

My set theory exercises

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Useful things

I think that it is pretty straightforward to define some function based on axioms that we get. For example pairing axiom allows us to define $PA : S \times S \rightarrow S$ by

$$PA(u, v) = \{u, v\}$$

same goes for union axiom

$$UA(u) = \{\text{elements of elements of } U\}$$

Later some other function might be defined in the same manner.

In logic notation, I denote tautology as 'true' and contradiction as 'false'

There is a rule that I've used

$$a \wedge (b \vee \neg a) \Leftrightarrow (a \wedge b) \vee (a \wedge \neg a) \Leftrightarrow (a \wedge b) \vee (\text{false}) \Leftrightarrow a \wedge b$$

which I don't remember seeing in the book, but it's pretty useful.

Sometimes I use \oplus to denote xor.

I also denote ${}^B A$ as A^B , because it's more convinient.

Chapter 1

Introduction

1.1 Elementary Set Theory

Let A, B, C be sets

1.1.1

If $a \notin A \setminus B$ and $a \in A$, show that $a \in B$

Because $a \notin A \setminus B$, we follow that $x \in B$ or $x \notin A$. Since $x \in A$, we follow that $x \in B$, as desired.

1.1.2

Show that if $A \subseteq B$, then $C \setminus B \subseteq C \setminus A$

Let $c \in C \setminus B$. Then we follow that $c \in C$ or $c \notin B$. Since $A \subseteq B$, we follow that $c \notin B$ implies that $c \notin A$. Thus we follow that $c \in C \setminus B$ implies that $c \in C \setminus A$. Therefore $C \setminus B \subseteq C \setminus A$.

1.1.3

Suppose $A \setminus B \subseteq C$. Show that $A \setminus C \subseteq B$.

Suppose that $a \in A \setminus C$. Then we follow that $a \in A$ and $a \notin C$.

Given that $A \setminus B \subseteq C$ and $A \not\subseteq C$, we follow that $a \notin A \setminus B$. Thus $a \notin A$ or $a \in B$. Since $a \in A$, we follow that $a \in B$. Thus

$$a \in A \setminus C \rightarrow a \in B$$

$$A \setminus C \subseteq B$$

as desired.

1.1.4

Suppose $A \subseteq B$ and $A \subseteq C$. Show that $A \subseteq B \cap C$

Suppose that $a \in A$. Then we follow that $a \in B$ and $a \in C$. Thus $a \in B \cap C$. Therefore we follow that $A \subseteq B \cap C$.

1.1.5

Suppose $A \subseteq B$ and $B \cap C = \emptyset$. Show that $A \subseteq B \setminus C$

Suppose that $a \in A$. Then we follow that $a \in B$ and since $B \cap C = \emptyset$, we follow that $a \notin C$. Thus $a \in B \setminus C$ by definition. Therefore $A \subseteq B \setminus C$.

1.1.6

Show that $A \setminus (B \setminus C) \subseteq (A \setminus B) \cup C$.

Suppose that $a \in A \setminus (B \setminus C)$. Then we follow that $a \in A$ and $a \notin B \setminus C$. Thus $a \notin B$ and $a \in C$. Thus we follow that $a \in A \setminus B$ or $a \in C$. Thus $A \setminus (B \setminus C) \subseteq (A \setminus B) \cup C$ as desired.

1.1.7

Show that $A \setminus B \subseteq C$ and $A \not\subseteq C$ then $A \cap B = \emptyset$

Suppose that $A \cap B = \emptyset$. We follow that $A \setminus B = A$, thus $A \setminus B = A \subseteq C$, which is a contradiction.

1.1.8

Let $P(x)$ be the property $x > \frac{1}{x}$. Are the assertions $P(2)$, $P(-2)$, $P(\frac{1}{2})$, $P(\frac{-1}{2})$ true or false

$$\begin{aligned} 2 &> \frac{1}{2} \rightarrow P(2) = \text{true} \\ -2 &< \frac{-1}{2} \rightarrow P(-2) = \text{false} \end{aligned}$$

last two are reversed.

1.1.9

Show that each of the following sets can be expressed as an interval

$$a) (-3, 3)$$

$$b) (-3, \infty)$$

$$c)(-3, 3)$$

all of them follow from order properties of real numbers.

1.1.10

Express the following sets as truth sets

$$A = \{1, 4, 9, 16, 25, \dots\} \iff A = \{x \in N : x = y^2 \text{ for some } y \in N\}$$

$$B = \{\dots, -15, -10, -5, 0, 5, \dots\} \iff A = \{x \in N : x = 5y \text{ for some } y \in N\}$$

1.2 Logical Notation

1.2.1

Using truth tables, show that $\neg(P \Rightarrow Q) \Leftrightarrow (P \wedge \neg Q)$

P	Q	$P \Rightarrow Q$	$\neg(P \Rightarrow Q)$	$\neg Q$	$P \wedge \neg Q$
false	false	true	false	true	false
false	true	true	false	false	false
true	false	false	true	true	true
true	true	true	false	false	false

from this we can see that they are equivalent.

Following 4 exercises are the same as this one, so I'm skipping them

1.2.5

Show that $(P \Rightarrow Q) \wedge (P \Rightarrow R) \Leftrightarrow P \Rightarrow (Q \wedge R)$, using logic laws

$$(P \Rightarrow Q) \wedge (P \Rightarrow R) \Leftrightarrow (\neg P \vee Q) \wedge (\neg P \vee R) \Leftrightarrow \neg P \vee (Q \wedge R) \Leftrightarrow P \Rightarrow (Q \wedge R)$$

Laws used:

$$CL \rightarrow DIST \rightarrow CL$$

1.2.6

Show that $(P \Rightarrow R) \vee (Q \Rightarrow R) \Leftrightarrow (P \wedge Q) \Rightarrow R$, using logic laws

$$\begin{aligned} (P \Rightarrow R) \vee (Q \Rightarrow R) &\Leftrightarrow (\neg P \vee R) \vee (\neg Q \vee R) \Leftrightarrow \neg P \vee R \vee \neg Q \vee R \Leftrightarrow (\neg Q \vee \neg P) \vee R \Leftrightarrow \\ &\Leftrightarrow \neg(Q \wedge P) \vee R \Leftrightarrow (Q \wedge P) \Rightarrow R \end{aligned}$$

Laws used:

$$CL \rightarrow ASC \rightarrow ID, ASC \rightarrow DML \rightarrow CL$$

1.2.7

Show that $P \Rightarrow (Q \Rightarrow R) \Leftrightarrow (P \wedge Q) \Rightarrow R$, using logic laws

$$P \Rightarrow (Q \Rightarrow R) \Leftrightarrow \neg P \vee (Q \Rightarrow R) \Leftrightarrow \neg P \vee (\neg Q \vee R) \Leftrightarrow (\neg P \vee \neg Q) \vee R \Leftrightarrow \neg(P \wedge Q) \vee R \Leftrightarrow (P \wedge Q) \Rightarrow R$$

Laws used:

$$CL \rightarrow CL \rightarrow ASC \rightarrow DML \rightarrow CL$$

1.2.8

Show that $(P \Rightarrow Q) \Rightarrow R$ and $P \Rightarrow (Q \Rightarrow R)$ are not logically equivalent

We're gonna show that $q \wedge w \Leftrightarrow false$

$$\begin{aligned} ((P \Rightarrow Q) \Rightarrow R) \wedge (P \Rightarrow (Q \Rightarrow R)) &\Leftrightarrow (\neg(\neg P \vee Q) \vee R) \wedge (\neg P \vee (\neg Q \vee R)) \Leftrightarrow \\ &\Leftrightarrow ((P \wedge \neg Q) \vee R) \wedge (\neg P \vee \neg Q \vee R) \Leftrightarrow ((P \wedge Q) \wedge (\neg P \vee \neg Q)) \vee R \Leftrightarrow \\ &\Leftrightarrow ((P \wedge Q) \wedge \neg(P \wedge Q)) \vee R \Leftrightarrow false \vee R \Leftrightarrow false \end{aligned}$$

1.3 Predicates and Quantifiers**1.4 A Formal Language for Set Theory****1.4.1**

What does the formula $\exists x \forall y (x \notin y)$ say in English?

There exists x such that for every y we've got that x is not in y . In other words, there exists an empty set.

1.4.2

What does the formula $\forall y \exists x (y \notin x)$ say in English?

For every y there exists set x such that y is not in x .

1.4.3

What does the formula $\forall y \exists x (x \notin y)$ say in English?

For every y there exists x such that x is not in y .

1.4.4

What does the formula $\forall y \neg \exists x (x \notin y)$ say in English?

For every y there does not exist an x such that x is not in y .

1.4.5

What does the formula $\forall z \exists x \exists y (x \in y \wedge y \in z)$ say in English?

For every z there exists x and y such that x is in y and y is in z

1.4.6

Let $\phi(x)$ be a formula. What does $\forall z \forall y ((\phi(x) \wedge \phi(y)) \rightarrow z = y)$

For every z and y , $\phi(x)$ and $\phi(y)$ implies that $z = y$.

1.4.7

Translate each of the following into the language of set theory.

(a) x is the union of a and b

$$\forall (y \in x)(y \in a \vee y \in b)$$

(b) x is not a subset of y

$$\exists (z \in x)(z \notin y)$$

(c) x is the intersection of a and b

$$\forall (y \in x)(y \in a \wedge y \in b)$$

(d) a and b have no elements in common

$$\forall (x \in a) \forall (y \in b)(x \neq y)$$

1.4.8

Let a , b , C and D be sets. Show that the relationship

$$y = \begin{cases} a & \text{if } x \in C \setminus D \\ b & \text{if } x \notin C \setminus D \end{cases}$$

$$((x \in C \wedge \neg x \in D) \rightarrow (y = a)) \wedge ((\neg x \in C \wedge \neg x \in D) \rightarrow (y = b))$$

1.5 The Zermelo-Fraenkel Axioms

1.5.1

Let u, v, w be sets. By pairing axiom, the sets $\{u\}$ and $\{v, w\}$ exist. Using the pairing and union axioms, show that the set $\{u, v, w\}$ exists.

By pairing axiom we've got that

$$PA(u, u) = \{u\}$$

$$PA(v, w) = \{v, w\}$$

thus

$$PA(\{u\}, \{v, w\}) = \{\{u\}, \{v, w\}\}$$

and therefore by union axiom we follow that

$$UA(\{\{u\}, \{v, w\}\}) = \{u, v, w\}$$

as desired.

1.5.2

Let A be a set. Show that the pairing axiom implies that the set $\{A\}$ exists

$$PA(A, A) = \{A, A\}$$

which by extension axiom is equal to $\{A\}$, as desired.

1.5.3

Let A be a set. The pairing axiom implies that the set $\{A\}$ exists. Using the regularity axiom, show that $A \cap \{A\} = \emptyset$. Conclude that $A \notin A$.

Since $\{A\} \neq \emptyset$, we follow that there exists x such that $x \in \{A\}$ and $x \cap \{A\} = \emptyset$. Since A is the only element of $\{A\}$, we follow that $A \cap \{A\} = \emptyset$, as desired.

1.5.4

For sets A, B , the set $\{A, B\}$ exists by the pairing axiom. Let $A \in B$. Using the regularity axiom, show that $A \cap \{A, B\} = \emptyset$, and thus $B \notin A$.

$\{A, B\}$ consists of sets A and B , thus it is not empty and therefore there exists $x \in \{A, B\}$ such that $x \in \{A, B\} \wedge x \cap \{A, B\} = \emptyset$. For B we've got that $B \in \{A, B\}$. Since $A \in B$ and $A \in \{A, B\}$, we can follow that $A \in (B \cap \{A, B\})$. By pairing axiom we follow that the element with desired property must exist, and given that the only other choice is A , we conclude that $A \cap \{A, B\} = \emptyset$. Therefore we can follow that $B \notin A$, as desired.

1.5.5

Let A, B, C be sets. Suppose that $A \in B$ and $B \in C$. Using the regularity axiom, show that $C \notin A$.

This is an expansion of previous exercise. We can follow that

$$B \in \{A, B, C\} \wedge B \in C \Rightarrow B \in C \cap \{A, B, C\} \Rightarrow C \cap \{A, B, C\} \neq \emptyset$$

$$A \in \{A, B, C\} \wedge A \in B \Rightarrow A \in B \cap \{A, B, C\} \Rightarrow B \cap \{A, B, C\} \neq \emptyset$$

thus the only other choice is A , and therefore $A \cap \{A, B, C\} = \emptyset$. Therefore $C \notin A$, as desired.

1.5.6

Let A, B be sets. Using the subset and power set axioms, show that the set $\mathcal{P}(A) \cap B$ exists.

Because set A exists we follow that $\mathcal{P}(A)$ exists. By setting $\phi(x) : x \in B$ and subset axiom we follow that there exists a subset of $\mathcal{P}(A)$ such that $x \in S \Leftrightarrow x \in \mathcal{P}(A) \wedge x \in B$. Thus we follow by Extensionality axiom that $S = \mathcal{P}(A) \cap B$. Thus $\mathcal{P}(A) \cap B$ exists.

1.5.7

Let A, B be sets. Using the subset axiom, show that the set $A \setminus B$ exists.

$$\phi(x) : \neg x \in B$$

thus by subset axiom

$$x \in S \Leftrightarrow x \in A \wedge \neg x \in B$$

thus $A \setminus B$ exists.

1.5.8

Show that no two of the sets $\emptyset, \{\emptyset\}, \{\emptyset, \{\emptyset\}\}$ are equal to each other.

I had a little confusion with this one at first because I thought that every set has empty set in it, which is false. Every set has an empty set as a subset, but it might be so that empty set is not in the set itself.

$$\emptyset \notin \emptyset \wedge \emptyset \in \{\emptyset\} \Rightarrow \emptyset \neq \{\emptyset\}$$

$$\emptyset \notin \emptyset \wedge \emptyset \in \{\emptyset, \{\emptyset\}\} \Rightarrow \emptyset \neq \{\emptyset, \{\emptyset\}\}$$

$$\{\emptyset\} \notin \{\emptyset\} \wedge \{\emptyset\} \in \{\emptyset, \{\emptyset\}\} \Rightarrow \{\emptyset\} \neq \{\emptyset, \{\emptyset\}\}$$

all of the implication follow from extensionality axiom.

1.5.9

Let A be a set with no elements. Show that for all x , we have that $x \in A$ if and only if $x \in \emptyset$. Using the extensionality axiom, conclude that $A = \emptyset$.

Suppose that $\neg x \in A$. Then we follow that x is an element, therefore $\neg x \in \emptyset$. Thus

$$\neg x \in A \Rightarrow \neg x \in \emptyset \iff x \in \emptyset \Rightarrow x \in A$$

Suppose that $\neg x \in \emptyset$. Then we follow that x is an element. Thus $\neg x \in A$. Thus

$$\neg x \in \emptyset \Rightarrow \neg x \in A \iff x \in A \Rightarrow x \in \emptyset$$

thus we follow that

$$x \in \emptyset \Leftrightarrow x \in A$$

thus by extensionality axiom we follow that

$$\emptyset = A$$

which gives us nice follow-up that

$$\emptyset = \{\}$$

1.5.10

Let $\phi(x, y)$ be the formula $\forall z(z \in y \Leftrightarrow z = x)$ which asserts that $y = \{x\}$. For all x the set $\{x\}$ exists. So $\forall x \exists! y \phi(x, y)$. Let A be a set. Show that the collection $\{\{x\} : x \in A\}$ is a set.

