$ | $x \notin B$ | $x \in C$ | $x \in A + (B + C)$ | $x \in (A + B) + C$ |
| $x \notin A$ | $x \notin B$ | $x \notin C$ | $x \notin A + (B + C)$ | $x \notin (A + B) + C$ |

In every case, we have $x \in A + (B + C) \Leftrightarrow x \in (A + B) + C$.

Exercise 16

$$[(A \cup B \cup C) \cap (A \cup B)] - [(A \cup (B - C)) \cap A] = (A \cup B) - A \\ = B - A$$

Exercise 17

(a) \Leftrightarrow (b)

$A \subseteq B \Leftrightarrow$ Every element of A is an element of B

\Leftrightarrow There is no element of A that is not an element of B

$\Leftrightarrow A - B = \emptyset$

(a) \Rightarrow (c) Suppose $A \subseteq B$. We have $B \subseteq A \cup B$ from the definition of $A \cup B$; we must prove that $A \cup B \subseteq B$. So let $x \in A \cup B$. Then $x \in A$ or $x \in B$. But in either case $x \in B$, since $x \in A \Rightarrow x \in B$. Thus we have $x \in B$ as required.

(c) \Rightarrow (a) We always have $A \subseteq A \cup B$. So if $A \cup B = B$ then we have $A \subseteq B$.

(a) \Rightarrow (d) Suppose $A \subseteq B$. We have $A \cap B \subseteq A$ from the definition of $A \cap B$; we must prove that $A \subseteq A \cap B$. So let $x \in A$. Then $x \in B$ since $A \subseteq B$, hence $x \in A \cap B$ as required.

(d) \Rightarrow (a) We always have $A \cap B \subseteq B$. So if $A \cap B = A$ then $A \subseteq B$.

Exercise 18 We can make the following 16 sets:

- $\emptyset (= A - A)$
- $A - B$
- $A \cap B$
- $B - A$
- $S - (A \cup B)$
- A
- $A + B$
- $S - B$
- B
- $S - (A + B)$
- $S - A$
- $A \cup B$
- $S - (B - A)$
- $S - (A \cap B)$
- $S - (A - B)$

Exercise 19 They are never equal, because for all A, B , we have $\emptyset \in \mathcal{P}(A - B)$ but $\emptyset \notin \mathcal{P}A - \mathcal{P}B$ since $\emptyset \in \mathcal{P}B$.

Exercise 20 Assume $A \cup B = A \cup C$ and $A \cap B = A \cap C$.

We first show $B \subseteq C$. Let $x \in B$; we show $x \in C$. We have $x \in A \cup B = A \cup C$, so either $x \in A$ or $x \in C$. If $x \in C$, we are done. If $x \in A$, then we have $x \in A \cap B = A \cap C$, and so $x \in C$ in this case too.

We can show $C \subseteq B$ similarly. Hence $B = C$.

Exercise 21 For any x , we have

$$\begin{aligned}
 x \in \bigcup (A \cup B) &\Leftrightarrow \text{there exists } C \text{ such that } C \in A \cup B \text{ and } x \in C \\
 &\Leftrightarrow \text{there exists } C \in A \text{ such that } x \in C, \text{ or there exists } C \in B \text{ such that } x \in C \\
 &\Leftrightarrow x \in \bigcup A \cup \bigcup B
 \end{aligned}$$

Exercise 22 For any x , we have

$$\begin{aligned}
 x \in \bigcap (A \cup B) &\Leftrightarrow \text{for all } C, \text{ if } C \in A \text{ or } C \in B \text{ then } x \in C \\
 &\Leftrightarrow \text{for all } C \in A \text{ we have } x \in C, \text{ and for all } C \in B \text{ we have } x \in C \\
 &\Leftrightarrow x \in \bigcap A \cap \bigcap B
 \end{aligned}$$

Exercise 23 PROOF:

- $\langle 1 \rangle 1. A \subseteq \bigcap \{A \cup X \mid X \in \mathcal{B}\}$
- $\langle 2 \rangle 1. \text{ LET: } x \in A$
- $\langle 2 \rangle 2. \text{ LET: } X \in \mathcal{B}$
- $\langle 2 \rangle 3. x \in A \cup X$
- $\langle 1 \rangle 2. \bigcap \mathcal{B} \subseteq \bigcap \{A \cup X \mid X \in \mathcal{B}\}$
- $\langle 2 \rangle 1. \text{ LET: } x \in \bigcap \mathcal{B}$
- $\langle 2 \rangle 2. \text{ LET: } X \in \mathcal{B}$
- $\langle 2 \rangle 3. x \in X$
- $\langle 2 \rangle 4. x \in A \cup X$
- $\langle 1 \rangle 3. \bigcap \{A \cup X \mid X \in \mathcal{B}\} \subseteq A \cup \bigcap \mathcal{B}$
- $\langle 2 \rangle 1. \text{ LET: } x \in \bigcap \{A \cup X \mid X \in \mathcal{B}\}$
- $\langle 2 \rangle 2. \text{ ASSUME: } x \notin A$
- PROVE: $x \in \bigcap \mathcal{B}$
- $\langle 2 \rangle 3. \text{ LET: } X \in \mathcal{B}$
- $\langle 2 \rangle 4. x \in A \cup X$
- $\langle 2 \rangle 5. x \in X$

□

Exercise 24

(a)

$$\begin{aligned}
 Y \in \mathcal{P} \bigcap \mathcal{A} &\Leftrightarrow Y \subseteq \bigcap \mathcal{A} \\
 &\Leftrightarrow \forall y \in Y. \forall X \in \mathcal{A}. y \in X \\
 &\Leftrightarrow \forall X \in \mathcal{A}. \forall y \in Y. y \in X \\
 &\Leftrightarrow \forall X \in \mathcal{A}. Y \in \mathcal{P}X \\
 &\Leftrightarrow Y \in \bigcap \{\mathcal{P}X \mid X \in \mathcal{A}\}
 \end{aligned}$$

(b) $\bigcup \{\mathcal{P}X \mid X \in \mathcal{A}\} \subseteq \mathcal{P} \bigcup \mathcal{A}$

PROOF:

- $\langle 1 \rangle 1. \text{ LET: } Y \in \bigcup \{\mathcal{P}X \mid X \in \mathcal{A}\}$
- $\langle 1 \rangle 2. \text{ PICK } X \in \mathcal{A} \text{ such that } Y \in \mathcal{P}X$
- $\langle 1 \rangle 3. Y \subseteq X$
- $\langle 1 \rangle 4. Y \subseteq \bigcup \mathcal{A}$
- $\langle 1 \rangle 5. Y \in \mathcal{P} \bigcup \mathcal{A}$

Equality holds if and only if $\bigcup \mathcal{A} \in \mathcal{A}$.

- ⟨1⟩1. If $\bigcup \{\mathcal{P}X \mid X \in \mathcal{A}\} = \mathcal{P} \bigcup \mathcal{A}$ then $\bigcup \mathcal{A} \in \mathcal{A}$
 - ⟨2⟩1. ASSUME: $\bigcup \{\mathcal{P}X \mid X \in \mathcal{A}\} = \mathcal{P} \bigcup \mathcal{A}$
 - ⟨2⟩2. $\bigcup \mathcal{A} \in \bigcup \{\mathcal{P}X \mid X \in \mathcal{A}\}$
 - ⟨2⟩3. PICK $X \in \mathcal{A}$ such that $\bigcup \mathcal{A} \in \mathcal{P}X$
 - ⟨2⟩4. $X = \bigcup \mathcal{A}$
 - ⟨1⟩2. If $\bigcup \mathcal{A} \in \mathcal{A}$ then $\bigcup \{\mathcal{P}X \mid X \in \mathcal{A}\} = \mathcal{P} \bigcup \mathcal{A}$
- PROOF: If $\bigcup \mathcal{A} \in \mathcal{A}$ then $\mathcal{P} \bigcup \mathcal{A} \in \{\mathcal{P}X \mid X \in \mathcal{A}\}$.
 \square

Exercise 25 We have $A \cup \bigcup \mathcal{B} = \bigcup \{A \cup X \mid X \in \mathcal{B}\}$ if and only if $A = \emptyset$ or $\mathcal{B} \neq \emptyset$

- ⟨1⟩1. If $A \cup \bigcup \mathcal{B} = \bigcup \{A \cup X \mid X \in \mathcal{B}\}$ then $A = \emptyset$ or $\mathcal{B} \neq \emptyset$
- PROOF: If $A \cup \bigcup \mathcal{B} = \bigcup \{A \cup X \mid X \in \mathcal{B}\}$ and $\mathcal{B} = \emptyset$ then
- $$A \cup \bigcup \emptyset = \bigcup \emptyset$$
- $$\therefore A = \emptyset$$
- ⟨1⟩2. If $A = \emptyset$ then $A \cup \bigcup \mathcal{B} = \bigcup \{A \cup X \mid X \in \mathcal{B}\}$
- PROOF: Both sides are equal to $\bigcup \mathcal{B}$
- ⟨1⟩3. If $\mathcal{B} \neq \emptyset$ then $A \cup \bigcup \mathcal{B} = \bigcup \{A \cup X \mid X \in \mathcal{B}\}$
 - ⟨2⟩1. ASSUME: $\mathcal{B} \neq \emptyset$
 - ⟨2⟩2. $A \cup \bigcup \mathcal{B} \subseteq \bigcup \{A \cup X \mid X \in \mathcal{B}\}$
 - ⟨3⟩1. LET: $x \in A \cup \bigcup \mathcal{B}$
 - PROVE: $x \in \bigcup \{A \cup X \mid X \in \mathcal{B}\}$
 - ⟨3⟩2. CASE: $x \in A$
 - ⟨4⟩1. PICK $X \in \mathcal{B}$
 - PROOF: By ⟨2⟩1
 - ⟨4⟩2. $x \in A \cup X$
 - ⟨3⟩3. CASE: $x \in \bigcup \mathcal{B}$
 - ⟨4⟩1. PICK $X \in \mathcal{B}$ such that $x \in X$
 - ⟨4⟩2. $x \in A \cup X$
 - ⟨2⟩3. $\bigcup \{A \cup X \mid X \in \mathcal{B}\} \subseteq A \cup \bigcup \mathcal{B}$
 - ⟨3⟩1. LET: $x \in \bigcup \{A \cup X \mid X \in \mathcal{B}\}$
 - ⟨3⟩2. PICK $X \in \mathcal{B}$ such that $x \in A \cup X$
 - ⟨3⟩3. $X \subseteq \bigcup \mathcal{B}$
 - ⟨3⟩4. $A \cup X \subseteq A \cup \bigcup \mathcal{B}$
 - ⟨3⟩5. $x \in A \cup \bigcup \mathcal{B}$

2.3 Review Exercises

Exercise 26 Sets A, B, D and F are all equal to each other. Sets C, E and G are equal to each other. None of the first list is equal to any of the second list.

Exercise 27 Take $A = \{\{0\}, \{1\}\}$ and $B = \{\{1\}\}$. Then $A \cap B = \{\{1\}\}$ and

$$\begin{aligned}\bigcap A \cap \bigcap B &= \emptyset \cap \{1\} \\ &= \emptyset \\ \bigcap (A \cap B) &= \bigcap \{\{1\}\} \\ &= \{1\}\end{aligned}$$

Exercise 28

$$\bigcup \{\{3, 4\}, \{\{3\}, \{4\}\}, \{3, \{4\}\}, \{\{3\}, 4\}\} = \{3, 4, \{3\}, \{4\}\}$$

Exercise 29

(a) \emptyset

(b) We have

$$\begin{aligned}\{\emptyset\} &\subseteq \mathcal{P}\{\emptyset\} \\ \therefore \mathcal{P}\{\emptyset\} &\subseteq \mathcal{PP}\{\emptyset\} \\ \{\emptyset\} &\subseteq \mathcal{PP}\{\emptyset\} \\ \therefore \mathcal{P}\{\emptyset\} &\subseteq \mathcal{PPP}\{\emptyset\} \\ \therefore \bigcap \{\mathcal{PPP}\{\emptyset\}, \mathcal{PP}\{\emptyset\}, \mathcal{P}\{\emptyset\}\} &= \mathcal{PPP}\{\emptyset\} \cap \mathcal{PP}\{\emptyset\} \cap \mathcal{P}\{\emptyset\} \\ &= \mathcal{P}\{\emptyset\} \\ &= \{\emptyset, \{\emptyset\}\}\end{aligned}$$

Exercise 30

(a) $\{\emptyset, \{\{\emptyset\}\}, \{\{\{\emptyset\}\}\}, \{\{\emptyset\}, \{\{\emptyset\}\}\}$

(b) $\{\emptyset, \{\emptyset\}\}$

(c) $\{\emptyset, \{\emptyset\}, \{\{\emptyset\}\}, \{\emptyset, \{\emptyset\}\}\}$

(d) $\{\{\emptyset\}, \{\{\emptyset\}\}\}$

Exercise 31

(a) $\{1, 2, 3, \emptyset\}$

(b) \emptyset

(c) \emptyset

(d) \emptyset

Exercise 32

(a) $a \cup b$

(b) a

(c)

$$\begin{aligned} \bigcap \bigcup S \cup (\bigcup \bigcup S - \bigcup \bigcap S) &= (a \cap b) \cup ((a \cup b) - a) \\ &= (a \cap b) \cup (b - a) \\ &= b \end{aligned}$$

Exercise 33 When $a \neq b$:

$$\begin{aligned} \bigcup (\bigcup S - \bigcap S) &= \bigcup (\{a, b\} - \{a\}) \\ &= \bigcup \{b\} \\ &= b \end{aligned}$$

When $a = b$:

$$\begin{aligned} \bigcup (\bigcup S - \bigcap S) &= \bigcup (\{a, b\} - \{a\}) \\ &= \bigcup \emptyset \\ &= \emptyset \end{aligned}$$

Exercise 34 For any set S , we have

$$\begin{aligned} \emptyset &\subseteq \mathcal{P}S \\ \therefore \emptyset &\in \mathcal{P}\mathcal{P}S \\ \emptyset &\subseteq S \\ \therefore \emptyset &\in \mathcal{P}S \\ \therefore \{\emptyset\} &\subseteq \mathcal{P}S \\ \therefore \{\emptyset\} &\in \mathcal{P}\mathcal{P}S \\ \therefore \{\emptyset, \{\emptyset\}\} &\subseteq \mathcal{P}\mathcal{P}S \\ \therefore \{\emptyset, \{\emptyset\}\} &\in \mathcal{P}\mathcal{P}\mathcal{P}S \end{aligned}$$

Exercise 35 Assume $\mathcal{P}A = \mathcal{P}B$. Then we have

$$\begin{aligned}
 A &\in \mathcal{P}A \\
 \therefore A &\in \mathcal{P}B \\
 \therefore A &\subseteq B \\
 B &\in \mathcal{P}B \\
 \therefore B &\in \mathcal{P}A \\
 \therefore B &\subseteq A \\
 \therefore A &= B
 \end{aligned}$$

Exercise 36

(a)

$$\begin{aligned}
 x \in A - (A \cap B) &\Leftrightarrow x \in A \ \& \neg(x \in A \ \& \ x \in B) \\
 &\Leftrightarrow x \in A \ \& \ x \notin B \\
 &\Leftrightarrow x \in A - B
 \end{aligned}$$

(b)

$$\begin{aligned}
 x \in A - (A - B) &\Leftrightarrow x \in A \ \& \neg(x \in A \ \& \ x \notin B) \\
 &\Leftrightarrow x \in A \ \& \ x \in B \\
 &\Leftrightarrow x \in A \cap B
 \end{aligned}$$

Exercise 37

(a)

$$\begin{aligned}
 x \in (A \cup B) - C &\Leftrightarrow (x \in A \text{ or } x \in B) \ \& \ x \notin C \\
 &\Leftrightarrow (x \in A \ \& \ x \notin C) \text{ or } (x \in B \ \& \ x \notin C) \\
 &\Leftrightarrow x \in (A - C) \cup (B - C)
 \end{aligned}$$

(b)

$$\begin{aligned}
 x \in A - (B - C) &\Leftrightarrow x \in A \ \& \neg(x \in B \ \& \ x \notin C) \\
 &\Leftrightarrow x \in A \ \& (x \notin B \text{ or } x \in C) \\
 &\Leftrightarrow (x \in A \ \& \ x \notin B) \text{ or } (x \in A \ \& \ x \in C) \\
 &\Leftrightarrow x \in (A - B) \cup (A \cap C)
 \end{aligned}$$

(c)

$$\begin{aligned}
 x \in (A - B) - C &\Leftrightarrow x \in A \ \& \ x \notin B \ \& \ x \notin C \\
 &\Leftrightarrow x \in A \ \& \neg(x \in B \vee x \in C) \\
 &\Leftrightarrow x \in A - (B \cup C)
 \end{aligned}$$

Exercise 38

(a) If every element of A is an element of C , and every element of B is an element of C , then everything that is an element of either A or B is an element of C .

(b) If every element of C is an element of A , and every element of C is an element of B , then every element of C is an element of both A and B .

Chapter 3

Chapter 3 — Relations and Functions

3.1 Ordered Pairs

Exercise 1 We have $\langle 0, 1, 0 \rangle^* = \langle 0, 1, 1 \rangle^* = \{\{0\}, \{0, 1\}\}$.

Exercise 2

(a)

$$\begin{aligned} z &\in A \times (B \cup C) \\ \Leftrightarrow \exists x, y (z = (x, y) \ \& \ x \in A \ \& \ (y \in B \text{ or } y \in C)) \\ \Leftrightarrow \exists x, y (z = (x, y) \ \& \ x \in A \ \& \ y \in B) \text{ or } (z = (x, y) \ \& \ x \in A \ \& \ y \in C) \\ \Leftrightarrow z &\in (A \times B) \cup (A \times C) \end{aligned}$$

(b)

$\langle 1 \rangle 1$. ASSUME: $A \times B = A \times C$ and $A \neq \emptyset$

$\langle 1 \rangle 2$. PICK $a \in A$

$\langle 1 \rangle 3$. For all x , $x \in B \Leftrightarrow x \in C$

PROOF: $x \in B$ iff $(a, x) \in A \times B$ iff $(a, x) \in A \times C$ iff $x \in C$.

□

Exercise 3

$$\begin{aligned} z &\in A \times \bigcup \mathcal{B} \\ \Leftrightarrow \exists x, y (z = (x, y) \ \& \ x \in A \ \& \ \exists X \in \mathcal{B}. y \in X) \\ \Leftrightarrow \exists X \in \mathcal{B}. \exists x, y (z = (x, y) \ \& \ x \in A \ \& \ y \in X) \\ \Leftrightarrow z &\in \bigcup \{A \times X : X \in \mathcal{B}\} \end{aligned}$$

Exercise 4 If every ordered pair belongs to A then every set belongs to $\bigcup\bigcup A$ contradicting Theorem 2A.

Exercise 5

(a) Apply a Subset Axiom to $\mathcal{P}(A \times B)$: we have $C = \{z \in \mathcal{P}(A \times B) \mid \exists x \in A. z = \{x\} \times B\}$.

(b)

$$\begin{aligned} z &\in \bigcup C \\ \Leftrightarrow \exists x \in A. z &\in \{x\} \times B \\ \Leftrightarrow \exists x \in A. \exists y \in B. z &= (x, y) \\ \Leftrightarrow z &\in A \times B \end{aligned}$$

3.2 Relations

Exercise 6 If $A \subseteq \text{dom } A \times \text{ran } A$ then A is a set of ordered pairs, i.e. a relation.

Conversely, suppose A is a relation. Let $z \in A$. Then z is an ordered pair; let $z = (x, y)$. We have $x \in \text{dom } A$ and $y \in \text{ran } A$ and so $z \in \text{dom } A \times \text{ran } A$ as required.

Exercise 7 We have $\text{fld } R \subseteq \bigcup\bigcup R$ by Lemma 3D.

Conversely, let $x \in \bigcup\bigcup R$. Pick a and b such that $x \in a$, $a \in b$ and $b \in R$. Then b is an ordered pair; let $b = (y, z)$. We have $a = \{y\}$ or $\{y, z\}$, hence $x = y$ or $x = z$. In either case, $x \in \text{fld } R$.

Exercise 8

(a)

$$\begin{aligned} x &\in \text{dom } \bigcup \mathcal{A} \\ \Leftrightarrow \exists y. \exists R \in \mathcal{A}. (x, y) &\in R \\ \Leftrightarrow \exists R \in \mathcal{A}. \exists y. (x, y) &\in R \\ \Leftrightarrow x &\in \bigcup \{\text{dom } R : R \in \mathcal{A}\} \end{aligned}$$

(b)

$$\begin{aligned}
y &\in \text{ran} \bigcup \mathcal{A} \\
&\Leftrightarrow \exists x. \exists R \in \mathcal{A}. (x, y) \in R \\
&\Leftrightarrow \exists R \in \mathcal{A}. \exists x. (x, y) \in R \\
&\Leftrightarrow y \in \bigcup \{\text{ran } R : R \in \mathcal{A}\}
\end{aligned}$$

Exercise 9 Assume \mathcal{A} is nonempty. We have $\text{dom} \bigcap \mathcal{A} \subseteq \bigcap \{\text{dom } R : R \in \mathcal{A}\}$.

PROOF:

$$\begin{aligned}
x &\in \text{dom} \bigcap \mathcal{A} \\
&\Leftrightarrow \exists y. \forall R \in \mathcal{A}. (x, y) \in R \\
&\Rightarrow \forall R \in \mathcal{A}. \exists y. (x, y) \in R \\
&\Leftrightarrow x \in \bigcap \{\text{dom } R : R \in \mathcal{A}\}
\end{aligned}$$

Equality holds iff the middle ' \Rightarrow ' can be reversed, i.e. iff for all x , if $\forall R \in \mathcal{A}. \exists y. (x, y) \in R$ then $\exists y. \forall R \in \mathcal{A}. (x, y) \in R$. I haven't found a simpler condition than this. The condition does not always hold, for example if $\mathcal{A} = \{\{(1, 2)\}, \{(1, 3)\}\}$ then $\text{dom} \bigcap \mathcal{A} = \emptyset$ while $\bigcap \{\text{dom } R : R \in \mathcal{A}\} = \{1\}$.

Similarly, $\text{ran} \bigcap \mathcal{A} \subseteq \bigcap \{\text{ran } R : R \in \mathcal{A}\}$, and equality holds iff, for any y , if $\forall R \in \mathcal{A}. \exists x. (x, y) \in R$ then $\exists x. \forall R \in \mathcal{A}. (x, y) \in R$.

3.3 n -ary Relations

Exercise 10 This follows from the equations at the top of page 42. An ordered 4-tuple $\langle a, b, c, d \rangle$ is also an ordered 1-tuple (because every set is), and the ordered pair $\langle \langle a, b, c \rangle, d \rangle$, and the ordered triple $\langle \langle a, b \rangle, c, d \rangle$.

3.4 Functions

Exercise 11 We prove $F \subseteq G$. Let $z \in F$. Since F is a relation, then z is an ordered pair; let $z = \langle x, y \rangle$. We have $x \in \text{dom } F$ and $y = F(x)$. Therefore $x \in \text{dom } G$ and $y = G(x)$ (because $\text{dom } F = \text{dom } G$ and $F(x) = G(x)$). Hence $\langle x, y \rangle \in G$, i.e. $z \in G$.

We have proved $F \subseteq G$. We can prove $G \subseteq F$ similarly. Thus $F = G$.