We know that A is a set and therefore $\mathcal{P}(A)$ is also a set. Thus by subset axiom there exists a set

$$\exists S(x \in S \Leftrightarrow x \in \mathcal{P}(A) \wedge \exists(y \in A)(\phi(x, y)))$$

which is precisely our collection.

Chapter 2

Basic Set-Building Axioms and Operations

2.1 The First Six Axioms

Prove the following theorems, where A, B, C, D are sets.

2.1.1

$$A \subseteq B \rightarrow (A \subseteq A \cup B \wedge A \cap B \subseteq A)$$

$$\begin{aligned} & \forall x(x \in A \rightarrow x \in B) \rightarrow ((\forall x(x \in A \Rightarrow x \in A \vee x \in B)) \wedge (\forall(x \in A \wedge x \in B \Rightarrow x \in A))) \Leftrightarrow \\ & \Leftrightarrow \forall x(x \in A \rightarrow x \in B) \rightarrow ((\forall x(\neg x \in A \vee x \in A \vee x \in B)) \wedge (\forall(\neg(x \in A \wedge x \in B) \vee x \in A))) \Leftrightarrow \\ & \Leftrightarrow \forall x(x \in A \rightarrow x \in B) \rightarrow ((\forall x(\text{true} \vee x \in B)) \wedge (\forall(\neg x \in A \vee \neg x \in B \vee x \in A))) \Leftrightarrow \\ & \Leftrightarrow \forall x(x \in A \rightarrow x \in B) \rightarrow (\text{true} \wedge (\forall(\text{true} \vee \neg x \in B))) \Leftrightarrow \\ & \Leftrightarrow \neg \forall x(x \in A \rightarrow x \in B) \vee (\text{true} \wedge \text{true}) \Leftrightarrow \\ & \Leftrightarrow \neg \forall x(x \in A \rightarrow x \in B) \vee \text{true} \Leftrightarrow \\ & \text{true} \end{aligned}$$

2.1.2

$$A \subseteq B \wedge B \subseteq C \rightarrow A \subseteq C$$

$$\begin{aligned} & (\forall x(x \in A \Rightarrow x \in B)) \wedge (\forall x(x \in B \Rightarrow x \in C)) \rightarrow \forall x(x \in A \Rightarrow x \in C) \Leftrightarrow \\ & \Leftrightarrow (\forall x(\neg x \in A \vee x \in B)) \wedge (\forall x(\neg x \in B \vee x \in C)) \rightarrow \forall x(\neg x \in A \vee x \in C) \Leftrightarrow \\ & \Leftrightarrow (\forall x((\neg x \in A \vee x \in B) \wedge (\neg x \in B \vee x \in C))) \rightarrow \forall x(\neg x \in A \vee x \in C) \Leftrightarrow \\ & \Leftrightarrow (\forall x((\neg x \in A \wedge (\neg x \in B \vee x \in C)) \vee (x \in B \wedge (\neg x \in B \vee x \in C)))) \rightarrow \forall x(\neg x \in A \vee x \in C) \Leftrightarrow \\ & \Leftrightarrow (\forall x(\neg x \in A \wedge (\neg x \in B \vee x \in C)) \vee ((x \in B \wedge \neg x \in B) \vee (x \in B \wedge x \in C))) \rightarrow \forall x(\neg x \in A \vee x \in C) \Leftrightarrow \\ & \Leftrightarrow (\forall x((\neg x \in A \wedge \neg x \in B) \vee (\neg x \in A \wedge x \in C) \vee (x \in B \wedge x \in C))) \rightarrow \forall x(\neg x \in A \vee x \in C) \Leftrightarrow \dots \end{aligned}$$

So this thing is tedious as hell and should be left to computers.

Suppose that $x \in A$. Then we follow by $A \subseteq B$ that $x \in B$. Thus by $B \subseteq C$ we follow that $x \in C$. Therefore $x \in A \rightarrow x \in C$. Therefore $A \subseteq C$, as desired.

2.1.3

$$B \subseteq C \Rightarrow A \setminus C \subseteq A \setminus B$$

Suppose that $x \in A \setminus C$. Then we follow that $x \in A$ and $x \notin C$. Therefore $x \in A$ and $x \notin B$ since $B \subseteq C$. Thus $x \in A \setminus B$. Therefore we follow that $B \subseteq C$ implies that $A \setminus C \subseteq A \setminus B$, as desired.

2.1.4

$$C \subseteq A \wedge C \subseteq B \iff C \subseteq A \cap B$$

Suppose that $x \in C$. Then we follow that $x \in A$ and $x \in B$. Thus $x \in A \cap B$. Therefore $C \subseteq A \cap B$. Thus we follow that $C \subseteq A \wedge C \subseteq B \Rightarrow C \subseteq A \cap B$

Suppose that $x \in C$. Then we follow that $x \in A \cap B$. Thus $x \in A$ and $x \in B$. Therefore $C \subseteq A \wedge C \subseteq B$. Therefore $C \subseteq A \cap B \Rightarrow C \subseteq A \wedge C \subseteq B$ thus we follow that

$$C \subseteq A \wedge C \subseteq B \iff C \subseteq A \cap B$$

as desired.

2.1.5

There exists an x such that $x \notin A$

Suppose that there does not exist x such that $x \notin A$. Then we follow that every set is a member of A , which is impossible.

2.1.6

$$A \cap B = B \cap A$$

$$x \in A \cap B \iff x \in A \wedge x \in B \iff x \in B \wedge x \in A \iff x \in B \cap A$$

2.1.7

$$A \cup B = B \cup A$$

$$x \in A \cup B \iff x \in A \vee x \in B \iff x \in B \vee x \in A \iff x \in B \cup A$$

2.1.8

$$A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$$

$$\begin{aligned} x \in A \cap (B \cup C) &\iff x \in A \wedge x \in (B \cup C) \iff x \in A \wedge (x \in B \vee x \in C) \iff \\ &\iff (x \in A \wedge x \in B) \vee (x \in A \wedge x \in C) \iff (x \in A \cap B) \vee (x \in A \cap C) \iff x \in (A \cap B) \cup (A \cap C) \end{aligned}$$

2.1.31

$$A \subseteq \mathcal{P}(\cup(A))$$

Let $x \in A$. Then we follow that $x \subseteq \cup(A)$. Thus $x \in \mathcal{P}(\cup(A))$. Thus $A \subseteq \mathcal{P}(\cup(A))$.

2.1.32

Let $C \in F$. Then $\mathcal{P}(C) \in \mathcal{P}(\mathcal{P}(\cup F))$

Suppose that $C \in F$. Then we follow that $C \subseteq \cup F$. Therefore $C \in \mathcal{P}(\cup F)$. Thus $\mathcal{P}(C) \in \mathcal{P}(\mathcal{P}(\cup F))$.

the rest of the exercises for this section are more of the same.

2.2 Operations on Sets

Prove the following theorems

2.2.1

Let A be a set and $F \neq \emptyset$. Then

$$A \setminus \cap F = \cup \{A \setminus C : C \in F\}$$

$x \in A \setminus \cap F \Leftrightarrow x \in A \wedge x \notin \cap F \Leftrightarrow x \in A \wedge \neg x \in \cap F \Leftrightarrow x \in A \wedge \neg(\forall(C \in F)(x \in C)) \Leftrightarrow$
 $\Leftrightarrow x \in A \wedge \exists(C \in F)(x \notin C) \Leftrightarrow \exists(C \in F)(x \notin C \wedge x \in A) \Leftrightarrow \exists(C \in F)(x \in A \setminus C) \Leftrightarrow x \in \cup \{A \setminus C : C \in F\}$
 which seems to hold.

2.2.2

Let A, F be sets. Then $A \cup (\cup F) = \cup \{A \cup C : C \in F\}$

$$\begin{aligned} x \in A \cup (\cup F) &\Leftrightarrow x \in A \vee x \in \cup F \Leftrightarrow x \in A \vee (\exists C \in F)(x \in C) \Leftrightarrow \\ &\Leftrightarrow (\exists C \in F)(x \in A) \vee \exists(C \in F)(x \in C) \Leftrightarrow \\ &\Leftrightarrow \exists(C \in F)(x \in A \vee x \in C) \Leftrightarrow \exists(C \in F)(x \in A \cup C) \Leftrightarrow x \in \cup \{A \cup C : C \in F\} \end{aligned}$$

Where we've used the fact that

$$x \in A \Leftrightarrow x \in A \wedge \text{true} \Leftrightarrow x \in A \wedge (\exists C \in F)(\text{true}) \Leftrightarrow (\exists C \in F)(x \in A \wedge \text{true}) \Leftrightarrow (\exists C \in F)(x \in A)$$

don't know if we can use it, but I used it anyways.

2.2.3

Let A, F be sets. Then $A \cap (\cup F) = \cup \{A \cap C : C \in F\}$

$$\begin{aligned} x \in A \cap (\cup F) &\Leftrightarrow x \in A \wedge x \in \cup F \Leftrightarrow x \in A \wedge (\exists C \in F)(x \in C) \Leftrightarrow \\ &\Leftrightarrow \exists(C \in F)(x \in A \wedge x \in C) \Leftrightarrow \exists(C \in F)(x \in A \cap C) \Leftrightarrow x \in \cup \{A \cap C : C \in F\} \end{aligned}$$

2.2.5

Let A and F be sets. Then there exists a unique set ϵ such that for all Y we have that $Y \in \epsilon$ if and only if $Y = A \cap C$ for some $C \in F$.

$\cup F$ exists by union axiom, $A \cap (\cup F)$ exists by subset axiom. Thus $\mathcal{P}(A \cap (\cup F))$ exists by power axiom. Since $Y = A \cap C \Rightarrow Y \subseteq A \cap (\cup F)$, we follow that Y is a subset of $\mathcal{P}(A \cap (\cup F))$, which exists by subset axiom. By extensionality axiom we follow that the set is unique.

2.2.12

If F and G are nonempty sets, then

$$\cap(F \cup G) = \cap(F) \cap \cap(G)$$

$$\begin{aligned} x \in \cap(F \cup G) &\Leftrightarrow (\forall C \in F \cup G)(x \in C) \Leftrightarrow (\forall C \in F)(x \in C) \wedge (\forall C \in G)(x \in C) \Leftrightarrow \\ &\Leftrightarrow x \in \cap(F) \wedge x \in \cap(G) \Leftrightarrow x \in (\cap(F)) \cap (\cap(G)) \end{aligned}$$

2.2.14

Let F be a nonempty set. Then

$$\mathcal{P}(\cap(F)) = \cap\{\mathcal{P}(C) : C \in F\}$$

$$\begin{aligned} x \in \mathcal{P}(\cap(F)) &\Leftrightarrow x \subseteq \cap(F) \Leftrightarrow (\forall y \in x)(y \in \cap(F)) \Leftrightarrow (\forall y \in x)(\forall(C \in F)(y \in F)) \Leftrightarrow \\ &\forall(C \in F)((\forall y \in x)y \in F) \Leftrightarrow \forall(C \in F)(x \subseteq C) \Leftrightarrow \forall(C \in F)(x \in \mathcal{P}(C)) \Leftrightarrow x \in \cap\{\mathcal{P}(C) : C \in F\} \end{aligned}$$

Chapter 3

Relations and Functions

3.1 Ordered Pairs in Set Theory

3.1.1

Define $\langle a, b, c \rangle = \langle \langle a, b \rangle, c \rangle$ for any sets a, b, c . Prove that this yields an ordered tuple; that is, prove that if $\langle x, y, z \rangle = \langle a, b, c \rangle$, then $x = a$, $y = b$, $z = c$.

Suppose that

$$\langle x_1, x_2, x_3 \rangle = \langle y_1, y_2, y_3 \rangle$$

then we follow that

$$\langle \langle x_1, x_2 \rangle, x_3 \rangle = \langle \langle y_1, y_2 \rangle, y_3 \rangle$$

from which we get that $\langle x_1, x_2 \rangle = \langle y_1, y_2 \rangle$ and $x_3 = y_3$. From $\langle x_1, x_2 \rangle = \langle y_1, y_2 \rangle$ we get that $x_1 = y_1$ and $x_2 = y_2$. In total we get that

$$\langle \langle x_1, x_2 \rangle, x_3 \rangle = \langle \langle y_1, y_2 \rangle, y_3 \rangle \Rightarrow x_1 = y_1 \wedge x_2 = y_2 \wedge x_3 = y_3$$

Thus we follow that given construction defines an ordered tuple, as desired.

3.1.2

Prove that $(A \cup B) \times C = (A \times C) \cup (B \times C)$

$$x \in (A \cup B) \times C \Leftrightarrow x = \langle y, z \rangle \wedge y \in A \cup B \wedge z \in C \Leftrightarrow x = \langle y, z \rangle \wedge (y \in A \vee y \in B) \wedge z \in C$$

$$\Leftrightarrow (x = \langle y, z \rangle \wedge z \in C) \wedge (y \in A \vee y \in B) \Leftrightarrow$$

$$\Leftrightarrow (x = \langle y, z \rangle \wedge z \in C \wedge y \in A) \vee (x = \langle y, z \rangle \wedge z \in C \wedge y \in B) \Leftrightarrow$$

$$\Leftrightarrow (x \in A \times C) \vee (x \in B \times C) \Leftrightarrow x \in (A \times C) \cup (B \times C)$$

as desired.

3.1.3

Prove that $(A \setminus B) \times C = (A \times C) \setminus (B \times C)$

$$\begin{aligned}
 x \in (A \setminus B) \times C &\Leftrightarrow x = \langle y, z \rangle \wedge y \in A \setminus B \wedge z \in C \Leftrightarrow x = \langle y, z \rangle \wedge (y \in A \wedge y \notin B) \wedge z \in C \\
 &\Leftrightarrow (x = \langle y, z \rangle \wedge z \in C) \wedge (y \in A \wedge y \notin B) \Leftrightarrow \\
 &\Leftrightarrow x = \langle y, z \rangle \wedge z \in C \wedge y \in A \wedge y \notin B \Leftrightarrow \\
 &\Leftrightarrow (x = \langle y, z \rangle \wedge y \in A \wedge z \in C) \wedge (x \neq \langle y, z \rangle \vee y \notin B \vee z \notin C) \Leftrightarrow \\
 &\Leftrightarrow (x = \langle y, z \rangle \wedge y \in A \wedge z \in C) \wedge (x \neq \langle y, z \rangle \vee y \notin B \vee z \notin C) \Leftrightarrow \\
 &\Leftrightarrow (x = \langle y, z \rangle \wedge y \in A \wedge z \in C) \wedge \neg(x = \langle y, z \rangle \wedge y \in B \wedge z \in C) \Leftrightarrow \\
 &\Leftrightarrow (x \in A \times C) \wedge \neg(x \in B \times C) \Leftrightarrow x \in (A \times C) \setminus (B \times C)
 \end{aligned}$$

Used a biconditional defined in "useful things"

3.1.4

Prove that

$$(\cup F) \times C = \cup \{A \times C : A \in F\}$$

$$\begin{aligned}
 x \in (\cup F) \times C &\Leftrightarrow x = \langle y, z \rangle \wedge y \in (\cup F) \wedge z \in C \Leftrightarrow x = \langle y, z \rangle \wedge (\exists A \in F)(y \in A) \wedge z \in C \Leftrightarrow \\
 &\Leftrightarrow (\exists A \in F)(y \in A \wedge x = \langle y, z \rangle \wedge z \in C) \Leftrightarrow (\exists A \in F)(x \in A \times C) \Leftrightarrow \\
 &\Leftrightarrow x \in \cup \{A \times C : A \in F\}
 \end{aligned}$$

3.2 Relations**3.2.1**

Explain why the empty set is a relation

Relation is defined to be a set of ordered pairs. That is, for every $x \in R$, x is an ordered pair. Since we haven't got any elements in the emptyset, we follow that the logical statement is true and therefore emptyset is a relation.

Other way to see it is to assume that it is not a relation. Then we follow that emptyset has an element that is not an ordered pair. Since emptyset does not have any elements, we follow that we have a contradiction.

3.2.2

Prove items 1-3 of Theorem 3.2.7

$$x \in \text{dom}(R^{-1}) \Leftrightarrow \exists y(\langle x, y \rangle \in R^{-1}) \Leftrightarrow \exists y(\langle y, x \rangle \in R) \Leftrightarrow x \in \text{ran}(R)$$

$$x \in \text{ran}(R^{-1}) \Leftrightarrow \exists y(\langle y, x \rangle \in R^{-1}) \Leftrightarrow \exists y(\langle x, y \rangle \in R) \Leftrightarrow x \in \text{dom}(R)$$

$$\begin{aligned} x \in (R^{-1})^{-1} &\Leftrightarrow \exists y \exists z (\langle y, z \rangle \in (R^{-1})^{-1}) \wedge x = \langle y, z \rangle \Leftrightarrow \exists y \exists z (\langle z, y \rangle \in (R^{-1})) \wedge x = \langle y, z \rangle \Leftrightarrow \\ &\Leftrightarrow \exists y \exists z (\langle y, z \rangle \in R) \wedge x = \langle y, z \rangle \Leftrightarrow x \in R \end{aligned}$$

3.2.4

$$\text{dom}(R) = \{0, 1, 2, 3, 4\}$$

$$\text{ran}(R) = \{0, 1, 2, 3, 4\}$$

$$R \circ R = \{\langle 0, 2 \rangle, \langle 0, 3 \rangle, \langle 0, 0 \rangle, \langle 0, 3 \rangle, \langle 0, 4 \rangle, \langle 1, 0 \rangle, \langle 1, 3 \rangle, \langle 1, 4 \rangle, \langle 1, 3 \rangle, \langle 1, 2 \rangle, \langle 2, 1 \rangle,$$

$$\langle 2, 2 \rangle, \langle 2, 3 \rangle, \langle 2, 2 \rangle, \langle 2, 4 \rangle, \langle 3, 3 \rangle, \langle 3, 2 \rangle, \langle 4, 4 \rangle\}$$

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

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

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

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

3.2.5

Suppose that R is a relation. Prove that $R|(A \cup B) = (R|A) \cup (R|B)$ for any sets A, B

$$\begin{aligned} x \in R|(A \cup B) &\Leftrightarrow (\exists y \in A \cup B)(\exists z \in \text{ran}(R))(\langle y, z \rangle \in R \wedge x = \langle y, z \rangle) \Leftrightarrow \\ &\Leftrightarrow (\exists y \in A)(\exists z \in \text{ran}(R))(\langle y, z \rangle \in R \wedge x = \langle y, z \rangle) \vee (\exists y \in B)(\exists z \in \text{ran}(R))(\langle y, z \rangle \in R \wedge x = \langle y, z \rangle) \Leftrightarrow \\ &\Leftrightarrow x \in R|A \vee x \in R|B \Leftrightarrow x \in (R|A \cup R|B) \end{aligned}$$

thus

$$R|(A \cup B) = (R|A) \cup (R|B)$$

as desired.

3.2.6

Let R be a relation. Prove that $\text{fld}(R) = \bigcup \bigcup R$.

$$\begin{aligned} x \in \text{fld}(R) &\Leftrightarrow x \in \text{dom}(R) \vee x \in \text{ran}(R) \Leftrightarrow (\exists z \in R)(\exists y)(z = \langle x, y \rangle \vee z = \langle y, x \rangle) \Leftrightarrow \\ &\Leftrightarrow (\exists z \in R)(\exists y)(z = \{\{x\}, \{x, y\}\} \vee z = \{\{y\}, \{y, x\}\}) \Leftrightarrow (\exists z \in R)(x \in \bigcup z) \Leftrightarrow x \in \bigcup \bigcup R \end{aligned}$$

3.2.7

Let R and S be two relations and let A, B, C be sets. Prove that $R[A]$, $R^{-1}[B]$, $R[C]$ and $R \circ S$ are sets.

Given that R and S are relation, we follow that both of them are sets, $\bigcup \bigcup R$ and $\bigcup \bigcup S$ are sets and $\text{dom}(R), \text{ran}(R), \text{dom}(S), \text{ran}(S)$ are sets. Thus we follow that $R[A]$ is a subset of R , which is a set; $R^{-1}[B]$ and $R[C]$ are subsets of $\bigcup \bigcup R$, and $R \circ S$ are subsets of a set $\text{dom}(R) \times \text{ran}(S)$, which is a set.

3.2.8

Let R be a relation and G be a set. Prove that $\{R[C] : C \in G\}$ is a set. Prove that if G is nonempty, then $\{R[C] : C \in G\}$ is also nonempty.

If R is a relation, then $\text{ran}(R)$ is a set. Therefore $\mathcal{P}(\text{ran}(R))$ is a set. Thus for any set C , $R[C] \subseteq \text{ran}(R)$, therefore $R[C] \in \mathcal{P}(\text{ran}(R))$. Thus $\{R[C] : C \in G\}$ is a subset of $\mathcal{P}(\mathcal{P}(\text{ran}(R)))$, which is a set.

Suppose that G is nonempty. Then we follow that there exists $C \in G$. Thus $R[C]$ is a set. Thus $R[C] \in \{R[C] : C \in G\}$. Therefore $\{R[C] : C \in G\}$ is nonempty.

3.2.10

Let R be a relation on A . Prove that R is symmetric if and only if

$$R^{-1} \subseteq R$$

In forward direction: Suppose that R is symmetric. Let $y \in R^{-1}$. We follow that there exists u, v such that $y = \langle u, v \rangle$. Thus $\langle v, u \rangle \in R$ by the definition. Since R is symmetric, we follow that $\langle u, v \rangle \in R$. Therefore $y \in R \Rightarrow y \in R$, as desired.

In reverse direction: Suppose that $R^{-1} \subseteq R$. Let $y \in R$. Then we follow that there exists u, v such that $y = \langle u, v \rangle$. Thus $\langle v, u \rangle \in R^{-1}$. Since $R^{-1} \subseteq R$, we follow that $\langle v, u \rangle \in R$. Thus we follow that $\langle u, v \rangle \in R \Rightarrow \langle u, v \rangle \in R$. Thus R is symmetric by definition, as desired.

3.2.19

Prove item (2) of Theorem 3.2.8

$$R[\bigcup G] = \bigcup R[C] : C \in G$$

$$\begin{aligned} x \in R[\bigcup G] &\Leftrightarrow (\exists y \in \bigcup G)(\langle y, x \rangle \in R) \Leftrightarrow (\exists C \in G)(y \in C \wedge \langle y, x \rangle \in R) \Leftrightarrow \\ &\Leftrightarrow (\exists C \in G)(x \in R[C]) \Leftrightarrow x \in \bigcup R[C] : C \in G \end{aligned}$$

3.2.20

Prove item (4) of Theorem 3.2.8

$$\begin{aligned} x \in R[\bigcap G] &\Leftrightarrow (\exists y \in \bigcap G)(\langle y, x \rangle \in R) \Leftrightarrow \exists y(\forall C \in G)(y \in C \wedge \langle y, x \rangle \in R) \Rightarrow \\ &\Rightarrow (\forall C \in G)(\exists y \in C)(\langle y, x \rangle \in R) \Leftrightarrow (\forall C \in G)(x \in R[C]) \Leftrightarrow x \in \bigcap \{R[C] : C \in G\} \end{aligned}$$

3.2.22

Let R and S be single-rooted relations. Prove that $R \circ S$ is single-rooted

Suppose that $\langle x, y \rangle \in R \circ S$. Then we follow that there exists $z \in \text{fld}(R)$ such that $\langle x, z \rangle \in S$ and $\langle z, y \rangle \in R$. Suppose that there exists $\langle x', y \rangle \in R \circ S$ such that $x \neq x'$. Then we follow that there exists $j \in \text{fld}(R)$ such that $\langle x', j \rangle \in S$ and $\langle j, y \rangle \in R$. If $j = z$, then we follow that $\langle x', z \rangle \in S \wedge \langle x, z \rangle \in S \wedge x \neq x'$. Thus we conclude that S is not single rooted, which is a contradiction. If $j \neq z$, then we follow that

$$\langle j, y \rangle \in R \wedge \langle z, y \rangle \in R \wedge j \neq z$$

thus R is not single-rooted, which is also a contradiction. Therefore we conclude that if $\langle x', y \rangle \in R \circ S$, then $x' = x$. Therefore we follow that $R \circ S$ is single rooted, as desired.

3.3 Functions

3.3.1

Prove Lemma 3.3.5 and Lemma 3.3.13

Suppose that F and G are functions such that $\text{dom}(F) = \text{dom}(G)$. Lemma 3.3.5 states that $F = G$ iff $F(x) = G(x)$ for every $x \in \text{dom}(F)$. If $F = G$, then

$$F(x) = y \Leftrightarrow \langle x, y \rangle \in F \Leftrightarrow \langle x, y \rangle \in G \Leftrightarrow G(x) = y$$

thus $F(x) = G(x)$ for every $x \in \text{dom}(F)$.

Now suppose that $F(x) = G(x)$ for every $x \in \text{dom}(F)$. Then we follow that

$$z \in F \Leftrightarrow z = \langle x, y \rangle \wedge F(x) = y \Leftrightarrow z = \langle x, y \rangle \wedge G(x) = y \Leftrightarrow z \in G$$

as desired.

Lemma 3.3.13 states that a function F is one-to-one if and only if F is single-rooted.

Suppose that F is one-to-one and F is not single rooted. Then we follow that there exists $x, y \in F$ such that $x = \langle u, w \rangle \in F, y = \langle j, w \rangle \in F$. Then we follow that $F(u) = w = F(j)$, which is a contradiction.

Proof of converse is extremely simular.

3.3.2

Let F be a function and let $A \subseteq B \subseteq \text{dom}(F)$. Prove that $F[A] \subseteq F[B]$.

$$x \in F[A] \Leftrightarrow x = \langle u, v \rangle \wedge u \in A \wedge \langle u, v \rangle \in F \Rightarrow x = \langle u, v \rangle \wedge u \in B \wedge \langle u, v \rangle \in F \Leftrightarrow x \in F[B]$$

3.3.5

Let $g : C \rightarrow D$ be a one-to-one function, $A \subseteq C$ and $B \subseteq C$. Prove that if $A \cup B = \emptyset$, then $g[A] \cap g[B] = \emptyset$.

Suppose that $A \cap B = \emptyset$ and $g[A] \cap g[B] \neq \emptyset$. Then we follow that there exists $x \in g[A] \cap g[B]$. Thus

$$x \in g[A] \wedge x \in g[B] \Leftrightarrow (\exists y \in A)(\langle y, x \rangle \in g) \wedge (\exists z \in B)(\langle z, x \rangle \in g)$$

since g is one-to-one, we follow that $z = y$. Thus there exists $z \in A \cap B$, therefore $A \cap B \neq \emptyset$, which is a contradiction.

3.3.9

Suppose that $F : X \rightarrow Y$ is a function. Prove that if $C \subseteq Y$ and $D \subseteq Y$, then $F^{-1}[C \cap D] = F^{-1}[C] \cap F^{-1}[D]$.

Since F is a function, we follow that F^{-1} is a single-rooted relation. Thus we follow that

$$F^{-1}[C \cap D] = F^{-1}[C] \cap F^{-1}[D]$$

as desired.

3.3.10

Let F, G be functions from A to B . Suppose $F \subseteq G$. Prove that $F = G$.

Suppose that $x \in A$. Then we follow that

$$(\exists y \in B)(\langle x, y \rangle \in F) \Rightarrow (\exists y \in B)(\langle x, y \rangle \in G)$$

Thus we follow that for every $x \in A$ (where $\text{dom}(F) = A = \text{dom}(G)$)

$$F(x) = G(x)$$

thus by the lemma 3.3.5 we follow that

$$F = G$$

as desired.

3.3.11

Let C be a set of functions. Suppose that for all f and g in C , we have either $f \subseteq g$ or $g \subseteq f$.

(a) Prove that $\cup C$ is a function

Firstly, since C is a set of sets of ordered pairs, we follow that $\cup C$ is a set of ordered pairs, and therefore it is a relation. Suppose that $x \in \cup C$. Then we follow that there exist $f \in C$ such that $x \in f$ and $x = \langle u, v \rangle$. Suppose that there exists $y \in \cup C$, such that $y = \langle u, v' \rangle$, where $u' \neq u$. Since $y \in \cup C$, we follow that there exists $g \in C$ such that $y \in g$. Because $u' \neq u$, we follow that $g \neq f$. Therefore either $g \subset f$, or $f \subset g$. In both cases we follow that we can't have the case that $u' \neq u$. Thus we follow that for $x, y \in \cup C$, whenever the first part of the x is equal to the first part of y , we follow that the last parts are also equal. Thus we follow that $\cup C$ is a single-valued relation, and therefore it is a function.

3.3.13

Assume $f : A \rightarrow B$ is onto B . Let $C \subseteq B$. Prove that $f[f^{-1}[C]] = C$

$$\begin{aligned} x \in f[f^{-1}[C]] &\Leftrightarrow (\exists y \in f^{-1}[C])(f(y) = x) \Leftrightarrow (\exists z \in C)(\langle y, z \rangle \in f \wedge f(y) = x) \Leftrightarrow \\ &\Leftrightarrow (\exists z \in C)(f(y) = z \wedge f(y) = x) \Leftrightarrow (\exists z \in C)(x = z) \Leftrightarrow x \in C \end{aligned}$$

this notation may be a bit sloppy, but the result is derived faithfully.

3.3.15

Let $f : A \rightarrow B$ be a one-to-one function. Define $G : \mathcal{P}(A) \rightarrow \mathcal{P}(B)$ by $G(X) = f[X]$, for each $X \in \mathcal{P}(A)$. Prove that G is one-to-one.

Let $X_1, X_2 \in \mathcal{P}(A)$ be such that $G(X_1) = G(X_2)$. Then we follow that

$$f[X_1] = f[X_2]$$

thus

$$x \in X_1 \Leftrightarrow (\exists y \in f[X_1])(\langle x, y \rangle \in f) \Leftrightarrow (\exists y \in f[X_2])(\langle x, y \rangle \in f) \Leftrightarrow x \in X_2$$

thus we follow that $X_1 = X_2$. Therefore $G(X_1) = G(X_2) \rightarrow X_1 = X_2$, thus G is one-to-one, as desired.

3.3.21

Let $\langle A_i : i \in I \rangle$ be an indexed function with nonempty terms. Prove that there is an indexed function $x_i : i \in I$ is that $x_i \in A_i$ for all $i \in I$, using theorem 3.3.24

Let C be defined as

$$C = \text{ran}(A)$$

then by theorem 3.3.24 we follow that there exists a function $H : C \rightarrow \cup C$ such that

$$H(A_i) \in A_i$$

define $x = H \circ A$. Then we follow that

$$x(i) = H(A(i)) = H(A_i) \in A_i$$

thus we have the desired function.

3.4 Order Relations**3.4.1**

Define a relation \preceq on the set of integers Z by $x \preceq y$ if and only if $x \leq y$ and $x + y$ is even for all $x, y \in Z$. Prove that \preceq is a partial order on Z

Suppose that $x, y \in Z$. Poset requirements of \leq are going to be omitted.