Exercise 12 PROOF:

- $\langle 1 \rangle 1$. If $f \subseteq g$ then $\text{dom } f \subseteq \text{dom } g$ and $\forall x \in \text{dom } f. f(x) = g(x)$
- $\langle 2 \rangle 1$. ASSUME: $f \subseteq g$
- $\langle 2 \rangle 2$. LET: $x \in \text{dom } f$
- $\langle 2 \rangle 3$. $(x, f(x)) \in f$
- $\langle 2 \rangle 4$. $(x, f(x)) \in g$
- $\langle 2 \rangle 5$. $x \in \text{dom } g$ and $g(x) = f(x)$

- ⟨1⟩2. If $\text{dom } f = \text{dom } g$ and $\forall x \in \text{dom } f. f(x) = g(x)$ then $f \subseteq g$
- ⟨2⟩1. ASSUME: $\text{dom } f = \text{dom } g$ and $\forall x \in \text{dom } f. f(x) = g(x)$
- ⟨2⟩2. LET: $z \in f$
- ⟨2⟩3. LET: $z = (x, y)$
- ⟨2⟩4. $x \in \text{dom } f$ and $y = f(x)$
- ⟨2⟩5. $x \in \text{dom } g$ and $y = g(x)$
- ⟨2⟩6. $z = (x, y) \in g$

□

Exercise 13 PROOF:

- ⟨1⟩1. ASSUME: f and g are functions
- ⟨1⟩2. ASSUME: $f \subseteq g$
- ⟨1⟩3. ASSUME: $\text{dom } g \subseteq \text{dom } f$
- ⟨1⟩4. $\text{dom } f = \text{dom } g$
- PROOF: We have $\text{dom } f \subseteq \text{dom } g$ from ⟨1⟩2 and $\text{dom } g \subseteq \text{dom } f$ from ⟨1⟩3
- ⟨1⟩5. For $x \in \text{dom } f$ we have $f(x) = g(x)$
- PROOF: From ⟨1⟩2 and Exercise 12
- ⟨1⟩6. Q.E.D.
- PROOF: From Exercise 11.

□

Exercise 14

(a) If (x, y) and (x, z) are members of $f \cap g$ then they are both members of f , hence $y = z$.

(b) PROOF:

- ⟨1⟩1. If $f \cup g$ is a function then, for all $x \in \text{dom } f \cap \text{dom } g$, we have $f(x) = g(x)$.
- ⟨2⟩1. ASSUME: $f \cup g$ is a function.
- ⟨2⟩2. LET: $x \in \text{dom } f \cap \text{dom } g$
- ⟨2⟩3. $(x, f(x))$ and $(x, g(x))$ are both elements of $f \cup g$
- ⟨2⟩4. $f(x) = g(x)$
- ⟨1⟩2. If, for all $x \in \text{dom } f \cap \text{dom } g$, we have $f(x) = g(x)$, then $f \cup g$ is a function.
- ⟨2⟩1. ASSUME: For all $x \in \text{dom } f \cap \text{dom } g$, we have $f(x) = g(x)$
- ⟨2⟩2. $f \cup g$ is a relation.
- PROOF: Since every element of either f or g is an ordered pair.
- ⟨2⟩3. Whenever (x, y) and (x, z) are elements of $f \cup g$ we have $y = z$
- ⟨3⟩1. LET: $(x, y), (x, z) \in f \cup g$
- ⟨3⟩2. CASE: $(x, y), (x, z) \in f$
- PROOF: Then $y = z$ since f is a function.
- ⟨3⟩3. CASE: $(x, y) \in f, (x, z) \in g$
- PROOF: Then $y = z$ by ⟨2⟩1
- ⟨3⟩4. CASE: $(x, y) \in g, (x, z) \in f$
- PROOF: Then $y = z$ by ⟨2⟩1
- ⟨3⟩5. CASE: $(x, y), (x, z) \in g$

PROOF: Then $y = z$ since g is a function.

□

Exercise 15 PROOF:

⟨1⟩1. $\bigcup \mathcal{A}$ is a relation.

PROOF: Since every member of \mathcal{A} is a relation.

⟨1⟩2. Whenever (x, y) and (x, z) are elements of $\bigcup \mathcal{A}$ then $y = z$

⟨2⟩1. LET: $(x, y), (x, z) \in \bigcup \mathcal{A}$

⟨2⟩2. PICK $f, g \in \mathcal{A}$ such that $(x, y) \in f$ and $(x, z) \in g$

⟨2⟩3. ASSUME: w.l.o.g. $f \subseteq g$

⟨2⟩4. $(x, y), (x, z) \in g$

⟨2⟩5. $y = z$

PROOF: Since g is a function.

□

Exercise 16 If every function belongs to \mathcal{A} then every set belongs to $\text{dom} \bigcup \mathcal{A}$ contradiction Theorem 2A.

Exercise 17 PROOF:

⟨1⟩1. LET: R and S be single-rooted.

⟨1⟩2. LET: $(x, z), (y, z) \in R \circ S$

⟨1⟩3. PICK t and t' such that $(x, t) \in S, (t, z) \in R, (y, t') \in S$ and $(t', z) \in R$

⟨1⟩4. $t = t'$

PROOF: Since R is single-rooted.

⟨1⟩5. $x = y$

PROOF: Since S is single-rooted.

Thus if F and G are one-to-one functions then $F \circ G$ is single-rooted and a function by Theorem 3H, hence a one-to-one function.

Exercise 18

$$R \circ R = \{\langle 0, 2 \rangle, \langle 0, 3 \rangle, \langle 1, 3 \rangle\}$$

$$R \upharpoonright \{1\} = \{\langle 1, 2 \rangle, \langle 1, 3 \rangle\}$$

$$R^{-1} \upharpoonright \{1\} = \{\langle 1, 0 \rangle\}$$

$$R[\{1\}] = \{2, 3\}$$

$$R^{-1}[\{1\}] = \{0\}$$

Exercise 19

$$\begin{aligned}
A(\emptyset) &= \{\emptyset, \{\emptyset\}\} \\
A[\emptyset] &= \emptyset \\
A[\{\emptyset\}] &= \{\{\emptyset, \{\emptyset\}\}\} \\
A[\{\emptyset, \{\emptyset\}\}] &= \{\{\emptyset, \{\emptyset\}\}, \emptyset\} \\
A^{-1} &= \{\langle \{\emptyset, \{\emptyset\}\}, \emptyset \rangle, \langle \emptyset, \{\emptyset\} \rangle\} \\
A \circ A &= \{\langle \{\emptyset\}, \{\emptyset, \{\emptyset\}\} \rangle\} \\
A \upharpoonright \emptyset &= \emptyset \\
A \upharpoonright \{\emptyset\} &= \{\langle \emptyset, \{\emptyset, \{\emptyset\}\} \rangle\} \\
A \upharpoonright \{\emptyset, \{\emptyset\}\} &= \{\langle \emptyset, \{\emptyset, \{\emptyset\}\} \rangle, \langle \{\emptyset\}, \emptyset \rangle\} \\
&= A \\
\bigcup A &= \{\emptyset, \{\emptyset, \{\emptyset\}\}, \{\emptyset\}\}
\end{aligned}$$

Exercise 20

$$\begin{aligned}
z \in F \upharpoonright A &\Leftrightarrow z \in F \ \& \ \exists x, y. (z = \langle x, y \rangle \ \& \ x \in A) \\
&\Leftrightarrow z \in F \ \& \ \exists x, y. (z = \langle x, y \rangle \ \& \ x \in A \ \& \ y \in \text{ran } F) \\
&\Leftrightarrow z \in F \cap (A \times \text{ran } F)
\end{aligned}$$

Exercise 21 Both are equal to $\{\langle x, w \rangle \mid \exists y, z. xTy \ \& \ ySz \ \& \ zRw\}$.

Exercise 22

(a) PROOF:
 $\langle 1 \rangle 1$. ASSUME: $A \subseteq B$
 $\langle 1 \rangle 2$. LET: $y \in F[A]$
 $\langle 1 \rangle 3$. PICK $x \in A$ such that xFy
 $\langle 1 \rangle 4$. $x \in B$ and xFy
 \square

(b) Both are equal to $\{z : \exists x, y. x \in A \ \& \ xGy \ \& \ yFz\}$

(c) Both are equal to $\{\langle x, y \rangle : (x \in A \text{ or } x \in B) \ \& \ xQy\}$

Exercise 23

$$\begin{aligned}
B \circ I_A &= \{\langle x, z \rangle : \exists y(xI_A y \ \& \ yBz)\} \\
&= \{\langle x, z \rangle : \exists y(x \in A \ \& \ x = y \ \& \ yBz)\} \\
&= \{\langle x, z \rangle : x \in A \ \& \ xBz\} \\
&= B \upharpoonright A \\
I_A[C] &= \{y : \exists x \in C.xI_A y\} \\
&= \{y : \exists x \in C(x \in A \ \& \ x = y)\} \\
&= \{y : y \in C \ \& \ y \in A\} \\
&= A \cap C
\end{aligned}$$

Exercise 24

$$\begin{aligned}
F^{-1}[A] &= \{x : \exists y \in A.yF^{-1}x\} \\
&= \{x : \exists y \in A.xFy\} \\
&= \{x \in \text{dom } F : F(x) \in A\}
\end{aligned}$$

Exercise 25**(a)** PROOF: $\langle 1 \rangle 1$. LET: G be a one-to-one function. $\langle 1 \rangle 2$. G^{-1} is a function.

PROOF: Theorem 3F.

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

PROOF: Theorem 3H.

 $\langle 1 \rangle 4$. $\text{dom}(G \circ G^{-1}) = \text{ran } G$

PROOF:

$$\begin{aligned}
\text{dom}(G \circ G^{-1}) &= \{x \in \text{dom } G^{-1} : G^{-1}(x) \in \text{dom } G\} && \text{(Theorem 3H)} \\
&= \{x \in \text{ran } G : G^{-1}(x) \in \text{dom } G\} && \text{(Theorem 3E)} \\
&= \text{ran } G
\end{aligned}$$

 $\langle 1 \rangle 5$. $\forall x \in \text{ran } G.(G \circ G^{-1})(x) = x$

PROOF: Theorem 3G.

□

(b) Let G be a function. Then

$$\begin{aligned}
G \circ G^{-1} &= \{\langle x, z \rangle : \exists y(xG^{-1}y \ \& \ yGz)\} \\
&= \{\langle x, z \rangle : \exists y(yGx \ \& \ yGz)\} \\
&= \{\langle x, x \rangle : \exists y.yGx\} && (G \text{ is a function}) \\
&= I_{\text{ran } G}
\end{aligned}$$

Exercise 26

(a)

$$\begin{aligned} F[\bigcup \mathcal{A}] &= \{y : \exists x. \exists A \in \mathcal{A} (x \in A \ \& \ xFy)\} \\ &= \{y : \exists A \in \mathcal{A}. \exists x (x \in A \ \& \ xFy)\} \\ &= \bigcup \{F[A] : A \in \mathcal{A}\} \end{aligned}$$

(b)

$$\begin{aligned} F[\bigcup \mathcal{A}] &= \{y : \exists x. \forall A \in \mathcal{A} (x \in A \ \& \ xFy)\} \\ &\subseteq \{y : \forall A \in \mathcal{A}. \exists x (x \in A \ \& \ xFy)\} \\ &= \bigcap \{F[A] : A \in \mathcal{A}\} \end{aligned}$$

Exercise 27

$$\begin{aligned} \text{dom}(F \circ G) &= \{x : \exists y. x(F \circ G)y\} \\ &= \{x : \exists y \exists z (xGz \ \& \ zFy)\} \\ &= \{x : \exists z (zG^{-1}x \ \& \ z \in \text{dom } F)\} \\ &= G^{-1}[\text{dom } F] \end{aligned}$$

Exercise 28 PROOF:

$\langle 1 \rangle 1.$ $G : \mathcal{P}A \rightarrow \mathcal{P}B$

PROOF: Since $f[X] \subseteq \text{ran } f \subseteq B$

$\langle 1 \rangle 2.$ For all $X, Y \in \mathcal{P}A$, if $G(X) = G(Y)$ then $X = Y$

$\langle 2 \rangle 1.$ LET: $X, Y \in \mathcal{P}A$

$\langle 2 \rangle 2.$ ASSUME: $f[X] = f[Y]$

$\langle 2 \rangle 3.$ $X \subseteq Y$

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

$\langle 3 \rangle 2.$ $f(x) \in f[X]$

$\langle 3 \rangle 3.$ $f(x) \in f[Y]$

$\langle 3 \rangle 4.$ PICK $y \in Y$ such that $f(x) = f(y)$

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

PROOF: Because f is one-to-one.

$\langle 3 \rangle 6.$ $x \in Y$

PROOF: Similar.

$\langle 2 \rangle 4.$ $Y \subseteq X$

□

Example 29 PROOF:

$\langle 1 \rangle 1.$ ASSUME: f maps A onto B

$\langle 1 \rangle 2.$ LET: $b, b' \in B$

$\langle 1 \rangle 3.$ ASSUME: $G(b) = G(b')$

$\langle 1 \rangle 4.$ PICK $x \in A$ such that $f(x) = b$

PROOF: By $\langle 1 \rangle 1$.