Then we follow that

$$x + x = 2x$$

, therefore we've got symmetry. If $x \leq y$, $y \leq z$, $x + y$ is even and $y + z$ is even, then we follow that $x + y + y + z$ is even, therefore $x + z - 2y$ is also even. Antisymmetry follows from \leq .

Then answer the following questions about the poset (Z, \preceq)

(a) Is $S = \{1, 2, 3, 4, 5, 6, \dots\}$ a chain in Z

No, since $1 + 2 = 3$ is not even, we follow that $1 \not\preceq 2 \wedge 2 \not\preceq 1$.

(b) Is $S = \{1, 3, 5, 7, \dots\}$ a chain in Z ?

Suppose that $x, y \in Z$. Then we follow that there exist $m, n \in Z$ such that

$$x = 2m + 1$$

$$y = 2n + 1$$

thus

$$x + y = 2m + 2n + 2$$

thus $x + y$ is even for all cases. Since \preceq is a total order, we follow that S is indeed a chain in Z .

(c) Does the set $S = \{1, 2, 3, 4, 5\}$ have a lower bound or an upper bound?

No, since we've got both odd and even numbers in S , we follow that there is no $x \in Z$ such that $x + s$ is even for all $s \in S$, thus there does not exist an element such that $x \preceq s$ or $s \preceq x$ for all $s \in S$

(d) Does $S = \{1, 2, 3, 4, 5\}$ have any maximal or minimal elements?

Yes, 1, 2 are minimal elements and 4, 5 are maximal elements.

3.4.2

Prove Lemma 3.4.5

Suppose that (A, \preceq) is a poset and let \prec be the strict order corresponding to \preceq . Let $x, y, z \in A$. Then we follow that:

(1)

Since $x = x$, we follow that $x \not\prec x$ by definition of a strict order

(2)

Suppose that $x \prec y$. Then we follow that $x \preceq y$ and $y \neq x$. Thus by antisymmetry of \preceq we follow that $y \not\preceq x$, and therefore $y \not\prec x$ by definition.

(3)

Suppose that $x \prec y$ and $y \prec z$. Therefore we follow that $x \preceq y$ and $y \preceq z$, which gives us that $x \preceq z$. Suppose that $x = z$. Then we follow that $z \preceq y$ and thus $z = y$, which is a contradiction. Thus we follow that $x \preceq z$ and $x \neq z$, therefore $x \prec z$, as desired.

(4)

If $x = y$ then $x \not\prec y$ and $y \not\prec x$ by definition of strict order

Both $x \prec y$ and $y \prec x$ imply that $x \neq y$, and by case (2) we follow that for given $x, y \in A$ only one of $x = y$, $x \prec y$ or $y \prec x$ hold.

3.4.3

Find the greatest lower bound of the set $S = \{15, 20, 30\}$ in the poset $(A, |)$, where $A = \{n \in \mathbb{N} : n > 0\}$. Now find the least upper bound of S .

5 and 60 (gcd and lcm) respectively.

3.4.4

Let (A, \preceq) be a poset and let $S \subseteq A$. Suppose that b is the largest element of S . Prove that b is also the least upper bound of S .

Suppose that s is an upper bound of S . Then from the definition of the lower bound we follow that $x \prec s$ for every $x \in A$. Since $b \in S$ we follow that $b \prec s$. Thus b is the least upper bound (can't we just call it supremum?) of A by definition.

3.4.11

Let (B, \preceq') be a poset. Suppose $h : A \rightarrow B$ is an injective function. Define the relation \preceq on A by $x \preceq y$ if and only if $h(x) \preceq' h(y)$, for all $x, y \in A$. Prove that \preceq is a partial order.

Let $x, y, z \in A$. Since h is a function, we follow that $x = x$ implies that $h(x) = h(x)$, therefore $h(x) \preceq' h(x)$, thus $x \preceq x$. Thus we've got reflexivity.

If $x \preceq y$ and $y \preceq z$ we follow that $h(x) \preceq' h(y)$ and $h(y) \preceq' h(z)$, from which we follow that $h(x) \preceq' h(z)$ and therefore $x \preceq z$.

Suppose that $x \preceq y$ and $y \preceq x$. Then we follow that $h(x) \preceq' h(y)$ and $h(y) \preceq' h(x)$. Thus $h(y) = h(x)$. Because h is one-to-one, we follow that this implies that $x = y$. Thus we've got antisymmetry. Therefore \preceq is indeed a poset.

3.4.12

Let (B, \preceq') be a totally ordered. Suppose $h : A \rightarrow B$ is an injective function. Define the relation \preceq on A by $x \preceq y$ if and only if $h(x) \preceq' h(y)$, for all $x, y \in A$. Prove that \preceq is a partial order.

We follow that \preceq is a poset from previous exercise. Suppose that $x, y \in A$. then we follow that $h(x) \preceq' h(y) \vee h(y) \preceq' h(x)$. Thus $x \preceq y \vee y \preceq x$. Therefore \preceq is a total order.

3.4.14

Analogous to 4

3.4.14

Let \preceq be a partial order of A . Let $C \subseteq A$. Show that \preceq_C is a partial order on C . Show that if \preceq is a total order on A , then \preceq_C is a total order on C .

Everything follows directly from definitions.

3.4.17

Let \preceq be a partial order on A . Show that $\text{fld}(\preceq) = A$.

For every $x \in A$ we've got that $x \preceq x$, thus we follow that $\langle x, x \rangle \in \preceq$, thus $x \in \text{fld}(\preceq)$. Thus $A \subseteq \text{fld}(\preceq)$. Since $\text{fld}(\preceq) \subseteq A$ we follow that $A = \text{fld}(\preceq)$, as desired.

3.4.18

Let C be a set where each $\preceq \in C$ is a partial order on its field. Suppose that for any \preceq, \preceq' in C either $\preceq \subseteq \preceq'$ or $\preceq' \subseteq \preceq$

(a) Show that for every \preceq, \preceq' in C if $\preceq \subseteq \preceq'$, then $\text{fld}(\preceq) \subseteq \text{fld}(\preceq')$

Suppose that $\preceq \subseteq \preceq'$. Then we follow that $\text{fld}(\preceq) = \bigcup \preceq$ and $\text{fld}(\preceq') = \bigcup \preceq'$. Suppose that

$$x \in \text{fld}(\preceq)$$

then we follow that there exists y such that $\langle x, y \rangle \in \preceq$ or $\langle y, x \rangle \in \preceq$. Since $\preceq \subseteq \preceq'$, we follow that $\langle x, y \rangle \in \preceq'$ or $\langle y, x \rangle \in \preceq'$. Thus $x \in \text{fld}(\preceq')$. Thus $x \in \text{fld}(\preceq) \Rightarrow x \in \text{fld}(\preceq')$, as desired.

(b) Let \preceq^C be the relation $\bigcup C$ with field $\bigcup \{\text{fld}(\preceq) : \preceq \in C\}$. Prove that \preceq^C is a partial order on its field

Since $\preceq^C = \bigcup C$ we follow that if $x \in \bigcup \{\text{fld}(\preceq) : \preceq \in C\}$, then there exists $\preceq' \in C$ such that $x \in \text{fld}(\preceq')$. Thus, by the fact that \preceq' is a partial order, we follow that $\langle x, x \rangle \in \preceq'$. Thus $\langle x, x \rangle \in \bigcup C$, and therefore $\langle x, x \rangle \in \preceq^C$. Thus \preceq^C is reflexive.

Suppose that $x, y, z \in \bigcup \{\text{fld}(\preceq) : \preceq \in C\}$. Then we follow that there exist $\preceq_x, \preceq_y, \preceq_z$ such that

$$x \in \text{fld}(\preceq_x)$$

and so on. From the description of C we follow that $\preceq_x \subseteq \preceq_y$ or $\preceq_y \subseteq \preceq_x$, which in any case means that there exists \preceq_{xy} (equal to either of them) such that

$$\{x, y\} \subseteq \text{fld}(\preceq_{xy})$$

same goes for \preceq_z and \preceq_{xy} , which means that there exists \preceq' such that

$$\{x, y, z\} \subseteq \text{fld}(\preceq')$$

Since \preceq' is a partial order, we follow that if $x \preceq' y$ and $y \preceq' z$ implies that $x \preceq' z$, therefore $\langle x, z \rangle \in \preceq'$, and therefore $\langle x, z \rangle \in \preceq^C$, thus the relation is transitive.

Now let's go back a bit and focus on \preceq_{xy} . We follow that if $x \preceq_{xy} y$ and $y \preceq_{xy} x$, then by antisymmetry of \preceq_{xy} we follow that $x = y$. Thus we've got the antisymmetry of \preceq^C .

Thus \preceq^C satisfies all requirements of a poset, as desired.

3.4.19

Let (A, \preceq) and (B, \preceq') be posets. Define the relation \preceq_l on $A \times B$ by

$$\langle a, b \rangle \preceq_l \langle x, y \rangle \iff a \prec x \vee (a = x \wedge b \preceq' y)$$

for all $\langle a, b \rangle$ and $\langle x, y \rangle$ in $A \times B$.

(a) Prove that \preceq_l is a partial order on $A \times B$

Let $a \in A$ and $b \in B$. Then we follow that $b \preceq' b$ and $a = a$, thus

$$\langle a, b \rangle \preceq_l \langle a, b \rangle$$

If for some $a_1, a_2, a_3 \in A$ and $b_1, b_2, b_3 \in B$ it is true that

$$\langle a_1, b_1 \rangle \preceq_l \langle a_2, b_2 \rangle$$

and

$$\langle a_2, b_2 \rangle \preceq_l \langle a_3, b_3 \rangle$$

then we follow that

$$a_1 \prec a_2 \vee (a_1 = a_2 \wedge b_1 \preceq' b_2)$$

and

$$a_2 \prec a_3 \vee (a_2 = a_3 \wedge b_2 \preceq' b_3)$$

If $a_1 = a_2 = a_3$, then we follow that $b_1 \preceq' b_2$ and $b_2 \preceq' b_3$, from which we follow that $b_1 \preceq b_3$ and therefore $\langle a_1, b_1 \rangle \preceq \langle a_3, b_3 \rangle$.

If $a_1 \neq a_2$ and $a_2 = a_3$ then we follow that $a_1 \prec a_2$, thus $a_1 \prec a_3$, therefore $\langle a_1, b_1 \rangle \preceq_l \langle a_3, b_3 \rangle$. Similar case holds if $a_1 = a_2$ and $a_2 \neq a_3$

If $a_1 \neq a_2$ and $a_2 \neq a_3$, then we follow that $a_1 \prec a_2$ and $a_2 \prec a_3$, from which we follow that $a_1 \preceq a_3$. If $a_1 = a_3$, then we follow that $a_1 \neq a_2$, which is a contradiction. Thus $a_1 \neq a_3$. Thus $a_1 \prec a_3$. Therefore $\langle a_1, b_1 \rangle \preceq_l \langle a_3, b_3 \rangle$

Thus we follow that $\langle a_1, b_1 \rangle \preceq_l \langle a_3, b_3 \rangle$ for all a_1, a_3 , thus we've got the transitive condition.

Now suppose that $\langle a_1, b_1 \rangle \preceq_l \langle a_2, b_2 \rangle$ and $\langle a_2, b_2 \rangle \preceq_l \langle a_1, b_1 \rangle$. If $a_1 \neq a_2$, then we follow that $a_1 \prec a_2$ and $a_2 \prec a_1$, which is not possible, thus we conclude that $a_1 = a_2$. Thus we follow that $b_1 \preceq' b_2$ and $b_2 \preceq' b_1$, from which we follow that $b_1 = b_2$. Thus $\langle a_1, b_1 \rangle \preceq_l \langle a_2, b_2 \rangle$ and $\langle a_2, b_2 \rangle \preceq_l \langle a_1, b_1 \rangle$, then we follow that $\langle a_1, b_1 \rangle = \langle a_2, b_2 \rangle$. Thus we've got antisymmetry.

Now we can follow that \preceq_l satisfies all of the conditions of poset, as desired.

(b) Suppose that both \preceq and \preceq' are total orders on their respective sets. Prove that \preceq_l is a total order on $A \times B$.

Suppose that $\langle a_1, b_1 \rangle, \langle a_2, b_2 \rangle \in A \times B$ are arbitrary. It follow that $a_1 \preceq a_2$ or $a_2 \preceq a_1$. Thus $a_1 \prec a_2 \vee a_2 \prec a_1 \vee a_1 = a_2$. We also follow that $b_1 \preceq' b_2$ or $b_2 \preceq' b_1$. This it can be shown that

$$\langle a_1, b_1 \rangle \preceq_l \langle a_2, b_2 \rangle$$

or

$$\langle a_2, b_2 \rangle \preceq_l \langle a_1, b_1 \rangle$$

as desired.

3.5 Congruence and Preorder

3.5.1

Let \sim be an equivalence relation on A . Let $f : A \rightarrow A/\sim$ be defined by

$$f(x) = [x]$$

for all $x \in A$. Show that the function f is one-to-one if and only if each equivalence class in A/\sim is a singleton.

In forward direction: Suppose that

$$f(x) = [x]$$

is one-to-one. Suppose that $x, y \in [x]$. Then we follow that $f(x) = f(y)$. Thus by the fact that f is one-to-one we follow that $x = y$. Thus $[x]$ is a singleton.

In reverse direction: Suppose that each $[x]$ is a singleton. Then we follow that if $x \neq y$, then $f(x) \neq f(y)$. Therefore f is one-to-one, as desired.

3.5.2

Prove theorem 3.5.6

Let \sim be an equivalence relation on A and let $f : A \times A \rightarrow A$.

Suppose that there exists a function $\hat{f} : A/\sim \times A/\sim \rightarrow A/\sim$ such that $\hat{f}([x], [y]) = [f(x, y)]$ then we follow that if $x \sim w$ and $y \sim z$, then $[x] = [w]$ and $[y] = [z]$, thus

$$\hat{f}([x], [y]) = [f(x, y)] = \hat{f}([w], [z]) = [f(w, z)]$$

thus we follow that $[f(x, y)] = [f(w, z)]$, therefore $f(x, y) \sim f(w, z)$. Thus we follow that $x \sim w$ and $y \sim z$ implies that $f(x, y) \sim f(w, z)$, therefore f is congruent with \sim .

If $x \sim w$ and $y \sim z$ implies that $f(x, y) \sim f(w, z)$, then we follow that we can construct a relation \hat{f} by

$$\hat{f} = \{ \langle [x], [y] \rangle, [f(x, y)] \mid x, y \in A \}$$

if $[x] = [w]$ and $[y] = [z]$, then we follow that $x \sim w$ and $y \sim z$, therefore $f(x, y) \sim f(w, z)$, therefore $[f(x, y)] = [f(w, z)]$. Thus this relation is a function, as desired.

3.5.3

Prove theorem 3.5.7

Suppose that \sim is an equivalence relation on A and R is a relation on A .

If there exists a relation \hat{R} on A/\sim such that $\hat{R}([x], [y]) \iff R(x, y)$ then we follow that if xRy for some $x, y \in A$ then $\hat{R}([x], [y])$. If there exist $w, z \in A$ such that $x \sim w$ and $y \sim z$, then $[x] = [w]$ and $[y] = [z]$, therefore $\hat{R}([w], [z])$ and thus wRz . Thus we follow that xRy iff wRz . Thus R is congruent with \sim .

If R is congruent with \sim , then we can create a relation \hat{R} by

$$\hat{R} = \{ \langle [x], [y] \rangle : \langle x, y \rangle \in R \}$$

that will satisfy the desired conditions.