$\langle 1 \rangle 5$. $x \in G(b)$

$\langle 1 \rangle 6$. $x \in G(b')$

$\langle 1 \rangle 7$. $f(x) = b'$

$\langle 1 \rangle 8$. $b = b'$

□

The converse does not hold. Let $A = \{0\}$ and $B = \{0, 1\}$. Let f be the function that maps 0 to 0. Then

$$G(0) = \{0\}$$

$$G(1) = \emptyset$$

Thus G is one-to-one but f does not map A onto B .

Exercise 30

(a) PROOF:

$\langle 1 \rangle 1$. $F(B) = B$

$\langle 2 \rangle 1$. $F(B) \subseteq B$

$\langle 3 \rangle 1$. LET: $X \in \mathcal{P}A$ be such that $F(X) \subseteq X$

PROVE: $F(B) \subseteq X$

$\langle 3 \rangle 2$. $B \subseteq X$

$\langle 3 \rangle 3$. $F(B) \subseteq F(X)$

$\langle 3 \rangle 4$. $F(B) \subseteq X$

PROOF: From $\langle 3 \rangle 1$ and $\langle 3 \rangle 3$.

$\langle 2 \rangle 2$. $B \subseteq F(B)$

PROOF: From $\langle 2 \rangle 1$ and the definition of B , since B is one of the sets X such that $F(X) \subseteq X$

$\langle 1 \rangle 2$. $F(C) = C$

$\langle 2 \rangle 1$. $C \subseteq F(C)$

$\langle 3 \rangle 1$. LET: $X \in \mathcal{P}A$ with $X \subseteq F(X)$

PROVE: $X \subseteq F(C)$

$\langle 3 \rangle 2$. $X \subseteq C$

$\langle 3 \rangle 3$. $F(X) \subseteq F(C)$

$\langle 3 \rangle 4$. $X \subseteq F(C)$

PROOF: From $\langle 3 \rangle 1$ and $\langle 3 \rangle 3$

$\langle 2 \rangle 2$. $F(C) \subseteq C$

PROOF: From $\langle 2 \rangle 1$ and the definition of C .

□

(b) If $F(X) = X$ then we have $B \subseteq X$ (because $F(X) \subseteq X$) and $X \subseteq C$ (because $X \subseteq F(X)$).

3.5 Infinite Cartesian Products

Exercise 31 PROOF:

- ⟨1⟩1. If the Axiom of Choice is true then, for any set I and any function H with domain I , if $H(i) \neq \emptyset$ for all $i \in I$, then $\prod_{i \in I} H(i) \neq \emptyset$.
- ⟨2⟩1. ASSUME: The Axiom of Choice.
- ⟨2⟩2. LET: I be a set.
- ⟨2⟩3. LET: H be a function with domain I .
- ⟨2⟩4. ASSUME: $H(i) \neq \emptyset$ for all $i \in I$.
- ⟨2⟩5. LET: $R = \{(i, x) : i \in I, x \in H(i)\}$
- ⟨2⟩6. PICK a function $F \subseteq R$ with $\text{dom } F = \text{dom } R$
PROVE: $F \in \prod_{i \in I} H(i)$
PROOF: By the Axiom of Choice.
- ⟨2⟩7. $\text{dom } H = I$
PROOF: We have $\text{dom } R = I$ since for all $i \in I$ there exists x such that $x \in H(i)$.
- ⟨2⟩8. $\forall i \in I. F(i) \in H(i)$
PROOF: Since $iRF(i)$.
- ⟨1⟩2. If, for any set I and any function H with domain I , if $H(i) \neq \emptyset$ for all $i \in I$, then $\prod_{i \in I} H(i) \neq \emptyset$, then the Axiom of Choice is true.
- ⟨2⟩1. ASSUME: For any set I and any function H with domain I , if $H(i) \neq \emptyset$ for all $i \in I$, then $\prod_{i \in I} H(i) \neq \emptyset$
- ⟨2⟩2. LET: R be a relation
- ⟨2⟩3. LET: $I = \text{dom } R$
- ⟨2⟩4. Define the function H with domain I by: for $i \in I$, $H(i) = \{y : iRy\}$
- ⟨2⟩5. $H(i) \neq \emptyset$ for all $i \in I$
- ⟨2⟩6. PICK $F \in \prod_{i \in I} H(i)$
PROOF: By ⟨2⟩1
- ⟨2⟩7. F is a function
- ⟨2⟩8. $F \subseteq R$
PROOF: For all $i \in I$ we have $F(i) \in H(i)$ and so $iRF(i)$.
- ⟨2⟩9. $\text{dom } F = \text{dom } R$
-

3.6 Equivalence Relations

Exercise 32

(a)

$$\begin{aligned}
& R \text{ is symmetric} \\
& \Leftrightarrow \forall x, y (xRy \Rightarrow yRx) \\
& \Leftrightarrow \forall x, y (\langle y, x \rangle \in R^{-1} \Rightarrow \langle y, x \rangle \in R) \\
& \Leftrightarrow R^{-1} \subseteq R
\end{aligned}$$

(b)

$$\begin{aligned}
& R \text{ is transitive} \\
& \Leftrightarrow \forall x, y, z (xRy \ \& \ yRz \Rightarrow xRz) \\
& \Leftrightarrow \forall x, z (\exists y (xRy \ \& \ yRz) \Rightarrow xRz) \\
& \Leftrightarrow \forall x, z (\langle x, z \rangle \in R \circ R \Rightarrow \langle x, z \rangle \in R) \\
& \Leftrightarrow R \circ R \subseteq R
\end{aligned}$$

Exercise 33 PROOF:

$\langle 1 \rangle 1$. If R is a symmetric and transitive relation then $R = R^{-1} \circ R$.

$\langle 2 \rangle 1$. ASSUME: R is a symmetric and transitive relation.

$\langle 2 \rangle 2$. $R \subseteq R^{-1} \circ R$

$\langle 3 \rangle 1$. LET: xRy

$\langle 3 \rangle 2$. yRy

PROOF: By Theorem 3M.

$\langle 3 \rangle 3$. xRy and $yR^{-1}y$

$\langle 3 \rangle 4$. $x(R^{-1} \circ R)y$

$\langle 2 \rangle 3$. $R^{-1} \circ R \subseteq R$

PROOF:

$$R^{-1} \circ R \subseteq R \circ R \quad (\text{Exercise 32(a)})$$

$$\subseteq R \quad (\text{Exercise 32(b)})$$

$\langle 1 \rangle 2$. If $R = R^{-1} \circ R$ then R is a symmetric and transitive relation.

$\langle 2 \rangle 1$. ASSUME: $R = R^{-1} \circ R$

$\langle 2 \rangle 2$. R is a relation.

$\langle 2 \rangle 3$. R is symmetric.

$\langle 3 \rangle 1$. LET: xRy

$\langle 3 \rangle 2$. PICK z such that xRz and $zR^{-1}y$

$\langle 3 \rangle 3$. yRz and $zR^{-1}x$

$\langle 3 \rangle 4$. $y(R^{-1} \circ R)x$

$\langle 3 \rangle 5$. yRx

$\langle 2 \rangle 4$. R is transitive.

$\langle 3 \rangle 1$. LET: xRy and yRz

$\langle 3 \rangle 2$. zRy

PROOF: By $\langle 2 \rangle 3$

$\langle 3 \rangle 3$. xRy and $yR^{-1}z$

$\langle 3 \rangle 4$. $x(R^{-1} \circ R)z$

$\langle 3 \rangle 5$. xRz

□

Exercise 34

(a) $\bigcap \mathcal{A}$ is a transitive relation.

PROOF:

$\langle 1 \rangle 1$. $\bigcap \mathcal{A}$ is a relation.

PROOF: Every member of a member of \mathcal{A} is an ordered pair.

$\langle 1 \rangle 2$. $\bigcap \mathcal{A}$ is transitive.

$\langle 2 \rangle 1$. LET: $\langle x, y \rangle$ and $\langle y, z \rangle$ be in $\bigcap \mathcal{A}$

PROVE: $\langle x, z \rangle \in \bigcap \mathcal{A}$

$\langle 2 \rangle 2$. LET: $R \in \mathcal{A}$

$\langle 2 \rangle 3$. xRy and yRz

$\langle 2 \rangle 4$. xRz

PROOF: Since R is transitive.

□

(b) Not necessarily. If $\mathcal{A} = \{\langle 0, 1 \rangle, \langle 1, 2 \rangle\}$ then each member of \mathcal{A} is transitive but $\bigcup \mathcal{A} = \{\langle 0, 1 \rangle, \langle 1, 2 \rangle\}$ is not.

Example 35

$$\begin{aligned} R[\{x\}] &= \{y : \exists z(z \in \{x\} \ \& \ zRy)\} \\ &= \{y : \exists z(z = x \ \& \ zRy)\} \\ &= \{y : xRy\} \\ &= [x]_R \end{aligned}$$

Example 36 PROOF:

$\langle 1 \rangle 1$. Q is a relation on A .

PROOF: By definition.

$\langle 1 \rangle 2$. Q is reflexive on A .

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

$\langle 2 \rangle 2$. $f(x)Rf(x)$

PROOF: Since R is reflexive on B .

$\langle 2 \rangle 3$. xQx

$\langle 1 \rangle 3$. Q is symmetric.

$\langle 2 \rangle 1$. ASSUME: xQy

$\langle 2 \rangle 2$. $f(x)Rf(y)$

$\langle 2 \rangle 3$. $f(y)Rf(x)$

PROOF: R is symmetric.

$\langle 2 \rangle 4$. yQx

$\langle 1 \rangle 4$. Q is transitive.

$\langle 2 \rangle 1$. ASSUME: xQy and yQz

$\langle 2 \rangle 2$. $f(x)Rf(y)$ and $f(y)Rf(z)$

$\langle 2 \rangle 3$. $f(x)Rf(z)$

PROOF: R is transitive.

$\langle 2 \rangle 4$. xQz

□

Exercise 37 PROOF:

$\langle 1 \rangle 1$. R_Π is a relation on A .

PROOF: If $B \in \Pi$, $x \in B$ and $y \in B$ then $x, y \in A$.

$\langle 1 \rangle 2$. R_Π is reflexive on A .

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

$\langle 2 \rangle 2$. PICK $B \in \Pi$ such that $x \in B$

PROOF: Because Π is exhaustive.

$\langle 2 \rangle 3$. $x \in B$ and $x \in B$

$\langle 2 \rangle 4$. $xR_\Pi x$

$\langle 1 \rangle 3$. R_Π is symmetric.

$\langle 2 \rangle 1$. ASSUME: $xR_\Pi y$

$\langle 2 \rangle 2$. PICK $B \in \Pi$ such that $x \in B$ and $y \in B$

$\langle 2 \rangle 3$. $y \in B$ and $x \in B$

$\langle 2 \rangle 4$. $yR_\Pi x$

$\langle 1 \rangle 4$. R_Π is transitive.

$\langle 2 \rangle 1$. ASSUME: $xR_\Pi y$ and $yR_\Pi z$

$\langle 2 \rangle 2$. PICK $B \in \Pi$ such that $x \in B$ and $y \in B$

$\langle 2 \rangle 3$. PICK $C \in \Pi$ such that $y \in C$ and $z \in C$

$\langle 2 \rangle 4$. $B = C$

PROOF: Since $y \in B$ and $y \in C$

$\langle 2 \rangle 5$. $x \in B$ and $z \in B$

$\langle 2 \rangle 6$. $xR_\Pi z$

□

Exercise 38 PROOF:

$\langle 1 \rangle 1$. If $B \in \Pi$ and $x \in B$ then $B = [x]_{R_\Pi}$

$\langle 2 \rangle 1$. LET: $B \in \Pi$

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

$\langle 2 \rangle 3$. $[x]_{R_\Pi} \subseteq B$

$\langle 3 \rangle 1$. LET: $y \in [x]_{R_\Pi}$

$\langle 3 \rangle 2$. $xR_\Pi y$

$\langle 3 \rangle 3$. PICK $C \in \Pi$ such that $x \in C$ and $y \in C$

$\langle 3 \rangle 4$. $B = C$

PROOF: Since $x \in B$ and $x \in C$.