3.5.4

Prove lemma 3.5.9

Let (A, \preceq) be a preordered set and let \sim be the relation on A defined by

$$a \sim b \iff a \preceq b \wedge b \preceq a$$

Then we follow that for $a \in A$ $a \preceq a$ by reflexivity of \preceq , therefore $a \sim a$ and thus \sim is reflexive.

If $a, b, c \in A$ such that $a \sim b$ and $b \sim c$, then we follow that

$$a \preceq b \wedge b \preceq c \Rightarrow a \preceq c$$

$$c \preceq b \wedge b \preceq a \Rightarrow c \preceq a$$

thus $a \sim c$. Therefore \sim is transitive.

Suppose that $x \sim y$. Then we follow that $x \preceq y$ and $y \preceq x$. Thus we follow that $y \sim x$, therefore \sim is symmetric. Thus \sim is an equivalence relation, as desired.

3.5.5

Prove lemma 3.5.10

Suppose that (A, \preceq) is a preordered set. Let \sim be the derived equivalence relation on A . Suppose that $a, b, c, d \in A$ are such that $a \sim c$ and $b \sim d$.

If $a \preceq b$ then we follow that $b \preceq d$ by $b \sim d$, therefore $a \preceq d$ by transitive property. From $a \sim c$ we derive that $c \preceq a$, therefore we follow that $c \preceq d$. Similar implication hold for reverse case. Thus we follow that \preceq is congruent with \sim .

Chapter 4

The Natural Numbers

4.1 Inductive Sets

4.1.1

Let I and J be inductive sets. Prove that $I \cap J$ is also inductive.

Since I and J are both inductive, we follow that $\emptyset \in I$ and $\emptyset \in J$, thus $\emptyset \in I \cap J$.

Suppose that $x \in I \cap J$. Then we follow that $x \in I$ and $x \in J$. Since both of them are inductive, we follow that $x^+ \in I$ and $x^+ \in J$, therefore $x^+ \in I \cap J$. Thus we've got that

$$\emptyset \in I \cap J \wedge (\forall x \in I \cap J)(x^+ \in I \cap J)$$

thus we follow that $I \cap J$ is inductive, as desired.

4.1.2

Prove that if A is a transitive set, then A^+ is also a transitive set.

Suppose that A is transitive. That means that $(\forall x \in A)(x \subseteq A)$. By definition, $A^+ = A \cup \{A\}$. Now let $y \in A^+$. We follow that $y = A \vee y \in A$. If $y = A$, then we follow that $y \subseteq A^+$. If $y \in A$, then we follow that $y \subseteq A$ by the fact that A is transitive, therefore $y \subseteq A^+$. Thus we've got that

$$(\forall y \in A^+)(y \subseteq A^+)$$

thus we follow that A^+ is a transitive set, as desired.

4.1.3

Prove that if A is a transitive set if and only if $A \subseteq \mathcal{P}(A)$.

Suppose that A is transitive. Then we follow that $(\forall x \in A)(x \subseteq A)$. Thus if $x \in A$, then $x \subseteq A$ and therefore $x \in \mathcal{P}(A)$. Thus we follow that $A \subseteq \mathcal{P}(A)$.

If $A \subseteq \mathcal{P}(A)$, then we follow that if $x \in A$, then $x \in \mathcal{P}(A)$ and therefore $x \subseteq A$. Thus A is transitive.

4.1.6

Prove Proposition 4.1.9

4.1.9 states that

$$\bigcup(A \cup B) = (\bigcup A) \cup (\bigcup B)$$

$$\begin{aligned} x \in \bigcup(A \cup B) &\Leftrightarrow (\exists C \in A \cup B)(x \in C) \Leftrightarrow (\exists C \in A)(x \in C) \vee (\exists C \in B)(x \in C) \Leftrightarrow \\ &\Leftrightarrow x \in \bigcup A \vee x \in \bigcup B \Leftrightarrow x \in (\bigcup A) \cup (\bigcup B) \end{aligned}$$

4.1.7

Prove that $n \neq n^+$ for all $n \in \omega$

This is true in general by regularity axiom, but let's apply some induction. Let

$$I = \{n \in \omega : n \neq n^+\}$$

$0 \neq \{0\}$, since $0 \in \{0\}$ and $0 \notin 0$ (because it is an empty set). Thus $0 \in I$.

Suppose that $n \in I$. Then we follow that $n \neq n^+$. Suppose that $n^+ = (n^+)^+$. Then we follow by 4.1.12 that $n = n^+$, which is a contradiction, because $n \in I$. Thus we follow that $n \in I \Rightarrow n^+ \in I$, therefore I is inductive, therefore $I = \omega$, as desired.

4.1.8

Prove that $n^+ \not\subseteq n$ for all $n \in \omega$

Suppose that $n^+ \subseteq n$. Since $n^+ = n \cup \{n\}$, we follow that $n \subseteq n^+$. Thus by double inclusion we've got that $n^+ = n$, which contradicts previous exercise.

4.1.9

Prove that for all $m \in \omega$ and all $n \in \omega$, if $m \in n$, then $n \not\subseteq m$.

Let

$$I = \{n \in \omega : m \in n \Rightarrow n \not\subseteq m\}$$

Since $m \in 0 \Leftrightarrow m \in \emptyset$ is always false, we follow that 0 is vacuously in I .

Let $n \in I$. Let $m \in \omega$ be such that $m \in n^+$. Thus $m \in n \cup \{n\}$. Thus $m \in n \vee m = n$.

If $m \in n$, then we follow that $n \not\subseteq m$, thus $(\exists y \in n)(y \notin m)$. Thus $(\exists y \in n \cup \{n\})(y \notin m)$. Therefore $n^+ \not\subseteq m$.

If $m = n$, then we follow that $n^+ \not\subseteq n$ by exercise 4.1.8. Thus we conclude that $n \in I \Rightarrow n^+ \in I$. Therefore I is inductive and thus $I = \omega$, as desired.

4.1.10

Conclude from exercise 9 that $n \notin n$ for all $n \in \omega$.

Suppose that $n \in n$. Then we follow by previous exercise that $n \not\subseteq n$, which is bonkers.

4.1.11

Let A be a set and suppose that $\bigcup A = A$. Prove that A is transitive and for all $x \in A$ there is a $y \in A$ such that $x \in y$.

Let $x \in A$ be arbitrary. Then we follow that $x \subseteq \bigcup A$ and thus $x \subseteq A$. Thus we follow that A is transitive, as desired.

Suppose that $x \in A$ and suppose that for all $y \in A$ we've got that $x \notin y$. Then we follow that $(\forall y \in A)(x \notin y)$. Thus

$$(\forall y \in A)(x \notin y) \Leftrightarrow \neg(\exists y \in A)(x \in y) \Leftrightarrow x \notin \bigcup A \Leftrightarrow x \notin A$$

which is a contradiction.

4.2 The Recursion Theorem on ω

How would one modify the proof of Theorem 4.2.1 in order to establish the following:

Theorem. Let A be a set and let $a \in A$. Suppose that $f : \omega \times A \rightarrow A$ is a function. Then there exists a unique function $h : \omega \rightarrow A$ such that

$$h(0) = a$$

$$h(n^+) = f(n, h(n))$$

We can define S and h in normal fashion, then prove that $\langle 0, a \rangle \in h$ and $\langle n, u \rangle \in h$ will imply that $\langle n^+, f(n^+, h(n)) \rangle \in h$, thus concluding the proof of claim 1.

Proof of claim 2 for the base case will not be altered. (IH) Will be modified in notation.

Proof of uniqueness does not depend on the domain of the functions and is true in general.

4.2.2

Let $a \in A$ and $f : A \rightarrow A$ be a function such that $a \notin \text{ran}(f)$. Suppose that $h : \omega \rightarrow A$ satisfies

$$(1) h(0) = a$$

$$(2) h(n^+) = f(h(n))$$

Assume that h is one-to-one and onto A . Prove that f is one-to-one.

Suppose that f is not one-to-one. Then we follow that there exist $x \neq y \in A$ such that $f(x) = f(y)$. Since h is onto, we follow that there exist $x', y' \in \omega$ such that $h(x') = x$ and $h(y') = y$. Since $x \neq y$ we follow that $h(x') \neq h(y')$ and therefore $x' \neq y'$ because h is a function.

Thus we follow that $x'^+ \neq y'^+$. Because h is one-to-one we follow that

$$h(x'^+) \neq h(y'^+)$$

thus

$$f(h(x')) \neq f(h(y'))$$

$$f(x) \neq f(y)$$

which is a contradiction. Thus we follow that f is one-to-one.

4.2.3

Let A be a set and let $a \in A$. Suppose that $f : A \rightarrow A$ satisfies

$$a \in f(a)$$

$$(\forall x, y \in A)(x \in y \rightarrow f(x) \in f(y))$$

Let $h : \omega \rightarrow A$ be states as in theorem 4.2.1. Prove that $h(n) \in h(n^+)$ for all $n \in \omega$.

We follow that $h(0) = a$ and $h(n^+) = f(h(n))$. For base case we've got that $h(0) = a \in f(a) = h(0^+) = h(1)$. Let I be defined as a subset of ω such that $m \in I$ implies that $h(m) \in h(m^+)$. Base case gives us that $0 \in I$. Suppose that $n \in I$. Then we follow that

$$h(n) \in h(n^+)$$

Since $h(n), h(n^+) \in A$, we follow that

$$f(h(n)) \in f(h(n^+))$$

by definition of h we follow that

$$h(n^+) \in h((n^+)^+)$$

thus $n^+ \in I$. Thus we follow that I is an inductive set. Since $I \subseteq \omega$, we follow that $I = \omega$, as desired.

4.2.4

Let $F : A \rightarrow A$ be a function and let $y \in A$.

(a) Prove that the class $S = \{B : B \subseteq A, y \in B, F[B] \subseteq B\}$

From this definition we follow that $B \in S \Rightarrow B \subseteq A$. Thus $B \in S \Rightarrow B \in \mathcal{P}(A)$. Thus $S \subseteq \mathcal{P}(A)$. Since A is a set we follow that its power set is a set, therefore the subset of a power set is also a set.

(b) Show that S is nonempty

We follow that $A \subseteq A$ by basic properties, $y \in B$ by the given restraints, and $F[B] \subseteq A$ since $F : A \rightarrow A$, and therefore $\text{ran}(F) \subseteq A$. Thus we follow that $A \in S$, therefore S is nonempty.

(c) Let $C = \bigcap S$. Prove that $y \in C$ and $F[C] \subseteq C$.

We follow that

$$(\forall B \in S)(y \in B)$$

from definition of S . Suppose that $y \in F[C]$. Then we follow that because $R[\bigcap G] \subseteq \bigcap \{R[C] : C \in G\}$ for any relation, we follow that

$$y \in \bigcap \{F[B] : B \in S\}$$

$$(\forall B \in S)(y \in F[B])$$

Since for every B we've got that $F[B] \subseteq B$, therefore we can follow that

$$(\forall B \in S)(y \in B)$$

thus $y \in \bigcap S$. Thus $y \in F[C] \Rightarrow y \in C$. Thus $F[C] \subseteq C$, as desired.

(d) Prove that for all $B \subseteq A$, if $y \in B$ and $F[B] \subseteq B$, then $C \subseteq B$

If $y \in B$ and $F[B] \subseteq B$, then we follow that $B \in S$. Since $C = \bigcap S$, we follow that $(\forall x \in C)(x \in C \rightarrow x \in B)$. Thus $C \subseteq B$, as desired.

(e) Prove that $y \in F[C]$ if and only if $F[C] = C$

If $F[C] = C$, then we follow that since $y \in C$, then $y \in F[C]$.

For C we've got that $F[C] \subseteq C$. Thus $F[F[C]] \subseteq C$. Thus if $y \in F[C]$, then $F[C]$ satisfies requirements presented in the previous point, and thus $C \subseteq F[C]$. By double inclusion we follow that $F[C] = C$, as desired.

4.3 Arithmetic on ω

Note

Although not explicitly, but we've started to use the associative and commutative properties of addition pretty liberally at this point. To be more precise, we explicitly define the notation of several pluses in a row to be left-associative (e.g.

$$a_1 + a_2 + a_3 = (a_1 + a_2) + a_3 = A(A(a_1, a_2), a_3)$$

is one such example). Associative and distributive properties guarantee us that the order in which the functions are applied does not matter, and thus the notation is justified.

The order of operations of addition and multiplication is followed from the properties, that are proven in the chapter, and we follow that

$$a \cdot b + c = (a \cdot b) + c = A(M(a, b), c)$$

thus the usual rules of order of operations applies.

In general, all of the operations are defined in terms of functions, and the usual notation of addition and multiplication is nothing but a syntactic sugar. If in doubt, one can prove that the usual notation makes sense pretty easily.

4.3.1

Let $m \in \omega$. Suppose that $m + n = 0$. Prove that $m = n = 0$.

Suppose that $n \neq 0$. Then we follow that there exists j such that $j^+ = n$. Thus

$$m + n = m + j^+ = (m + j)^+ \neq 0$$

thus we get the contradiction.

4.3.2

Let $m \in \omega$ and $n \in \omega$. Show that if $m \cdot n = 0$, then $m = 0$ or $n = 0$.

Suppose that $m \neq 0$ and $n \neq 0$. Then we follow that there exist $n_p \in \omega$ such that $n = n_p^+$. Thus

$$m \cdot n = m \cdot n_p^+ = m \cdot n_p + m$$

Since $m \neq 0 \in \omega$ and $m \cdot n_p^+ \in \omega$, we follow from previous exercise that $m \cdot n_p = 0$ and $m = 0$, which contradicts the assumptions that $m \neq 0$.

4.3.3

Let $m \in \omega$ and $n \in \omega$. Prove that for all $p \in \omega$, if $m + p = n + p$, then $m = n$.

Let

$$I = \{a \in \omega : (\forall m, n \in \omega)(m + a = n + a \Rightarrow m = n)\}$$

If $p = 0$, then $m + 0 = m$, $n + 0 = n$, thus $m + 0 = n + 0$ implies that $m = n$. Thus $0 \in I$.

(IH) Suppose that p is such that $m + p = n + p$. Suppose that $m + p^+ = n + p^+$. Then

$$m + p^+ = (m + p)^+ = (n + p)^+ = n + p^+$$

thus we follow that $p \in I$ implies that $p^+ \in I$. Thus I is inductive, and therefore $I = \omega$.

4.3.4

Prove that for all $n \in \omega$, the inequality $0 \cdot n = 0$ holds.

Suppose that I is the set such that $I = \{n \in \omega : 0 \cdot n = 0\}$. Since $0 \cdot 0 = 0$, we follow that $0 \in I$. Suppose that $0 \cdot n = 0$. Then we follow that

$$0 \cdot n^+ = 0 \cdot n + 0 = 0 + 0 = 0$$

Thus $n \in I \rightarrow n^+ \in I$. Thus $I = \omega$, as desired.

4.3.5

Prove that for all $m \in \omega$ and $n \in \omega$, we have that $m^+ \cdot n = m \cdot n + n$

Suppose that

$$I = \{n \in \omega : (\forall m \in \omega)(m^+ \cdot n = (m \cdot n) + n)\}$$

We follow from $M1$ that $m^+ \cdot 0 = 0$ and $(m \cdot 0) + 0 = m \cdot 0 = 0$ from $A1$ and $M1$. Thus $0 \in I$

Suppose that $n \in I$. Then we follow that

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

where theorems used are

$$M2 \Rightarrow IH \Rightarrow 4.3.4 \Rightarrow 4.3.4 \Rightarrow 4.3.10 \Rightarrow 4.3.4 \Rightarrow M2$$

4.3.6

Let $n \in \omega$. Prove theorem 4.3.13

Let

$$I = \{n \in \omega : n \cdot m = m \cdot n\}$$

We follow that $0 \cdot n = n \cdot 0 = 0$ from the previous exercises/theorems in the chapter. Thus $0 \in I$.

Suppose that $n \cdot m = m \cdot n$. Then for n^+ we've got that

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

where we've used previous exercise, IH , and $M2$ respectively. Thus we follow that $n \in I \Rightarrow n^+ \in I$, thus $I = \omega$, as desired.

4.3.7

Prove that if $n \in \omega$, then n is either even or odd (details of definition of evenness in the exercise)

Let

$$I : \{n \in \omega : (\exists k \in \omega : n = 2 \cdot k + 1 \vee n = 2 \cdot k)\}$$

Since $0 = 2 \cdot 0$, we follow that $0 \in I$.

Suppose that $n \in I$. Then we follow that n is even or odd (or both, we don't know yet).

If n is even, then we follow that $n = 2 \cdot k$. Thus $n^+ = n + 1 = 2 \cdot k + 1$. Thus n^+ is odd, therefore $n^+ \in I$.

If n is odd, then we follow that $n = 2 \cdot k + 1$. Thus $n^+ = n + 1 = 2 \cdot k + 1 + 1 = 2 \cdot k + 2 = 2 \cdot k^+$. Thus we follow that $n^+ \in I$.

Thus we follow that $n \in I \Rightarrow n^+ \in I$, thus $I = \omega$, as desired.

4.3.8

Let $I = \{n \in \omega : \neg((\exists k, j \in \omega)(n = 2 \cdot k \wedge n = 2 \cdot j + 1))\}$ Prove that I is inductive. Conclude that no natural number is both odd and even.

Let $I = \{n \in \omega : \neg((\exists k, j \in \omega)(n = 2 \cdot k \wedge n = 2 \cdot j + 1))\}$

We've shown earlier that 0 is even. Suppose that 0 is odd. Then we follow that

$$0 = 2 \cdot k + 1 = (2 \cdot k)^+$$

which is a contradiction.

Suppose that $n \in I$. Then we follow that

$$\neg((\exists k, j \in \omega)(n = 2 \cdot k \wedge n = 2 \cdot j + 1))$$

thus

$$\begin{aligned} & \neg((\exists k, j \in \omega)(n^+ = (2 \cdot k)^+ \wedge n^+ = (2 \cdot j + 1)^+)) \Leftrightarrow \\ & \Leftrightarrow \neg((\exists k, j \in \omega)(n^+ = 2 \cdot k + 1 \wedge n^+ = 2 \cdot j + 2)) \Leftrightarrow \\ & \Leftrightarrow \neg((\exists k, j \in \omega)(n^+ = 2 \cdot k + 1 \wedge n^+ = 2 \cdot j^+)) \Leftrightarrow \\ & \Leftrightarrow \neg((\exists k, l \in \omega)(n^+ = 2 \cdot k + 1 \wedge n^+ = 2 \cdot l)) \end{aligned}$$

(i've changed a variable under the quantifier for avoid confusion, which does not change the meaning) thus $n \in I \Rightarrow n^+ \in I$. Thus I is inductive, and $I = \omega$. Therefore every natural number is either odd or even, but not both.

4.3.9

Prove for all $m, n, k \in \omega$ that $m^{n+k} = m^n \cdot m^k$,

Let

$$I = \{k \in \omega : (\forall m, n \in \omega)(m^{n+k} = m^n \cdot m^k)\}$$

We follow that if $k = 0$ then

$$E(m, n + k) = E(m, n + 0) = E(m, n) = E(m, n) \cdot 1 = E(m, n) \cdot E(m, k)$$

thus we follow that $0 \in I$.

Suppose that $k \in I$. We follow that for k^+ we've got

$$E(m, n + k^+) = E(m, n + k) \cdot m = E(m, n) \cdot E(m, k) \cdot m = E(m, n) \cdot E(m, k^+)$$

thus we follow that $k \in I \Rightarrow k^+ \in I$. Thus we follow that $I = \omega$, as desired.

4.4 Order on ω **Note**

I'm using the symbol \leq instead of "in or equal" because it's more convinient. Theorems in the chapter provide us with the equivalence of two, and therefore the justification for this notation.

4.4.1

Let $n \in \omega$. Show that $1 \leq n^+$

We know that for every $n \in \omega$, $0 \leq n$. Thus $0 \leq n \Rightarrow 0^+ \leq n^+ \Leftrightarrow 1 \leq n^+$, as desired.

4.4.2

Let $m, n \in \omega$. Show that if $m \in n^+$, then $m \leq n$.

Suppose that $m \in n^+$. We follow that

$$m \in n^+ \Leftrightarrow m \in n \cup \{n\} \Leftrightarrow m \in n \vee m = n \Leftrightarrow m \leq n$$

4.4.3

Let $n, a \in \omega$. Show that if $n \in a$, then $n^+ \leq a$

Suppose that $n \in a$. We know that one of $n^+ = a$, $n^+ \in a$ or $a \in n^+$ holds. Suppose that $a \in n^+$. We follow that

$$a \in n \cup \{n\} \Leftrightarrow a \in n \vee a = n$$

If $a \in n$, then we've got that $n \in a$ and $a \in n$, which is impossible. If $a = n$, then $n \in n$, which is also not good. Thus we follow that $a \in n^+$ is impossible. Thus we follow that $n^+ \in a$ or $n^+ = a$. In other words, $n \leq a$, as desired.

4.4.4

Let I be inductive and let $a \in \omega$. Prove that $\{n \in I : n \in a \vee a \subseteq n\}$ is inductive

Let

$$Q = \{n \in I : n \in a \vee a \subseteq n\}$$

We follow that $0 \in Q$ since 0 is in every inductive set (by virtue of being a natural number), and by trichotomy property $0 \in a$ or $a \leq 0 \Leftrightarrow a \subseteq 0$.

Suppose that $q \in Q$. Since $Q \subseteq I$, we follow that $q \in I$, and because I is inductive, we follow that $q^+ \in I$ as well. We also follow that $q \in a \vee a \subseteq q$.

If $a \subseteq q$, then we follow that $a \subseteq q \cup \{q\}$, therefore $a \subseteq q^+$, and thus $q \in Q$.

Suppose that $q \in a$. Then we follow that since $a \in \omega \rightarrow a \subseteq \omega$, we follow that $q \in \omega$. Therefore $q^+ \in \omega$, and we've got by trichotomy that either $q^+ \in a$, $q^+ = a$ or $a \in q^+ \Leftrightarrow a \subset q^+$. Thus we follow that $q^+ \in a \vee a \subseteq q^+$, therefore $q^+ \in Q$.

Thus we can conclude that $0 = \emptyset \in Q$ and $q \in Q \Rightarrow q^+ \in Q$. Thus Q is inductive, as desired.

4.4.5

Let $m, n \in \omega$. Suppose that $m \leq n$. Prove that $\max(m, n) = n$.

From the chapter we follow that $\max(m, n) = m \cup n$. Since $m \leq n$, we follow that $m \subseteq n$. Thus $\max(m, n) = m \cup n = n$, as desired.

4.4.6

Let $m, n \in \omega$. Prove that for all $p \in \omega$ if $m \in n$, then $m + p \in n + p$

Let

$$I = \{p \in \omega : (\forall m, n \in \omega)(m \in n \Rightarrow m + p \in n + p)\}$$

Since $m + 0 = m$ and $n = n + 0$, we follow that $m \in n \Leftrightarrow m + 0 \in n + 0$.

Suppose that $p \in I$. Then we follow that

$$m \in n \Leftrightarrow m + p \in n + p \Leftrightarrow (m + p)^+ \in (n + p)^+ \Leftrightarrow m + p^+ \in n + p^+$$

thus $p^+ \in I$. Thus $I = \omega$, as desired.

4.4.7

Let $m, n \in \omega$. Prove that for all $p \in \omega$, if $m + p \in n + p$, then $m \in n$

In previous exercise we've got only biconditionals, thus we get the reverse case as well

4.4.8, 4.4.9

let $m, n \in \omega$. Prove that for all $p \in \omega$ $m \in n \Leftrightarrow m \cdot p^+ \in n \cdot p^+$

Let

$$I = \{p \in \omega : (\forall m, n \in \omega)(m \in n \Leftrightarrow m \cdot p^+ \in n \cdot p^+)\}$$

We first follow that if $p = 0$, then

$$m \cdot 0^+ \in n \cdot 0^+ \Leftrightarrow (m \cdot 0 + m) \in (n \cdot 0 + n) \Leftrightarrow (0 + m) \in (0 + n) \Leftrightarrow m \in n$$

thus $0 \in I$.

Suppose that $p \in I$. Then we follow that

$$m \in n \Leftrightarrow m \cdot p^+ \in n \cdot p^+$$

$m \in n$ if and only if $m + a \in n + a$ by previous exercise. Thus

$$m \in n \Leftrightarrow m + m \cdot p^+ \in n + m \cdot p^+$$

and also

$$m \cdot p^+ \in n \cdot p^+ \Leftrightarrow m \cdot p^+ + n \in n \cdot p^+ + n$$

by commutativity we follow that

$$m \cdot p^+ \in n \cdot p^+ \Leftrightarrow n + m \cdot p^+ \in n \cdot p^+ + n$$

thus

$$\begin{aligned} m \in n &\Leftrightarrow (m + m \cdot p^+ \in n + m \cdot p^+) \wedge (n + m \cdot p^+ \in n \cdot p^+ + n) \Leftrightarrow \\ &\Leftrightarrow (m + m \cdot p^+ \in n + m \cdot p^+) \wedge (n + m \cdot p^+ \in n \cdot p^+ + n) \Rightarrow \\ &m + m \cdot p^+ \in n \cdot p^+ + n \Leftrightarrow m \cdot (p^+)^+ \in n \cdot (p^+)^+ \end{aligned}$$

thus $m \in n \Rightarrow m \cdot (p^+)^+ \in n \cdot (p^+)^+$.

Let $m, n \in \omega$ be such that $m \cdot (p^+)^+ \in n \cdot (p^+)^+$. By trichotomy we follow that $m \in n$, $n \in m$ or $m = n$.

If $m = n$, then we follow that

$$n \cdot (p^+)^+ = m \cdot (p^+)^+ \in n \cdot (p^+)^+$$

which is a contradiction.

If $n \in m$, then we follow by implication that

$$n \cdot (p^+)^+ \in m \cdot (p^+)^+$$

and since $m \cdot (p^+)^+ \in n \cdot (p^+)^+$, we follow that $n \cdot (p^+)^+ \in n \cdot (p^+)^+$, which is also bad. Thus we follow that $m \cdot (p^+)^+ \in n \cdot (p^+)^+ \Rightarrow m \in n$. By including the implication we follow that

$$m \cdot (p^+)^+ \in n \cdot (p^+)^+ \Leftrightarrow m \in n$$

and therefore $p^+ \in I$. Thus $I = \omega$, as desired.

4.4.10

Use Theorem 4.4.11 and Theorem 4.4.9 to prove Corollary 4.4.12

Suppose that $m + p = n + p$. If $m \in n$, then we follow that $m + p \in n + p$, which is not the case. If $n \in m$, then we follow that $n + p \in m + p$, which is also not the case. Thus we follow that $m = p$. Thus $m + p = n + p \Leftrightarrow m = n$ (reverse case is trivial)

Suppose that $p \neq 0$ and we've got that $m \cdot p = n \cdot p$. Since $p \neq 0$, we follow that $p = j^+$ for some $j \in \omega$.

We follow that $m \in n$ and $n \in m$ are both impossible, because they would imply that $m \cdot p \in n \cdot p$ and $n \cdot p \in m \cdot p$, which are not the case. Thus we follow that

$$(\forall p \in (\omega \setminus 0))(m \cdot p = n \cdot p \Leftrightarrow m = n)$$

where reverse case is once again trivial.

4.4.11

Let $m \in \omega$. Prove that $m \in m + p^+$ for all $p \in \omega$.

We know that $m \in m^+$ for all $m \in \omega$. Thus we follow that for any $p \in \omega$ we've got that $m + p \in m^+ + p \Leftrightarrow m + p \in m + p^+$. We also can follow that for every $p \in \omega$ we've got that $m \leq m + p$ (can't find the exact reference, but it is easily followed by induction). Thus by transitive property we can follow that $m \in m + p^+$, as desired.

4.4.12

Let $m \in \omega$. Prove that for all $n \in \omega$, if $m \in n$ then $m + p^+ = n$ for some $p \in \omega$.

Let

$$I = \{j \in \omega : j \in m \vee (\exists p \in \omega)(j = m + p^+)\}$$

We follow that $0 \in m$, therefore $0 \in I$.

Suppose that $n \in I$. Then we follow that $n \in m \vee (\exists p \in \omega)(j = m + p^+)$. If $n \in m$, then we follow that $n^+ \in m \vee n^+ = m \Leftrightarrow n^+ \in m \vee n^+ = m + 0$. Thus we follow that if $n \in m$, then $n^+ \in I$.

If $(\exists p \in \omega)(n = m + p^+)$, then we follow that $n^+ = (m + p^+)^+ = m + (p^+)^+$. Since $p^+ \in \omega$, we follow $n^+ \in I$ as well.

Thus we can conclude that $n \in I \Rightarrow n^+ \in I$. Thus I is inductive, and since it is a subset of ω , we follow that $I = \omega$. Thus we follow that our initial $n \in I$. Thus $n \in m \vee (\exists p \in \omega)(n = m + p^+)$. Because $m \in n$, we follow by trichotomy that $n \notin m$, thus $(\exists p \in \omega)(n = m + p^+)$, as desired.

4.4.13

Combination of previous two exercises into one biconditional.

4.4.18

Prove for all $n \in \omega$, if $f : n \rightarrow \omega$, then $\text{ran}(f) \subseteq k$ for some $k \in \omega$.

Let

$$I = \{n \in \omega : (\forall f)(\exists k \in \omega)(f : n \rightarrow \omega \Rightarrow \text{ran}(f) \subseteq k)\}$$

We follow that if $f : 0 \rightarrow \omega$, then $\text{dom}(f) = \emptyset$, thus $f = \emptyset$, therefore $\text{ran}(f) = \emptyset = 0 \subseteq 0$. Thus $0 \in I$.

Suppose that $n \in I$. Let $f : n^+ \rightarrow \omega$. Then we follow that there exists $f|n : n \rightarrow \omega$, and thus $(\exists k \in \omega)(\text{ran}(f|n) \subseteq k)$. Since $n^+ = n \cup \{n\}$, we follow that

$$\text{ran}(f) = f[n^+] = f[n] \cup f[\{n\}] = f[n] \cup f(n) \subseteq k \cup f(n)$$

Since $f : n^+ \rightarrow \omega$, we follow that $f(n) \in \omega$. Thus $k \cup f(n) \in \omega$, thus there exists $j = k \cup f(n) \in \omega$ such that $f : n^+ \rightarrow \omega \Rightarrow \text{ran}(f) \subseteq j$. Thus we follow that $n^+ \in I$. Thus $n \in I \Rightarrow n^+ \in I$, therefore $I = \omega$, as desired.

Chapter 5

On the Size of Sets

Because of chapter 4'th construction of natural numbers and their ordering I think that we're justified to use basic number theory and some properties of the natural numbers, since it follows directly from the proven facts. One can argue even that we're justified to use \mathbb{Z} in general, but until the need arises I will refrain from doing so.