$\langle 3 \rangle 5$. $y \in B$

$\langle 2 \rangle 4$. $B \subseteq [x]_{R_\Pi}$

PROOF: For all $y \in B$, we have $x \in B$ and $y \in B$ hence $xR_\Pi y$.

$\langle 1 \rangle 2$. $A/R_\Pi \subseteq \Pi$

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

PROVE: $[x]_{R_\Pi} \in \Pi$

$\langle 2 \rangle 2$. PICK $B \in \Pi$ such that $x \in B$

$\langle 2 \rangle 3$. $[x]_{R_\Pi} = B$

PROOF: By $\langle 1 \rangle 1$

$\langle 2 \rangle 4$. $[x]_{R_\Pi} \in \Pi$

$\langle 1 \rangle 3$. $\Pi \subseteq A/R_\Pi$

$\langle 2 \rangle 1$. LET: $B \in \Pi$

$\langle 2 \rangle 2$. PICK $x \in B$

PROOF: Since every member of Π is nonempty.

$\langle 2 \rangle 3$. $B = [x]_{R_\Pi}$

PROOF: By $\langle 1 \rangle 1$.

$\langle 2 \rangle 4$. $B \in A/R_\Pi$

□

Exercise 39 PROOF:

$\langle 1 \rangle 1$. $R_\Pi \subseteq R$

$\langle 2 \rangle 1$. LET: $xR_\Pi y$

$\langle 2 \rangle 2$. PICK $B \in \Pi$ such that $x \in B$ and $y \in B$

$\langle 2 \rangle 3$. PICK $z \in A$ such that $B = [z]_R$

$\langle 2 \rangle 4$. zRx

$\langle 2 \rangle 5$. zRy

$\langle 2 \rangle 6$. xRy

PROOF: Since R is symmetric and transitive.

$\langle 1 \rangle 2$. $R \subseteq R_\Pi$

$\langle 2 \rangle 1$. LET: xRy

$\langle 2 \rangle 2$. $x \in [x]_R$

$\langle 2 \rangle 3$. $y \in [x]_R$

$\langle 2 \rangle 4$. $xR_\Pi y$

□

Exercise 40 We have $[2]_R = [3]_R$ but $[6]_R \neq [9]_R$ so there is no such function f .

Exercise 41

(a) PROOF:

$\langle 1 \rangle 1$. Q is reflexive on $\mathbb{R} \times \mathbb{R}$.

PROOF: For any $x, y \in \mathbb{R}$, we have $x + y = x + y$, hence $\langle x, y \rangle Q \langle x, y \rangle$

$\langle 1 \rangle 2$. Q is symmetric.

$\langle 2 \rangle 1$. ASSUME: $\langle u, v \rangle Q \langle x, y \rangle$

$\langle 2 \rangle 2$. $u + y = x + v$

$\langle 2 \rangle 3$. $x + v = u + y$

$\langle 2 \rangle 4$. $\langle x, y \rangle Q \langle u, v \rangle$

$\langle 1 \rangle 3$. Q is transitive.

$\langle 2 \rangle 1$. ASSUME: $\langle a, b \rangle Q \langle u, v \rangle$ and $\langle u, v \rangle Q \langle x, y \rangle$

$\langle 2 \rangle 2$. $a + v = u + b$

$\langle 2 \rangle 3$. $u + y = x + v$

$\langle 2 \rangle 4$. $a + y + x + b$

PROOF: Adding $\langle 2 \rangle 2$ and $\langle 2 \rangle 3$ gives $a + u + v + y = b + u + v + x$.

$\langle 2 \rangle 5$. $\langle a, b \rangle Q \langle x, y \rangle$

□

(b) We prove that, if $\langle u, v \rangle Q \langle x, y \rangle$ then $\langle u + 2v, v + 2u \rangle Q \langle x + 2y, y + 2x \rangle$. It follows from Theorem 3Q that the function G exists.

If $u + y = v + x$ then $u + 2v + y + 2x = v + 2u + x + 2y$ by adding $u + v + y + x$ to both sides.

Exercise 42 Assume that R is an equivalence relation on A and that $F : A \times A \rightarrow A$. Let us say that F is *compatible* with R iff, whenever xRx' and yRy' , then $F(\langle x, y \rangle)RF(\langle x', y' \rangle)$. If F is compatible with R then there exists a unique $\hat{F} : (A/R) \times (A/R) \rightarrow A/R$ such that

$$\hat{F}(\langle [x]_R, [y]_R \rangle) = [F(\langle x, y \rangle)]_R \text{ for all } x, y \in A.$$

If F is not compatible with R then no such \hat{F} exists.

3.7 Ordering Relations

Exercise 43 PROOF:

- $\langle 1 \rangle 1.$ R^{-1} is transitive.
- $\langle 2 \rangle 1.$ ASSUME: $xR^{-1}y$ and $yR^{-1}z$
- $\langle 2 \rangle 2.$ zRy and yRx
- $\langle 2 \rangle 3.$ zRx
- PROOF: Since R is transitive.
- $\langle 2 \rangle 4.$ $xR^{-1}z$
- $\langle 1 \rangle 2.$ R^{-1} satisfies trichotomy on A .
- $\langle 2 \rangle 1.$ LET: $x, y \in A$
- $\langle 2 \rangle 2.$ Exactly one of xRy , $x = y$, yRx holds.
- $\langle 2 \rangle 3.$ Exactly one of $yR^{-1}x$, $x = y$, $xR^{-1}y$ holds.

□

Exercise 44 PROOF:

- $\langle 1 \rangle 1.$ f is one-to-one.
- $\langle 2 \rangle 1.$ LET: $x, y \in A$ with $f(x) = f(y)$
- $\langle 2 \rangle 2.$ $f(x) < f(y)$ and $f(y) < f(x)$ do not hold.
- PROOF: By trichotomy.
- $\langle 2 \rangle 3.$ $x < y$ and $y < x$ do not hold.
- $\langle 2 \rangle 4.$ $x = y$
- PROOF: By trichotomy.
- $\langle 1 \rangle 2.$ Whenever $f(x) < f(y)$ then $x < y$
- $\langle 2 \rangle 1.$ LET: $x, y \in A$ with $f(x) < f(y)$
- $\langle 2 \rangle 2.$ $f(x) = f(y)$ and $f(y) < f(x)$ do not hold.
- PROOF: By trichotomy.
- $\langle 2 \rangle 3.$ $x = y$ and $y < x$ do not hold.
- $\langle 2 \rangle 4.$ $x < y$
- PROOF: By trichotomy.

□

Exercise 45 PROOF:

$\langle 1 \rangle 1.$ $<_L$ is transitive.

$\langle 2 \rangle 1.$ LET: $\langle a_1, b_1 \rangle <_L \langle a_2, b_2 \rangle$ and $\langle a_2, b_2 \rangle <_L \langle a_3, b_3 \rangle$

PROVE: $\langle a_1, b_1 \rangle < \langle a_3, b_3 \rangle$

$\langle 2 \rangle 2.$ CASE: $a_1 <_A a_2$ and $a_2 <_A a_3$

PROOF: Then $a_1 <_A a_3$

$\langle 2 \rangle 3.$ CASE: $a_1 <_A a_2$, $a_2 = a_3$, $b_2 <_B b_3$

PROOF: Then $a_1 <_A a_3$

$\langle 2 \rangle 4.$ CASE: $a_1 = a_2$, $b_1 <_B b_2$ and $a_2 <_A a_3$

PROOF: Then $a_1 <_A a_3$

$\langle 2 \rangle 5.$ CASE: $a_1 = a_2$, $b_1 <_B b_2$, $a_2 = a_3$, $b_2 <_B b_3$

PROOF: Then $a_1 = a_3$ and $b_1 <_B b_3$

$\langle 1 \rangle 2.$ $<_L$ satisfies trichotomy on $A \times B$.

$\langle 2 \rangle 1.$ LET: $\langle a_1, b_1 \rangle$ and $\langle a_2, b_2 \rangle$ be elements of $A \times B$

$\langle 2 \rangle 2.$ Exactly one of $a_1 <_A a_2$, $a_1 = a_2$, $a_2 <_A a_1$ holds.

$\langle 2 \rangle 3.$ Exactly one of $b_1 <_B b_2$, $b_1 = b_2$, $b_2 <_B b_1$ holds.

$\langle 2 \rangle 4.$ Exactly one of $a_1 <_A a_2$, $(a_1 = a_2 \text{ and } b_1 <_B b_2)$, $(a_1 = a_2 \text{ and } b_1 = b_2)$, $(a_1 = a_2 \text{ and } b_2 <_L b_1)$, $a_2 <_A a_1$ holds.

$\langle 2 \rangle 5.$ Exactly one of $\langle a_1, b_1 \rangle <_L \langle a_2, b_2 \rangle$, $\langle a_1, b_1 \rangle = \langle a_2, b_2 \rangle$, $\langle a_2, b_2 \rangle <_L \langle a_1, b_1 \rangle$ holds.

□

3.8 Review Exercises

Exercise 46

(a)

$$\bigcap \bigcap \langle x, y \rangle = \bigcap \{x\} \\ = x$$

(b)

$$\begin{aligned} \bigcap \bigcap \bigcap \{ \langle x, y \rangle \}^{-1} &= \bigcap \bigcap \bigcap \{ \langle y, x \rangle \} \\ &= \bigcap \bigcap \langle y, x \rangle \\ &= y \end{aligned} \quad \text{(by part (a))}$$

Exercise 47

(a) There are eight:

$$\begin{aligned} &\{\langle 0, 3 \rangle, \langle 1, 3 \rangle, \langle 2, 3 \rangle\}, \\ &\{\langle 0, 3 \rangle, \langle 1, 3 \rangle, \langle 2, 4 \rangle\}, \\ &\{\langle 0, 3 \rangle, \langle 1, 4 \rangle, \langle 2, 3 \rangle\}, \\ &\{\langle 0, 3 \rangle, \langle 1, 4 \rangle, \langle 2, 4 \rangle\}, \\ &\{\langle 0, 4 \rangle, \langle 1, 3 \rangle, \langle 2, 3 \rangle\}, \\ &\{\langle 0, 4 \rangle, \langle 1, 3 \rangle, \langle 2, 4 \rangle\}, \\ &\{\langle 0, 4 \rangle, \langle 1, 4 \rangle, \langle 2, 3 \rangle\}, \\ &\{\langle 0, 4 \rangle, \langle 1, 4 \rangle, \langle 2, 4 \rangle\} \end{aligned}$$

(b) There are six:

$$\begin{aligned} &\{\langle 0, 3 \rangle, \langle 1, 4 \rangle, \langle 2, 5 \rangle\}, \\ &\{\langle 0, 3 \rangle, \langle 1, 5 \rangle, \langle 2, 4 \rangle\}, \\ &\{\langle 0, 4 \rangle, \langle 1, 3 \rangle, \langle 2, 5 \rangle\}, \\ &\{\langle 0, 4 \rangle, \langle 1, 5 \rangle, \langle 2, 3 \rangle\}, \\ &\{\langle 0, 5 \rangle, \langle 1, 3 \rangle, \langle 2, 4 \rangle\}, \\ &\{\langle 0, 5 \rangle, \langle 1, 4 \rangle, \langle 2, 3 \rangle\} \end{aligned}$$

Exercise 48

(a) The only ordered pair in \mathcal{PT} is $\langle \emptyset, \emptyset \rangle = \{\{\emptyset\}\}$.