5.1 Finite Sets

5.1.1

In our proof of Theorem 5.1.3, under the case that $k \in m$, we did not show that the function g is one-to-one. Complete the proof by proving that g is one-to-one.

We need to prove that

$$g(a) = \begin{cases} k & \text{if } f(a) = m \\ f(a) & \text{if } f(a) \neq m \end{cases}$$

is one-to-one.

Suppose that $a_1, a_2 \in A$ are such that $a_1 \neq a_2$. Suppose that $f(a_1) \neq m$. Then we follow that if $f(a_2) \neq m$, then we've got that $f(a_1) \neq f(a_2)$ by the fact that f is injective, thus $g(a_1) = f(a_1) \neq f(a_2) = g(a_2)$ as well. If $f(a_2) = m$, then we follow that $g(a_2) = k$. Thus we follow that $f(a_1) = g(a_1) \in \text{ran}(f)$ and $g(a_2) = k \notin \text{ran}(f)$. Thus we follow that $g(a_1) \neq g(a_2)$.

Since f is injective, we can follow that $a_1 \neq a_2 \Rightarrow f(a_1) \neq f(a_2)$, thus we follow that the case when $f(a_1) = f(a_2) = m$ can't happen. Thus we follow that $a_1 \neq a_2 \Rightarrow g(a_1) \neq g(a_2)$, therefore g is injective, as desired.

5.1.2

Suppose that the set B is finite and $A \subseteq B$. Prove that A is finite.

We follow that there exists $n \in \omega$ $|B| = n$. Thus we follow that there exists $f : B \rightarrow n$, that is injective. Since f is injective and $A \subseteq B$, we follow that $f|_A$ is also one-to-one. Thus we follow that A is finite, as desired.

5.1.3

Let A and B be two finite sets, and let $f : A \rightarrow B$ be one-to-one. Prove that $|A| \leq |B|$.

Given that A and B are finite, we follow that there exist natural numbers $n = |A|$ and $m = |B|$. We can also follow that there exist bijections $h : A \rightarrow n$ and $g : B \rightarrow m$. Because h is a bijection, we follow that $h^{-1} : n \rightarrow A$ is also a bijection. Thus we follow that $g \circ f \circ h^{-1} : n \rightarrow m$ is a composition of injective functions, and therefore it's injective as well. Thus we follow that $|n| \leq m$, therefore

$$|A| \leq |B|$$

$$|A| \leq |B|$$

as desired.

5.1.4

Prove theorem 5.1.7

Let A and B be finite. Let $n = |A|$ and $m = |B|$. We follow that there exist bijections $f : A \rightarrow n$ and $g : B \rightarrow m$.

Thus we follow that if there exists a bijection $h : A \rightarrow B$, then we follow that $g \circ h \circ f^{-1} : n \rightarrow m$ is a bijection. Thus $g \circ h \circ f^{-1} : n \rightarrow m$ is injective and $(g \circ h \circ f^{-1} : n \rightarrow m)^{-1}$ is injective, thus we follow that $n \geq m$ and $m \geq n$, thus by antisymmetry we've got that $n = m$ and $|A| = |B|$.

If $|A| = |B|$, then we follow that $f : A \rightarrow |A|$ and $g : B \rightarrow |B|$ are bijections, and thus $g^{-1} \circ f : A \rightarrow B$ is also a bijection.

5.1.5

Let $n \in \omega$ and let $f : n \rightarrow A$. Prove that $f[n]$ is finite.

Let us firstly prove a theorem (which I'm sure that it was proven in the book before, but I can't find it) assuming for a moment that n is a general set.

If $f : n \rightarrow A$ is a function, then there exists an injective function g such that $g \subseteq f^{-1}$.

Suppose that $y \in f[n]$. Then we follow that there exists a nonempty set

$$A_y = \{x \in n : \langle x, y \rangle \in f\}$$

Thus we can define an indexed function $\langle A_y : y \in f[n] \rangle$, from which by axiom of choice we follow that there exists a function g such that

$$g(y) \in A_y$$

Thus we follow that $g : f[n] \rightarrow n$. From a definition of A_y we can follow that $g \subseteq f^{-1}$. Suppose that $n_1 \neq n_2 \in f[n]$. We follow that because f is a function, there does not exist $x \in n$ such that $f(x) = n_1$ and $f(x) = n_2$. Thus $g(n_1) \neq g(n_2)$. Thus we follow that $n_1 \neq n_2 \Rightarrow g(n_1) \neq g(n_2)$. Therefore g is injective, as desired.

By provided theorem we can follow that there exists an injective function g from $f[n]$ to n . Thus we follow that $f[n]$ is finite by definition.

5.1.6

Let A be finite and let $f : A \rightarrow \omega$. Prove that $\text{ran}(f) \subseteq k$, for some $k \in \omega$.

Since A is finite, we follow that there exists a bijection $g : A \rightarrow n$ for some $n \in \omega$. Thus we follow that $g^{-1} : n \rightarrow A$ is also a bijection. We now follow that $f \circ g^{-1} : n \rightarrow \omega$ is a function with a finite domain, and because g^{-1} is a bijection, we follow that $\text{ran}(f \circ g^{-1}) = \text{ran}(f)$. By exercise 4.4.18 we follow that there exists $k \in \omega$ such that $\text{ran}(f \circ g^{-1}) \subseteq k$. Thus we follow that $\text{ran}(f) \subseteq k$ for some $k \in \omega$, as desired.

5.1.7

Suppose that $f : A \rightarrow n$ is a bijection, where $n \in \omega$. Prove that $|A| = n$.

Since f is a bijection, we follow that it is injective. Thus we follow that A is finite. Let $|A| = m$. We follow that there exists a bijection $g : A \rightarrow m$ and thus $g^{-1} : m \rightarrow A$ is also a bijection. Thus

$$f \circ g^{-1} : m \rightarrow n$$

is also a bijection. Thus we follow that $|n| = |m|$. Therefore $n = m$, and thus $|A| = n$, as desired.

5.1.8

Let $f : \omega \times \omega \rightarrow \omega$ be defined by $f(i, j) = 2^i \cdot 3^j$. Prove that f is one-to-one. Prove that if $i < m$ and $j < n$, then $f(i, j) \leq f(m, n)$.

I think that at this point we're kind of justified to use the normal stuff from the number theory, such as divisibility and whatnot (given the fact that we've justified all of the normal things such as \cdot), and deduce from it that given function is indeed one-to-one. The fact that $i < m$ and $j < n$ follows easily from induction on i and then by induction on j .

5.1.9

Prove that $p : \omega \times \omega \rightarrow \omega$ defined by

$$p(i, j) = 2^i(2j + 1) - 1$$

is one-to-one and onto ω . Prove that if $i \in M$ and $j \in n$, then $p(i, j) < p(m, n)$.

Suppose that $i, j, i', j' \in \omega$ and $i > i', j > j'$. Then we follow that

$$p(i, j) - p(i', j') = 2^i(2j + 1) - 2^{i'}(2j' + 1) = 2^i 2j + 2^i - 2^{i'} 2j' - 2^{i'} =$$

from which we follow that $2^i > 2^{i'}$ because exponentiation function is strictly increasing for bases greater than 1. We can also follow that $j > j'$ implies that $2j > 2j'$, and because we've seen earlier that $2^i > 2^{i'}$, we follow that $2^i 2j > 2^{i'} 2j'$. Thus we follow that

$$i > i' \wedge j > j' \Rightarrow p(i, j) > p(i', j')$$

and

$$i = i' \wedge j > j' \Rightarrow p(i, j) > p(i', j')$$

$$i > i' \wedge j = j' \Rightarrow p(i, j) > p(i', j')$$

thus we follow that

$$\langle i, j \rangle \neq \langle i', j' \rangle \Rightarrow p(i, j) \neq p(i', j')$$

thus the function is injective.

Now suppose that $n \in \omega$. Then we follow that

$$2^i(2j + 1) - 1 = n$$

$$2^i(2j + 1) = n + 1$$

we follow that since $n + 1 > 0 \Rightarrow n \in \mathbb{Z}^+$, there exist a finite set of prime divisors $P = \{p_1, p_2, \dots, p_q\}$ and set of powers $K = \{k_1, \dots, k_l\}$ such that

$$n + 1 = \prod p_l^{k_l}$$

from which we follow that we can set i to be the power of 2 in case that $2 \in P$, or 0 in case that $2 \notin P$ to get

$$n + 1 = 2^i \prod_{P \setminus 2} p_j^{k_j}$$

since $2 \notin P \setminus 2$, we follow that $\prod_{P \setminus 2} p_j^{k_j}$ is an odd number, and thus there exists j such that $2j + 1 = \prod_{P \setminus 2} p_j^{k_j}$. Thus we follow that

$$n + 1 = 2^i(2j + 1)$$

$$n = 2^i(2j + 1) - 1$$

thus we follow that $p(i, j)$ is a surjective function. Thus p is bijective, as desired.

5.1.10

Prove that there exists a one-to-one function $f : \omega \rightarrow \omega \times \omega$ that is onto $\omega \times \omega$

Take a function from previous exercise and take its inverse. We follow that because it is a bijection, then its inverse is a function and a bijection, thus we've got the desired function, as desired.

5.1.11

Suppose that A and B are finite disjoint sets. Prove that $A \cup B$ is finite.

We follow that since both of them are finite, we've got that there exist bijections $f : |A| \rightarrow A$ and $g : |B| \rightarrow B$. Thus we follow that we can relation $h : |A| + |B| \rightarrow A \cup B$ by

$$h(x) = \begin{cases} x < |A| \Rightarrow f(x) \\ x \geq |A| \Rightarrow g(x - |A|) \end{cases}$$

(I've used a bit of a notation abuse here, but the principle is pretty clear) We follow that if $x \in |A| + |B|$, then $x < |A| \oplus x \geq |A|$. Thus we follow that $h(x)$ is a well-defined function. Now suppose that $x, y \in |A| + |B| \wedge x \neq y$. If $x, y < |A|$ or $x, y \geq |A|$, then we follow that

$$\langle h(x), h(y) \rangle = \langle f(x), f(y) \rangle \oplus \langle h(x), h(y) \rangle = \langle g(x), g(y) \rangle$$

from which we follow that $h(x) \neq h(y)$. If $x < |A|$ and $y \geq |A|$ (or vice-versa), then we follow that $x \in A$ and $y \in B$, and since A and B are disjoint, we follow that $x \neq y$. Thus we can conclude that $x \neq y \Rightarrow h(x) \neq h(y)$, and therefore the function is injective.

Now suppose that $x \in A \cup B$. If $x \in A$, we follow that there exists $n \in |A| \Rightarrow n \in |A| + |B|$ such that $h(n) = f(n) = x$. If $x \in B$, we follow that there exists $n \in |B|$ such that $g(n) = x$. $n \in |B|$ implies that $n + |A| \in |A| + |B|$, and thus there exists $k = n + |A| \in |A| + |B|$ such that

$$h(k) = g(n + |A| - |A|) = g(n) = x$$

thus we follow that $x \in A \cup B \Rightarrow (\exists k \in |A| + |B|)(h(k) = x)$. Thus we follow that h is surjective.

Thus we follow that $h : |A| + |B| \rightarrow A \cup B$ is bijective, and since $|A| + |B| \in \omega$, we follow that $A \cup B$ is finite, as desired.

By setting $A = A'$ and $B = B' \setminus A$, we can conclude that union of two arbitrary finite sets A', B' is finite as well.

5.1.12

Let A be an infinite set and B be a finite set. Prove that $A \setminus B$ is infinite.

Suppose that $A \setminus B$ is finite. Then we follow that $A \setminus B$ and B are disjoint sets, thus $(A \setminus B) \cup B$ is finite by previous exercise. Since

$$(A \setminus B) \cup B = A \cup B$$

we follow that $A \cup B$ is finite. Thus $A \subseteq A \cup B$ is finite as well, which is a contradiction.

5.1.13

Let $k \in \omega$. Suppose that $|A| = k^+$ and $a \in A$. Prove that $|A \setminus \{a\}| = k$.

One of the implications of exercise 5.1.12 is that if A and B are finite and disjoint, then $|A \cup B| = |A| + |B|$. Applying this thing to our exercise we follow that

$$|A| = |A \setminus \{a\} \cup \{a\}| = k^+$$

Without providing trivial proof we gonna state here that

$$|\{a\}| = 1$$

thus we conclude that

$$|A \setminus \{a\}| + |\{a\}| = k^+$$

$$|A \setminus \{a\}| + 1 = k + 1$$

$$|A \setminus \{a\}| = k$$

as desired.

5.1.14

Suppose taht $|K| = k$, $|N| = n$, and $f : K \rightarrow N$ is onto N where $k, n \in \omega$. Show that there is a function $g : k \rightarrow n$ that is onto

We follow that there exist bijections $h : k \rightarrow K$ and $j' : n \rightarrow N$. Since j' is a bijection we're justified to define bijection $j : N \rightarrow n; j = j'^{-1}$. Thus we can define $g : k \rightarrow n$ by

$$g = j \circ f \circ h$$

since all of the j, f, h are surjective, we follow that g is surjective as well, as desired.

5.1.15

Suppose that A and B are finite. Prove that $A \cup B$ is finite.

GOTO last paragraph of 5.1.12

5.1.16

Let $n \in \omega$. Suppose that $f : n \rightarrow A$ is onto A . Prove that A is finite.

We follow that since f is surjective, there exists injective $g : A \rightarrow n$ such that $g \subseteq f^{-1}$. Thus we follow that A is finite, as desired.

5.1.17

Let A be finite set. Prove that there exists an $f : n \rightarrow A$ that is onto A for some $n \in \omega$.

We know that there exists a bijection $f : |A| \rightarrow A$, thus concluding the exercise.

5.1.18

Suppose that $f : A \rightarrow B$ is onto B where A is finite. Prove that B is finite.

Since A is finite, we follow that there exists a bijection $g : |A| \rightarrow A$. Thus there exists a surjective function $f \circ g : |A| \rightarrow B$, which by 5.1.16 means that B is finite, as desired.

5.1.19

Let $n \in \omega$ and $\{A_i : i \in n\}$ be such that A_i is finite for all $i \in n$. Prove, by induction, that $\bigcup_{i \in n} A_i$ is finite.

Let

$$I = \{n \in \omega : \bigcup_{i \in n} A_i \text{ is finite}\}$$

(we can make a more formal definition here, but it'll be a bit cumbersome).

We follow that if $n = 0$, then $\{A_i : i \in n\} = \emptyset$, thus we follow that

$$\bigcup_{i \in n} A_i : i \in n = \emptyset$$

thus

$$|\bigcup_{i \in n} A_i : i \in n| = 0$$

thus we follow that $0 \in I$.

Suppose now that $n \in I$. Then we follow that $\bigcup_{i \in n} A_i$ and A_{n+} are finite, thus $\bigcup_{i \in n+} A_i$ is finite as well. Thus we've got the desired conclusion.

5.1.20

Suppose that A and B are finite sets. Prove that $A \times B$ is finite.

We follow that $\mathcal{P}(A)$ is finite, $\mathcal{P}(B)$ is also finite, thus $\mathcal{P}(A) \cup \mathcal{P}(B)$ is finite, therefore $\mathcal{P}(\mathcal{P}(A) \cup \mathcal{P}(B))$ is finite, and since $A \times B \subseteq \mathcal{P}(\mathcal{P}(A) \cup \mathcal{P}(B))$, we follow that $A \times B$ is finite as well.