(b)

$$\begin{aligned} (\mathcal{PT})^{-1} \circ (\mathcal{PT} \upharpoonright \{\emptyset\}) &= \{\langle \emptyset, \emptyset \rangle\} \circ \{\langle \emptyset, \emptyset \rangle\} \\ &= \{\langle \emptyset, \emptyset \rangle\} \end{aligned}$$

Exercise 49 There are six:

$$\begin{aligned} &\{\langle 0, 0 \rangle, \langle 1, 1 \rangle, \langle 2, 2 \rangle\}, \\ &\{\langle 0, 0 \rangle, \langle 0, 1 \rangle, \langle 1, 0 \rangle, \langle 1, 1 \rangle, \langle 2, 2 \rangle\}, \\ &\{\langle 0, 0 \rangle, \langle 0, 2 \rangle, \langle 1, 1 \rangle, \langle 2, 0 \rangle, \langle 2, 2 \rangle\}, \\ &\{\langle 0, 0 \rangle, \langle 1, 1 \rangle, \langle 1, 2 \rangle, \langle 2, 1 \rangle, \langle 2, 2 \rangle\}, \\ &\{\langle 0, 0 \rangle, \langle 0, 1 \rangle, \langle 0, 2 \rangle, \langle 1, 0 \rangle, \langle 1, 1 \rangle, \langle 1, 2 \rangle, \langle 2, 0 \rangle, \langle 2, 1 \rangle, \langle 2, 2 \rangle\} \end{aligned}$$

Exercise 50

(a) $\{\langle 0, 1 \rangle, \langle 0, 2 \rangle, \langle 0, 3 \rangle, \langle 1, 3 \rangle, \langle 2, 1 \rangle, \langle 2, 3 \rangle\}$

$$(b) \quad \{\langle 0, 1 \rangle, \langle 0, 2 \rangle, \langle 0, 3 \rangle, \langle 2, 1 \rangle, \langle 3, 1 \rangle, \langle 3, 2 \rangle\}$$

Exercise 51 There are three:

$$\begin{aligned} &\{\langle 1, 0 \rangle, \langle 1, 2 \rangle, \langle 2, 0 \rangle\}, \\ &\{\langle 1, 0 \rangle, \langle 2, 0 \rangle, \langle 2, 1 \rangle\}, \\ &\{\langle 0, 1 \rangle, \langle 2, 0 \rangle, \langle 2, 1 \rangle\} \end{aligned}$$

Exercise 52 We can conclude this if we know that A and B are nonempty, or that C and D are nonempty.

Suppose A and B are nonempty. Then $A \times B = C \times D \neq \emptyset$ so C and D are nonempty. We now prove $A \subseteq C$.

Let $a \in A$. Pick some $b \in B$. Then $\langle a, b \rangle \in A \times B = C \times D$ and so $a \in C$.

We can similarly prove $C \subseteq A$, $B \subseteq D$ and $D \subseteq B$.

Exercise 53

$$\begin{aligned} x(R \cup S)^{-1}y &\Leftrightarrow y(R \cup S)x \\ &\Leftrightarrow yRx \text{ or } ySx \\ &\Leftrightarrow xR^{-1}y \text{ or } xS^{-1}y \\ &\Leftrightarrow x(R^{-1} \cup S^{-1})y \\ x(R \cap S)^{-1}y &\Leftrightarrow y(R \cap S)x \\ &\Leftrightarrow yRx \text{ and } ySx \\ &\Leftrightarrow xR^{-1}y \text{ and } xS^{-1}y \\ &\Leftrightarrow x(R^{-1} \cap S^{-1})y \\ x(R - S)^{-1}y &\Leftrightarrow y(R - S)x \\ &\Leftrightarrow yRx \text{ and } \neg ySx \\ &\Leftrightarrow xR^{-1}y \text{ and } \neg xS^{-1}y \\ &\Leftrightarrow x(R^{-1} - S^{-1})y \end{aligned}$$

Exercise 54

(a)

$$\begin{aligned} \langle x, y \rangle \in A \times (B \cap C) &\Leftrightarrow x \in A \text{ \& } y \in B \text{ \& } y \in C \\ &\Leftrightarrow \langle x, y \rangle \in (A \times B) \cap (A \times C) \end{aligned}$$

(b)

$$\begin{aligned} \langle x, y \rangle \in A \times (B \cup C) &\Leftrightarrow x \in A \text{ \& } (y \in B \text{ or } y \in C) \\ &\Leftrightarrow (x \in A \text{ \& } y \in B) \text{ or } (x \in A \text{ \& } y \in C) \\ &\Leftrightarrow \langle x, y \rangle \in (A \times B) \cup (A \times C) \end{aligned}$$

(c)

$$\begin{aligned}\langle x, y \rangle \in A \times (B - C) &\Leftrightarrow x \in A \ \& \ y \in B \ \& \ y \notin C \\ &\Leftrightarrow \langle x, y \rangle \in (A \times B) - (A \times C)\end{aligned}$$

Exercise 55

(a) No. Take $A = \{0\}$, $B = \{1\}$, $C = \{2\}$. Then $(A \times A) \cup (B \times C) = \{\langle 0, 0 \rangle, \langle 1, 2 \rangle\}$ while $(A \cup B) \times (A \cup C) = \{\langle 0, 0 \rangle, \langle 0, 2 \rangle, \langle 1, 0 \rangle, \langle 1, 2 \rangle\}$.

(b) Yes.

$$\begin{aligned}\langle x, y \rangle \in (A \times A) \cap (B \times C) &\Leftrightarrow x \in A \ \& \ y \in A \ \& \ x \in B \ \& \ y \in C \\ &\Leftrightarrow \langle x, y \rangle \in (A \cap B) \times (A \cap C)\end{aligned}$$

Exercise 56

(a) Yes.

$$\begin{aligned}x \in \text{dom}(R \cup S) &\Leftrightarrow \exists y(xRy \text{ or } xSy) \\ &\Leftrightarrow \exists y.xRy \text{ or } \exists y.xSy \\ &\Leftrightarrow x \in \text{dom } R \cup \text{dom } S\end{aligned}$$

(b) No. Take $R = \{\langle 0, 0 \rangle\}$ and $S = \{\langle 0, 1 \rangle\}$. Then $\text{dom}(R \cap S) = \text{dom } \emptyset = \emptyset$ while $\text{dom } R \cap \text{dom } S = \{0\} \cap \{0\} = \{0\}$.

Exercise 57

(a) Yes.

$$\begin{aligned}x(R \circ (S \cup T))y &\Leftrightarrow \exists z(x(S \cup T)z \ \& \ zRy) \\ &\Leftrightarrow \exists z(xSz \ \& \ zRy) \text{ or } \exists z(xTz \ \& \ zRy) \\ &\Leftrightarrow x((R \circ S) \cup (R \circ T))y\end{aligned}$$

(b) No. Take $R = \{\langle 0, 0 \rangle, \langle 1, 0 \rangle\}$, $S = \{\langle 0, 0 \rangle\}$ and $T = \{\langle 0, 1 \rangle\}$. Then

$$\begin{aligned}R \circ (S \cap T) &= R \circ \emptyset \\ &= \emptyset \\ (R \circ S) \cap (R \circ T) &= \{\langle 0, 0 \rangle\} \cap \{\langle 0, 0 \rangle\} \\ &= \{\langle 0, 0 \rangle\}\end{aligned}$$

Exercise 58 Take $F = \emptyset$ and $S = \{\emptyset\}$. Then $F[F^{-1}[\![S]\!]] = \emptyset \neq S$.

Exercise 59

$$\begin{aligned}
x(Q \upharpoonright (A \cap B))y &\Leftrightarrow xQy \ \& \ x \in A \ \& \ x \in B \\
&\Leftrightarrow x((Q \upharpoonright A) \cap (Q \upharpoonright B))y \\
x(Q \upharpoonright (A - B))y &\Leftrightarrow xQy \ \& \ x \in A \ \& \ x \notin B \\
&\Leftrightarrow (xQy \ \& \ x \in A) \ \& \ \neg(xQy \ \& \ x \in B) \\
&\Leftrightarrow x((Q \upharpoonright A) - (Q \upharpoonright B))y
\end{aligned}$$

Exercise 60

$$\begin{aligned}
x((R \circ S) \upharpoonright A)y &\Leftrightarrow \exists z(xRz \ \& \ zSy \ \& \ x \in A) \\
&\Leftrightarrow x(R \circ (S \upharpoonright A))y
\end{aligned}$$

Chapter 4

Chapter 4 — Natural Numbers

4.1 Inductive Sets

Exercise 1 We have

$$3 = 2 \cup \{2\} = 1 \cup \{1, 2\}$$

and so $1 \in 3$. But $1 \notin 1$ (since $1 = \{\emptyset\}$ and we know $\{\emptyset\} \neq \emptyset$ hence $\{\emptyset\} \notin \{\emptyset\}$). Therefore $1 \neq 3$.

4.2 Peano's Postulates

Exercise 2 If a is a transitive set then

$$\begin{aligned} \bigcup (a^+) &= a && \text{(Theorem 4E)} \\ &\subseteq a^+ \end{aligned}$$

Exercise 3

(a) Suppose a is a transitive set. Then $a \subseteq \mathcal{P}a$. Hence we have $\bigcup \mathcal{P}a = a \subseteq \mathcal{P}a$ and so $\mathcal{P}a$.

(b) Suppose $\mathcal{P}a$ is a transitive set. Then $a = \bigcup \mathcal{P}a \subseteq \mathcal{P}a$ hence a is transitive.

Exercise 4 If a is a transitive set then $\bigcup a \subseteq a$ so $\bigcup \bigcup a \subseteq \bigcup a$. Hence $\bigcup a$ is transitive.

Exercise 5

(a) PROOF:
 $\langle 1 \rangle 1.$ LET: $b \in \bigcup \mathcal{A}$
 $\langle 1 \rangle 2.$ PICK $A \in \mathcal{A}$ such that $b \in A$
 $\langle 1 \rangle 3.$ $b \subseteq A$
 PROOF: Since A is transitive.
 $\langle 1 \rangle 4.$ $b \subseteq \bigcup \mathcal{A}$
 \square

(b) PROOF:
 $\langle 1 \rangle 1.$ LET: $b \in \bigcap \mathcal{A}$
 $\langle 1 \rangle 2.$ For all $A \in \mathcal{A}$ we have $b \subseteq A$
 PROOF: Since $b \in A$ and A is transitive.
 $\langle 1 \rangle 3.$ $b \subseteq \bigcap \mathcal{A}$
 \square

Exercise 6 We have $\bigcup(a^+) = \bigcup a \cup a$ (see the proof of Theorem 4E). So if $\bigcup(a^+) = a$ we have $\bigcup a \cup a = a$ and so $\bigcup a \subseteq a$.

4.3 Recursion on ω

Exercise 7 We have $h_1(0) = h_2(0) = a$ so $0 \in S$.
 Now let $n \in S$; we prove $n^+ \in S$. We have $h_1(n) = h_2(n)$ and therefore

$$\begin{aligned} h_1(n^+) &= F(h_1(n)) \\ &= F(h_2(n)) \\ &= h_2(n^+) \end{aligned}$$

Exercise 8 PROOF:
 $\langle 2 \rangle 1.$ $\forall m, n \in \omega. h(n) = h(m) \Rightarrow n = m$
 $\langle 2 \rangle 1.$ $\forall n \in \omega. h(n) = h(0) \Rightarrow n = 0$
 $\langle 3 \rangle 1.$ LET: $n \in \omega$
 $\langle 3 \rangle 2.$ ASSUME: $h(n) = h(0)$
 $\langle 3 \rangle 3.$ $h(n) = c$
 $\langle 3 \rangle 4.$ $\forall p \in \omega. n \neq p^+$
 PROOF: Otherwise $f(h(p)) = c$ contradicting the fact that $c \in A - \text{ran } f$.
 $\langle 3 \rangle 5.$ $n = 0$
 PROOF: Theorem 4C.
 $\langle 2 \rangle 2.$ For all $m \in \omega$, if $\forall n \in \omega. h(n) = h(m) \Rightarrow n = m$, then $\forall n \in \omega. h(n) = h(m^+) \Rightarrow n = m^+$
 $\langle 3 \rangle 1.$ LET: $m \in \omega$
 $\langle 3 \rangle 2.$ ASSUME: $\forall n \in \omega. h(n) = h(m) \Rightarrow n = m$
 $\langle 3 \rangle 3.$ LET: $n \in \omega$
 $\langle 3 \rangle 4.$ ASSUME: $h(n) = h(m^+)$
 $\langle 3 \rangle 5.$ $h(n) = f(h(m))$

$\langle 3 \rangle 6. n \neq 0$

PROOF: Otherwise $c = f(h(m))$ contradicting the fact that $c \in A - \text{ran } f$.

$\langle 3 \rangle 7. \text{ PICK } p \text{ such that } n = p^+$

$\langle 3 \rangle 8. f(h(p)) = f(h(m))$

$\langle 3 \rangle 9. h(p) = h(m)$

PROOF: f is one-to-one.

$\langle 3 \rangle 10. p = m$

PROOF: By $\langle 3 \rangle 2$.

$\langle 3 \rangle 11. n = p^+ = m^+$

□

Exercise 9 PROOF:

$\langle 1 \rangle 1. C^* \subseteq C_*$

$\langle 2 \rangle 1. f[C_*] \subseteq C_*$

$\langle 3 \rangle 1. \text{ LET: } x \in C_*$

PROVE: $f(x) \in C_*$

$\langle 3 \rangle 2. \text{ PICK } n \text{ such that } x \in h(n)$

$\langle 3 \rangle 3. f(x) \in h(n^+)$

$\langle 3 \rangle 4. f(x) \in C_*$

$\langle 1 \rangle 2. C_* \subseteq C^*$

$\langle 2 \rangle 1. \forall n \in \omega. h(n) \subseteq C^*$

$\langle 3 \rangle 1. h(0) \subseteq C^*$

PROOF: If $A \subseteq X \subseteq B$ and $f[X] \subseteq X$ then $A \subseteq X$.

$\langle 3 \rangle 2. \forall n \in \omega. h(n) \subseteq C^* \Rightarrow h(n^+) \subseteq C^*$

$\langle 4 \rangle 1. \text{ LET: } n \in \omega$

$\langle 4 \rangle 2. \text{ ASSUME: } h(n) \subseteq C^*$

$\langle 4 \rangle 3. f[h(n)] \subseteq C^*$

$\langle 5 \rangle 1. \text{ LET: } X \text{ be such that } A \subseteq X \subseteq B \text{ and } f[X] \subseteq X$

PROVE: $f[h(n)] \subseteq X$

$\langle 5 \rangle 2. h(n) \subseteq X$

$\langle 5 \rangle 3. f[h(n)] \subseteq f[X]$

$\langle 5 \rangle 4. f[h(n)] \subseteq X$

$\langle 4 \rangle 4. h(n^+) \subseteq C^*$

□

Exercise 10 $C^* = C_* = (0, 1]$

Exercise 11 $\{n \in \mathbb{Z} \mid n \leq 0\}$

Exercise 12 Let $f : B \times B \rightarrow B$ and $A \subseteq B$. Let

$$C^* = \bigcap \{X \mid A \subseteq X \subseteq B \text{ \& } f[X \times X] \subseteq X\} .$$

Define the function $h : \omega \rightarrow \mathcal{P}B$ by

$$\begin{aligned} h(0) &= A \\ h(n^+) &= h(n) \cup f[h(n) \times h(n)] \end{aligned} \quad (n \in \omega)$$

Define $C_* = \bigcup \text{ran } h$. Then $C^* = C_*$.

4.4 Arithmetic

Exercise 13 We prove the contrapositive. Assume $m \neq 0$ and $n \neq 0$. Then by Theorem 4C there are natural numbers p, q such that $m = p^+$ and $n = q^+$. Hence $mn = p^+q^+ = (p^+q + p)^+ \neq 0$.

Exercise 14 We prove the following facts for any natural number n :

1. n is even if and only if n^+ is odd.

PROOF: If n is even, say $n = 2p$, then $n^+ = 2p + 1$ is odd.

If n^+ is odd, say $n^+ = 2p + 1$, then $n = 2p$ is even.

2. n is odd if and only if n^+ is even.

PROOF: If n is odd, say $n = 2p + 1$, then $n^+ = 2(p + 1)$ is even.

If n^+ is even, say $n^+ = 2p$, then we cannot have $p = 0$ (since $n^+ \neq 0$). So $p = q + 1$ for some q . But then $n^+ = 2q + 2$ so $n = 2q + 1$ and n is odd.

Now, 0 is even and 0 is not odd. By the two facts above, if n is either even or odd but not both, then n^+ is either odd or even but not both. The result follows by induction.

Exercise 15 We have

$$\begin{aligned} m + (n + 0) &= m + n && \text{by (A1)} \\ &= (m + n) + 0 && \text{by (A1)} \end{aligned}$$

If $m + (n + p) = (m + n) + p$ then

$$\begin{aligned} m + (n + p^+) &= m + (n + p)^+ && \text{by (A2)} \\ &= (m + (n + p))^+ && \text{by (A2)} \\ &= ((m + n) + p)^+ && \text{by induction hypothesis} \\ &= (m + n) + p^+ && \text{by (A2)} \end{aligned}$$

Exercise 16 We first prove that $0 \cdot n = 0$ for all n . We have $0 \cdot 0 = 0$ by (M1), and if $0 \cdot n = 0$ then

$$\begin{aligned} 0 \cdot n^+ &= 0 \cdot n + 0 && \text{by (M2)} \\ &= 0 \cdot n && \text{by (A1)} \\ &= 0 && \text{by induction hypothesis} \end{aligned}$$

Now we prove that $m^+ \cdot n = m \cdot n + n$ for all m, n . We have

$$\begin{aligned} m^+ \cdot 0 &= 0 && \text{by (M1)} \\ m \cdot 0 + 0 &= m \cdot 0 && \text{by (A1)} \\ &= 0 && \text{by (M1)} \end{aligned}$$

Thus, $m^+ \cdot 0 = m \cdot 0 + 0$.

If $m^+ \cdot n = m \cdot n + n$ then

$$\begin{aligned} m^+ \cdot n^+ &= m^+ \cdot n + m^+ && \text{by (M2)} \\ &= (m^+ \cdot n + m)^+ && \text{by (A2)} \\ &= ((m \cdot n + n) + m)^+ && \text{by induction hypothesis} \\ &= ((m \cdot n + m) + n)^+ && \text{by associativity and commutativity of addition} \\ &= (m \cdot n^+ + n)^+ && \text{by (M2)} \\ &= m \cdot n^+ + n^+ && \text{by (A2)} \end{aligned}$$

Exercise 17 The proof is by induction on p . We have

$$\begin{aligned} m^{n+0} &= m^n && \text{by (A1)} \\ &= 0 + m^n && \text{by Theorem 4K(2)} \\ &= m^n \cdot 0 + m^n && \text{by (M1)} \\ &= m^n \cdot 1 && \text{by (M2)} \\ &= m^n \cdot m^0 && \text{by (E1)} \end{aligned}$$

If $m^{n+p} = m^n \cdot m^p$ then

$$\begin{aligned} m^{n+p^+} &= m^{(n+p)^+} && \text{by (A2)} \\ &= m^{n+p} m && \text{by (E2)} \\ &= (m^n m^p) m && \text{by induction hypothesis} \\ &= m^n (m^p m) && \text{by Theorem 4K (4)} \\ &= m^n m^{p^+} && \text{by (E2)} \end{aligned}$$

4.5 Ordering on ω

Exercise 18

$$\begin{aligned} \in_{\omega}^{-1} [\{7, 8\}] &= \{x \in \omega \mid x \in 7 \text{ or } x \in 8\} \\ &= \{0, 1, 2, 3, 4, 5, 6, 7\} \end{aligned}$$

Exercise 19 The proof is by induction on m .

For $m = 0$, take $q = r = 0$. Then $m = d \cdot 0 + 0$ and $0 \in d$.

Suppose $m = dq + r$ and $r < d$. Then $r + 1 \leq d$. If $r + 1 < d$, then we have $m + 1 = dq + (r + 1)$ as required. If $r + 1 = d$, then we have $m + 1 = dq + d = d(q + 1) + 0$.

Exercise 20 We first prove A is closed downwards; that is, if $n \in A$ and $m \in n$ then $m \in A$. This holds because if $n \in A$ and $m \in n$ then $m \in \bigcup A$ and $\bigcup A = A$.

Now, we prove $\forall n \in \omega. n \in A$ by induction on n .

To prove $0 \in A$: we are given that A is nonempty. Pick some $a \in A$. Then $0 \in a$ so $0 \in A$ since A is closed downwards.

Now let $n \in A$; we prove $n^+ \in A$. We have $n \in \bigcup A$; pick some $k \in A$ such that $n \in k$. Then $n^+ \in k$ so $n^+ \in A$ since A is closed downwards.

This completes the induction. We have $\forall n \in \omega. n \in A$, i.e. $A = \omega$.

Exercise 21 Suppose n is a natural number, $k \in n$ and $n \subseteq k$. Then $k \in k$, contradicting Lemma 4L(b).

Exercise 22 We have $0 \in p^+$ (by trichotomy since $p^+ \not\subseteq 0$ because 0 is empty, and $p^+ \not\neq 0$ by Peano's First Postulate.) Hence $n = n + 0 \in n + p^+$ by Theorem 4N.

Exercise 23 The proof is by induction on n . The statement is vacuously true for $n = 0$.

Suppose the statement is true for n . Let $m \in n^+$. Then $m \subseteq n$.

If $m = n$, then we have $m + 0^+ = n^+$.

If $m \in n$, pick p such that $m + p^+ = n$ by the induction hypothesis. Then $m + p^{++} = n^+$.

Exercise 24 Suppose $m \in p$. Then we cannot have $n \in q$ or $n = q$, as either of these would imply $m + n \in p + q$. Hence $q \in n$ by trichotomy.

We prove $q \in n \Rightarrow m \in p$ similarly.

Exercise 25 By Exercise 23, pick natural numbers a and b such that $m = n + a^+$ and $p = q + b^+$. Then

$$\begin{aligned} mp + nq &= (n + a^+)(q + b^+) + nq \\ &= nq + nq + a^+q + nb^+ + a^+b^+ \\ &= (n + a^+)q + n(q + b^+) + a^+b^+ \\ &= mq + np + (a^+ + b^+)^+ \end{aligned}$$

Hence $mq + np \in mp + nq$ by Exercise 22.

Exercise 26 The proof is by induction on n .

If $n = 0$ then $\text{ran } f$ is a singleton and its sole element is the largest element.

Suppose the result is true for n . Let $f : n^{++} \rightarrow A$. Then $f \llbracket n^+ \rrbracket$ has a largest element $f(k)$, say. If $f(k) \subseteq f(n^+)$ then $f(n^+)$ is greatest in $\text{ran } f$; otherwise $f(k)$ is greatest.

Exercise 27 We prove $f_1(n) = f_2(n)$ for all $n \in \omega$ by strong induction on n . Assume that $(\forall m \in n) f_1(m) = f_2(m)$. Then $f_1 \upharpoonright n = f_2 \upharpoonright n$. So

$$\begin{aligned} f_1(n) &= G(f_1 \upharpoonright n) \\ &= G(f_2 \upharpoonright n) \\ &= f_2(n) \end{aligned}$$

Exercise 28 Suppose ω is not transitive. Then there exists a natural number n such that $n \not\subseteq \omega$. Let n be the least such number. There exists $x \in n$ such that $x \not\subseteq \omega$. Now, $n \neq \emptyset$ (because it is nonempty) so $n = p^+$ for some natural number p . We have $x \in p^+$ so $x \in p$ or $x = p$. We cannot have $x = p$ (because x is not a natural number) so we have $x \in p$. But this contradicts the minimality of n .

4.6 Review Exercises

Exercise 29 $4 = \{\emptyset, \{\emptyset\}, \{\emptyset, \{\emptyset\}\}, \{\emptyset, \{\emptyset\}, \{\emptyset, \{\emptyset\}\}\}$

Exercise 30 $\bigcup 4 = 0 \cup 1 \cup 2 \cup 3 = 3$ since 0, 1 and 2 are all subsets of 3.
 $\bigcap 4 = 0 \cap 1 \cap 2 \cap 3 = 0 (= \emptyset)$.

Exercise 31 Similarly to Exercise 30 we have $\bigcup \bigcup 7 = \bigcup 6 = 5$.

Exercise 32

(a) $A^+ = A \cup \{A\} = \{1, A\} = \{1, \{1\}\}$
 So $\bigcup A^+ = 1 \cup \{1\} = \{0, 1\} = 2$

(b) $\bigcup(\{2\}^+) = \bigcup\{2, \{2\}\} = \{0, 1, 2\} = 3$

Exercise 33

(a) Yes - if $x \in y \in \{0, 1, \{1\}\}$ then x is either 0 or 1, and in either case $x \in \{0, 1, \{1\}\}$

(b) No - $0 \in 1 \in \{1\}$ but $0 \notin \{1\}$

(c) No - $0 \in \{0\} \in \langle 0, 1 \rangle$ but $0 \notin \langle 0, 1 \rangle$.

Exercise 34

(a) Let $a = \{\emptyset\}$ and $b = \emptyset$

(b) Let $c = \{\{\emptyset\}\}$, $d = \{\emptyset\}$ and $e = \emptyset$

Exercise 35

(a) Let $T_1 = \{\{1\}, \{1, 0\}, 0, 1\}$

(b) Let $T_2 = \{\langle 1, 0 \rangle, \{1\}, \{1, 0\}, 0, 1\}$.

Exercise 36

$$\begin{aligned} h(4) &= 2h(3) \\ &= 4h(2) \\ &= 8h(1) \\ &= 16h(0) \\ &= 48 \end{aligned}$$

Exercise 37

(a) Let $f : m \rightarrow A$ and $g : n \rightarrow B$ be bijections. Define $h : m + n \rightarrow A \cup B$ by

$$\begin{aligned} h(p) &= f(p) && \text{if } p \in m \\ h(m + q) &= g(q) && \text{if } q \in n \end{aligned}$$

To show that this is well-defined, we must prove two things:

1. For all $p \in m + n$, then either $p \in m$ or there exists $q \in n$ such that $p = m + q$.
2. We never have $p \in m$ and $p = m + q$ for some $q \in n$.

We prove 1 by induction on n . For all $p \in m + 0$ we have $p \in m$, so the result holds for $n = 0$.

Now, suppose the result holds for n . Let $p \in m + n^+ = (m + n)^+$ so $p \in m + n$. If $p \in m + n$, we simply apply the induction hypothesis. If $p = m + n$ then $p = m + q$ where $q = n \in n^+$.

To prove 2, if $p = m + q$ then $m = m + 0$ and $m + q = p$ by Theorem 4N, hence $p \notin m$ by trichotomy.

It remains to show that h is a bijection.

To prove h is injective, we consider three cases. If $h(p) = h(p')$ where $p, p' \in m$, then $f(p) = f(p')$ so $p = p'$. If $h(m + q) = h(m + q')$ where $q, q' \in n$, then $g(q) = g(q')$ so $q = q'$. And we cannot have $h(p) = h(m + q)$ for $p \in m$ and $q \in n$ since $h(p) \in A$, $h(m + q) \in B$, and $A \cap B = \emptyset$.

To prove h is surjective, let $x \in A \cup B$. If $x \in A$, there is some $p \in m$ with $f(p) = x$, so $h(p) = x$. If $x \in B$, there is some $q \in n$ with $g(q) = x$, so $h(m + q) = x$.

(b) Let $f : m \rightarrow A$ and $g : n \rightarrow B$ be bijections.

We first show that, for any $p \in mn$, there exist unique $i \in m$ and $j \in n$ such that $p = mj + i$.

By Exercise 19, there exist j and $i \in m$ such that $p = mj + i$. We have $j \in n$ since otherwise $p = mj + i \in mn$.

For uniqueness, suppose $mj + i = mj' + i'$ where $i, i' \in m$ and $j, j' \in n$. Then we have

$$mj \in mj + i = mj' + i' \in mj' + m = m(j')^+$$

so $j \in (j')^+$ and $j \in j'$. Similarly $j' \in j$, and so $j = j'$. Therefore $i = i'$ by the cancellation law for addition.

Now define $h : mn \rightarrow A \times B$ by

$$h(mj + i) = \langle f(i), g(j) \rangle$$

where $i \in m$ and $j \in n$. It is easy to check that h is bijective.

Exercise 38 $h(n) = 3n + 1$

Exercise 39 $h(n) = n^2$

Exercise 40 $h(n^+) = h(n) + 5$

Chapter 5

Chapter 5 — Construction of the Real Numbers

5.1 Integers

Exercise 1 No, because $[\langle 0, 0 \rangle] = [\langle 1, 1 \rangle]$ but $[\langle 0, 0 \rangle] \neq [\langle 2, 1 \rangle]$.

Exercise 2 Yes, because if $[\langle m, n \rangle] = [\langle p, q \rangle]$ then $[\langle m, m \rangle] = [\langle p, p \rangle]$ because $m + p = m + p$.

Exercise 3 Yes, because if $[\langle m, n \rangle] = [\langle p, q \rangle]$ then $[\langle n, m \rangle] = [\langle q, p \rangle]$ because $n + p = m + q$.

Exercise 4 Let $a = [\langle m, n \rangle]$, $b = [\langle p, q \rangle]$ and $c = [\langle r, s \rangle]$. Then

$$\begin{aligned} a +_Z (b +_Z c) &= [\langle m, n \rangle] +_Z [\langle p + r, q + s \rangle] \\ &= [\langle m + (p + r), n + (q + s) \rangle] \\ &= [\langle (m + p) + r, (n + q) + s \rangle] \\ &= [\langle m + p, n + q \rangle] +_Z [\langle r, s \rangle] \\ &= (a +_Z b) +_Z c \end{aligned}$$

Exercise 5

$$[\langle m, n \rangle] - [\langle p, q \rangle] = [\langle m, n \rangle] + [\langle q, p \rangle] = [\langle m + q, n + p \rangle]$$

Exercise 6 Let $a = [\langle m, n \rangle]$. Then

$$\begin{aligned} a \cdot_Z 0_Z &= [\langle m, n \rangle] \cdot_Z [\langle 0, 0 \rangle] \\ &= [\langle m0 + n0, m0 + n0 \rangle] \\ &= [\langle 0, 0 \rangle] \\ &= 0_Z \end{aligned}$$

Exercise 7 We have $a \cdot_Z b +_Z a \cdot_Z (-b) = a \cdot_Z (b +_Z (-b)) = a \cdot_Z 0_Z = 0_Z$, hence $a \cdot_Z (-b) = -(a \cdot_Z b)$ by the uniqueness of inverses.

We prove $(-a) \cdot_Z b = -(a \cdot_Z b)$ similarly.

Exercise 8

(a) This says $[\langle m + n, 0 \rangle] = [\langle m, 0 \rangle] +_Z [\langle n, 0 \rangle]$, which is true from the definition of $+_Z$.

(b) We have

$$\begin{aligned} E(m) \cdot_Z E(n) &= [\langle m, 0 \rangle] \cdot_Z [\langle n, 0 \rangle] \\ &= [\langle mn + 0 \cdot 0, m0 + n0 \rangle] \\ &= E(mn) \end{aligned}$$

(c)

$$\begin{aligned} E(m) <_Z E(n) &\Leftrightarrow [\langle m, 0 \rangle] <_Z [\langle n, 0 \rangle] \\ &\Leftrightarrow m + 0 \in n + 0 \\ &\Leftrightarrow m \in n \end{aligned}$$

Exercise 9

$$\begin{aligned} E(m) - E(n) &= [\langle m, 0 \rangle] - [\langle n, 0 \rangle] \\ &= [\langle m, n \rangle] \end{aligned}$$

by Exercise 5.

5.2 Rational Numbers

Exercise 10 Let $r = [\langle a, b \rangle]$. Then

$$\begin{aligned} r \cdot_Q 0_Q &= [\langle a, b \rangle] \cdot_Q [\langle 0, 1 \rangle] \\ &= [\langle a \cdot_Z 0, b \cdot_Z 1 \rangle] \\ &= [\langle 0, b \rangle] \\ &= [\langle 0, 1 \rangle] \end{aligned}$$

since $\langle 0, b \rangle \sim \langle 0, 1 \rangle$ because $0 \cdot_Z 1 = 0 \cdot_Z b = 0$.

Exercise 11 Let $r = [\langle a, b \rangle]$ and $s = [\langle c, d \rangle]$. Suppose $r \cdot_Q s = 0_Q$. Then

$$[\langle ac, bd \rangle] = [\langle 0, 1 \rangle]$$

that is, $ac = 0$. Hence $a = 0$ or $c = 0$, which means $r = 0_Q$ or $s = 0_Q$.

Exercise 12 This follows from Theorem 5QJ(a) with $s = 0_Q$ and $t = -r$.

Exercise 13 Let $a, b, c \in \mathbb{Z}$. If $a +_Z c = b +_Z c$ then

$$\begin{aligned} a +_Z c +_Z (-c) &= b +_Z c +_Z (-c) \\ \therefore a +_Z 0 &= b +_Z 0 && \text{(Theorem 5ZD(b))} \\ \therefore a &= b && \text{(Theorem 5ZD(a))} \end{aligned}$$

Exercise 14 Suppose $p <_Q s$. Let $r = (p +_Q s)/2$. Then

$$\begin{aligned} p &<_Q s \\ \therefore 2p &<_Q p +_Q s \\ \therefore p &<_Q (p +_Q s)/2 \\ &= r \\ p &<_Q s \\ \therefore p +_Q s &<_Q 2s \\ \therefore (p +_Q s)/2 &<_Q s \\ \therefore r &<_Q s \end{aligned}$$

5.3 Real Numbers

Exercise 15 PROOF:

$\langle 1 \rangle 1.$ $\bigcup A$ is closed downwards.

$\langle 2 \rangle 1.$ LET: $q \in \bigcup A$ and $p < q$

$\langle 2 \rangle 2.$ PICK $x \in A$ such that $q \in x$

$\langle 2 \rangle 3.$ $p \in x$

PROOF: Since x is closed downwards.

$\langle 2 \rangle 4.$ $p \in \bigcup A$

$\langle 1 \rangle 2.$ $\bigcup A$ has no largest element.

$\langle 2 \rangle 1.$ LET: $q \in \bigcup A$

$\langle 2 \rangle 2.$ PICK $x \in A$ such that $q \in x$

$\langle 2 \rangle 3.$ PICK $r \in x$ such that $q < r$

PROOF: Since x has no largest element.

$\langle 2 \rangle 4.$ $r \in \bigcup A$

□

Exercise 16 PROOF:

- ⟨1⟩1. LET: $q \in x +_R y$
- ⟨1⟩2. PICK rationals $a \in x$ and $b \in y$ such that $q = a + b$
- ⟨1⟩3. PICK $a' \in x$ and $b' \in y$ such that $a < a'$ and $b < b'$

PROOF: Since x and y each have no largest element.

- ⟨1⟩4. $q < a' + b' \in x +_R y$

□

Exercise 17 If $b < 0$ we can take $k = 0$. If $b \geq 0$ then there is a natural number n such that $b = E(n)$; take $k = n^+$. Then $b < ak$ since $1 \leq a$ and $b < k$.

Exercise 18 Let $p = [\langle a, b \rangle]$ and $r = [\langle c, d \rangle]$ where a, b and d are positive. By Exercise 17, there exists a natural number k such that $bc < adE(k)$. Therefore $r < p \cdot E(E(k))$.

Exercise 19 Pick a rational $a \in x$ (which we can do since $x \neq \emptyset$). We first prove that there exists a natural number k such that $a + kp \notin x$.

Pick a rational $b \notin x$ (which we can do since $x \neq \mathbb{Q}$). We have $a < b$ (since x is closed downwards). By Exercise 18, there exists a natural number k such that

$$\begin{aligned} b - a &< kp \\ \therefore a + kp &> b \\ \therefore a + kp &\notin x \end{aligned}$$

Now, let k be the least natural number such that $a + kp \notin x$ (by the Well-Ordering Principle). We have $k \neq 0$ (since $a \in x$); let $k = n^+$. Then we have

$$a + np \in x \quad a + np + p \notin x$$

Take $q = a + np$.

Exercise 20 We must prove $0 \subseteq x \cup -x$. Let $q \in 0$ and assume $q \notin x$. Then $q < 0$ and $-0 = 0 \notin x$, so $q \in -x$.

Exercise 21 PROOF:

- ⟨1⟩1. LET: x, y be real numbers with $x < y$
- ⟨1⟩2. PICK $r \in y$ such that $r \notin x$
- ⟨1⟩3. PICK $s \in y$ such that $r < s$

PROVE: $x < E(s) < y$

- ⟨1⟩4. $x \subseteq E(s)$

PROOF: If $p \in x$ then $p < r < s$

- ⟨1⟩5. $x \neq E(s)$

PROOF: Since $r \in E(s)$ and $r \notin x$

- ⟨1⟩6. $E(s) \subseteq y$

PROOF: Since y is closed downwards.

$\langle 1 \rangle 7. E(s) \neq y$

PROOF: Since $s \in y$ but $s \notin E(s)$.

Exercise 22 $|x|$ is either x or $-x$, and they are both real numbers.