5.1.21

Prove Corollary 5.1.11

Suppose that $G : \omega \rightarrow A$ is one-to-one. Suppose that A is finite. Then we follow that there exists a bijection $f : A \rightarrow |A|$. Therefore we follow that $f \circ G : \omega \rightarrow |A|$ is injective,

and thus ω is a finite, which is a contradiction. Thus we follow that A is not finite (i.e. infinite), as desired.

5.1.22

Let $\langle A_i : i \in I \rangle$ be an indexed function where I is a finite set and $A_i \neq \emptyset$. Without using AoC prove by induction on $|I|$ that there is an indexed function $\langle x_i : i \in I \rangle$ such that $x_i \in A_i$ for all $i \in I$.

Define W to be the set, for which the conditions hold.

We follow that if $|I| = 0$, then $I = \emptyset$, thus $\langle A_i : i \in I \rangle = \emptyset$, and therefore \emptyset is an indexed function $\langle x_i : i \in I \rangle$ as well, thus $i \in W$.

Suppose that $n \in W$. We follow that we can have I' such that $|I'| = n + 1$ and indexed function $\langle A_i : i \in I' \rangle$. Since I' is finite, we follow that there exists a bijection $f : n + 1 \rightarrow I'$, therefore there exists an element $f(0) \in I'$. Define $a = f(0)$. We can follow that $|I' \setminus \{a\}| = n$. We follow that for

$$\langle A_i : i \in I' \setminus \{a\} \rangle$$

there exists

$$\langle x_i : i \in I' \setminus \{a\} \rangle$$

Let us now look at $A_{\{a\}}$. We follow that since $A_{\{a\}} \neq \emptyset$ we can follow that there exists $b \in A_{\{a\}}$. Define a function $h : I' \rightarrow \bigcup_{i \in I'} A_i$ by

$$h(x) = \begin{cases} x = a \Rightarrow b \\ x \neq a \Rightarrow \langle x_i : i \in I' \setminus \{a\} \rangle \end{cases}$$

then we follow that h is the desired indexed function, and thus $n^+ \in W$. Therefore $W = \omega$, as desired.

5.1.23

Modify the proof of Theorem 5.1.14 to show that if $|A| = n$, then $|\mathcal{P}(A)| = 2^n$.

Not gonna provide it, but we can follow that by making definition of I a bit more strict and following the same logic for the argument.

5.2 Countable Sets

5.2.1

Let $A = \{4, 8, 12, 16, \dots\}$ and let $B = \{n \in \mathbb{Z} : n < -25\}$. Define a bijection $f : A \rightarrow \omega$ and define a bijection $g : B \rightarrow \omega$.

$$\begin{aligned}f(x) &= x/4 - 1 \\g(x) &= -n + 26\end{aligned}$$

5.2.2

Let A and B be as in Exercise 1. Define an injection $h : A \cup B \rightarrow \omega$.

Because A and B are disjoint we can set

$$h(x) = \begin{cases} x = 2x \Rightarrow f^{-1}(x/2) \\ x = 2x + 1 \Rightarrow g^{-1}((x - 1)/2) \end{cases}$$

5.2.3

Show that the set of negative integers Z^- is countable

We can define $f : Z^- \rightarrow \omega$ by $f(x) = -x - 1$, which will be a bijection between Z^- and ω . Thus we conclude that Z^- is countable.

5.2.4

Conclude from Exercise 3 that set of integers Z is countable.

We can follow that sets Z^-, N are both countable, thus $Z^- \cup N = Z$ is countable as well.

5.2.5

Let $p : \omega \times \omega \rightarrow \omega$ be one-to-one. Using p , show that the set of positive rationals is countable. Conclude that the set of negative rationals is countable and the set of rationals is countable.

We can define an injection from Q^+ to $\omega \rightarrow \omega$ by

$$h(m/n) = \langle m, n \rangle$$

where m/n is in the lowest possible terms. From exercise 5.1.9 we follow that there exists an injection p from $\omega \times \omega$ to ω . Thus we conclude that $p \circ h$ is an injection from Q^+ to ω , thus Q^+ is countable.

Because we can define a bijection from Q^+ to Q^- by $f(x) = -x$ we follow that Q^+ is countable as well. Thus we follow that $Q^+ \cup Q^- \cup \{0\} = Q$ is a countable union of countable sets, and therefore is countable as well, as desired.

5.2.6

Let A and B be two countably infinite sets. Prove that there exists a bijection $f : A \rightarrow B$.

Since A and B are both countably infinite we follow that there exist bijections $h : A \rightarrow \omega$ and $g : B \rightarrow \omega$. Thus if we set $f = g^{-1} \circ h$ we get the desired bijection.

5.2.7

Let A and B be countable sets. Prove that $A \times B$ is countable.

We follow that there exist injections $f : A \rightarrow \omega$ and $g : B \rightarrow \omega$. Thus we can define an injection $p' : A \times B \rightarrow \omega \rightarrow \omega$ by

$$p'(x, y) = \langle f(x), g(y) \rangle$$

which we can plug into bijective $p : \omega \times \omega \rightarrow \omega$ to get injective $p \circ p' : A \times B \rightarrow \omega$, which proves that $A \times B$ is countable.

5.2.8

Let A be a set. Suppose that $f : \omega \rightarrow A$ is onto A . Prove that A is countable

We follow that there exists an injective function $g \subseteq f^{-1} : A \rightarrow \omega$, which proves that A is countable, as desired.

5.2.9

Let A be a nonempty countable set. Prove that there exists an $f : \omega \rightarrow A$ that is onto A .

Because A is nonempty, we follow that there exists $a \in A$. We follow that there exists an injection $f : A \rightarrow \omega$, therefore we can define a surjective function $h : \omega \rightarrow A$

$$h(x) = \begin{cases} x \in \text{ran}(f) \Rightarrow f^{-1}[\{x\}] \\ x \notin \text{ran}(f) \Rightarrow a \end{cases}$$

as desired.

5.2.10

Suppose that $f : A \rightarrow B$ is onto B where A is countable. Prove that B is also countable.

If $A = \emptyset$, then we follow that B is also an empty set, therefore B is countable.

If A is not empty, then we follow by previous exercise that there exists a surjective $g : \omega \rightarrow A$. Thus we follow that

$$f \circ g : \omega \rightarrow B$$

is surjective, therefore by exercise 5.2.8 we follow that B is countable, as desired.

5.2.11

Let A be an infinite set and let $C = \mathcal{P}(A) \setminus \{\emptyset\}$. By AoC there exists a function $g : C \rightarrow A$ such that $g(B) \in B$ for all $B \in C$. One can show that there is a function $h : \omega \rightarrow A$ such that

$$(\forall n \in \omega)(h(n) = g(A \setminus h[n]))$$

Prove that $h : \omega \rightarrow A$ is one-to-one

Suppose that $x < y \in \omega$ and $h(x) = h(y)$. We follow that $x \in y$, therefore

$$h(x) = h(y) = g(A \setminus h[y]) \in A \setminus h[y]$$

Since $x \in y$ we follow that $h(x) \in h[y]$, therefore we have a contradiction.

5.3 Uncountable Sets**5.3.1**

Let A be uncountable. Prove that $A \times B$ is uncountable for any nonempty set B .

Let $b \in B$. Define a function $f : A \rightarrow A \times B$ by

$$f(a) = \langle a, b \rangle$$

We follow that for $x, y \in A$

$$f(x) = f(y) \Rightarrow \langle x, b \rangle = \langle y, b \rangle \Rightarrow x = y$$

thus we follow that f is injective. Therefore we conclude that $A \times B$ is uncountable, as desired.

5.3.2

Let A be uncountable and B be countable. Prove that $A \setminus B$ is uncountable.

Suppose that $A \setminus B$ is countable. Then we follow that $A = A \setminus B \cup B$ is a countable union of countable sets, therefore it is countable as well, which is a contradiction.

5.3.3

Prove that the set of irrationals $R \setminus Q$ is uncountable.

R is uncountable, Q is countable, thus by previous exercise we follow this conclusion.

5.3.4

Suppose that A is uncountable and $A \subseteq B$. Prove that B is uncountable.

We follow that since $A \subseteq B$ we've got an injection $f : A \rightarrow B$ which is a restricted identity on A . Thus we follow that B is uncountable, as desired.

5.3.5

Prove that ω^ω is uncountable

We follow that $\{0,1\}^\omega$ is a subset of ω^ω and because the former is uncountable, we follow by previous exercise that ω^ω is uncountable.

5.3.6

Suppose that A is uncountable. Prove that $\mathcal{P}(A)$ is uncountable.

Let us define a function $f : A \rightarrow \mathcal{P}(A)$

$$f(x) = \{x\}$$

this function is clearly injective, thus $\mathcal{P}(A)$ is uncountable, as desired.

5.3.7

Let $A \neq \emptyset$. Prove that if B is uncountable, then B^A is uncountable.

Let $a \in A$ and define $f : B \rightarrow B^A$ to be so that $f(b)$ is a function such that

$$(\forall a' \in A)((f(a))(a') = b$$

(i.e. it sends every a to value b). We follow that f is injective, therefore we can follow that B^A is uncountable, as desired.

5.3.8

Let F be as in Theorem 5.3.2, and let $() f_1, f_2, \dots, f_n$ be a finite list of functions in F . Using the argument in the proof of Theorem 5.3.2 define a new function $g \in F$ that is not in the list $(*)$. Conclude that F is infinite*

$$g(i) = \begin{cases} i \leq n \Rightarrow \text{if } f_i(i) = 0 \text{ then } 1, \text{ otherwise } 0 \\ i > n \Rightarrow f_0(i) \end{cases}$$

will do

The rest of the exercises were handled in my real analysis course, specifically in Chapter 1

5.4 Cardinality**5.4.1**

Let $A = \{x \in \mathbb{R} : 0 < x < 1\}$ and let $B = \{x \in \mathbb{R} : 2 < x < 5\}$. Prove that $|A| =_c |B|$

Let $a < b \in \mathbb{R}$. Define $h = (b - a)/2$. We follow that we can define function $f : (a, b) \rightarrow \mathbb{R}$

$$f(x) = \frac{x - h}{|x - h|} \frac{h}{h - |x - h|}$$

where $|\cdot|$ denotes absolute value. We can prove that given function is a bijection (concrete proof given in real analysis book, but the idea is to put center the interval at the origin and then stretch it to the set of reals). Thus we follow that for any nonempty open interval we've got a bijection from it to \mathbb{R} . Therefore

$$a \neq b \in \mathbb{R} \Rightarrow |(a, b)| =_c |\mathbb{R}|$$

thus we follow from it that two sets, that are given in the text of the exercise (which are open intervals) have the same cardinality (there are easier ways to show that there exists a bijection from one open interval to another, but I wanted to show off a bit).

5.4.1 5.4.2

Prove that $|A^{\{0,1\}}| =_c |A \times A|$.

Define $f : A^{\{0,1\}} \rightarrow A \times A$ by

$$f(g) = \langle g(0), g(1) \rangle$$

obviously f is bijective, therefore we've got the necessary result.

5.4.3

Let A and B be countably infinite sets. Prove that $|A| =_c |B|$. Conclude that $|\omega \times \omega| =_c |\omega|$.

We know that there exists a bijection $f : \omega \times \omega \rightarrow \omega$ from some previous exercises. Thus we follow the desired result.

5.4.4

Let A and B be sets. Prove that $|A| =_c |A|$ and prove that if $|A| =_c |B|$, then $|B| =_c |A|$.

We follow that the identity function is bijective, thus $|A| =_c |A|$. Inverse of a bijection is a bijection, therefore if there exists a bijection $f : A \rightarrow B$, then there exists a bijection $f^{-1} : B \rightarrow A$, thus we follow the symmetric property.

5.4.5

Composition of bijections,

5.4.6

Prove that if $|A| <_c |B|$ and $|B| = |C|_i$, then $|A| <_c |C|$.

We follow that there exists an injection $f : A \rightarrow B$ and bijection $g : B \rightarrow C$, thus there exists an injection $g \circ f : A \rightarrow C$, thus $|A| \leq_C |C|$.

Suppose that there exists a bijection $h : A \rightarrow C$. Then we follow that $g^{-1} \circ h : A \rightarrow B$ is a bijection, which contradicts $|A| <_c |B|$

5.4.7

Let B be countable. Prove that if $|A| \leq_c |B|$, then A is countable.

We follow that there exist injections $f : A \rightarrow B$ and $g : B \rightarrow \omega$, thus there exists an injection $g \circ f : A \rightarrow \omega$, as desired.

5.4.8

Let A be uncountable. Prove that if $|A| \leq |B|$, then B is uncountable.

Suppose that it isn't. Then by previous exercise we follow that A is countable, which is a contradiction.

5.4.9

Prove that if $|A| <_c |B|$ and $|B| <_c |C|$, then $|A| <_c |C|$.

We can follow that $|A| \leq_c |C|$ by composition of injections. Suppose that $|A| =_c |C|$. Then we follow that there exists a bijection $f : C \rightarrow A$, thus we follow that $|C| <_c |B|$, which is a contradiction.

5.4.10

Prove that the function G in the proof of Theorem 5.4.3 is a bijection.

Firstly I want to state that the check for the fact that G is indeed a function is pretty trivial.

Let G be defined as in the theorem. Suppose that $f \neq g \in \{0,1\}^A$. We follow that there exists $a \in A$ such that $f(a) \neq g(a)$. Since $a = 0 \vee a = 1$ we follow that $f(a) \neq g(a) \Rightarrow f(a) = 1 \vee g(a) = 1$. Assume that $f(a) = 1$ and thus $g(a) = 0$. Now we can follow that $a \in G(f)$ and $a \notin G(g)$. Thus we conclude that $G(f) \neq G(g)$. Thus $f \neq g \Rightarrow G(f) \neq G(g)$, thus implying that G is injective.

The fact that G is surjective follows from the definition of X_f and G .

5.4.11

Prove that the set $\mathcal{P}(\omega)$ is uncountable.

Follows from Cantor's theorem.

5.4.12

Using Theorem 5.4.18 prove that $|A| =_c |R|$, where $A = [-\pi, \pi)$.

We follow that $|A| \leq_c |R|$ because of the identity. By the proof in the first exercise of this chapter we follow that there exists an injection from R to $(-\pi, \pi)$. Thus by Shroder-Bernstein Theorem (5.4.18) we follow that $|A| =_c |R|$, as desired.

5.4.13

a, y

5.4.14

Let $f : A \rightarrow B$ be onto B , and let $C = \{x \in A : x \notin f(x)\}$. Show that $C \notin B$.

Suppose that $C \in B$. Since f is surjective we follow that there exists $a \in A$ such that $f(a) = C$. If $a \in C$, then $a \notin f(a) \Rightarrow a \notin C$, which is not possible. Suppose that $a \notin C$. Then we follow that $a \notin f(a)$, therefore $a \in C$ by definition, which is also a contradiction. Thus we follow that it is impossible to have $C \in B$. Thus $C \notin B$, as desired.

5.4.15

Suppose $A \subseteq B$ and $|B| \leq_c |A|$. Prove that $|A| =_c |B|$.

We follow that since $A \subseteq B$, then there exists an injection (namely identity) from A to B , thus we follow that $|A| \leq_c |B|$. Thus we follow from Shroder-Bernstein Theorem that $|A| =_c |B|$, as desired.

5.4.16

Suppose $A \subseteq B \subseteq C$ and $|A| =_c |C|$. Prove that $|B| =_c |C|$.

We follow that there exists a injections $f : B \rightarrow C$ and $g : A \rightarrow B$, which are just the identities with modified codomain. We also follow that there exists a bijection $h : A \rightarrow C$. From this we can follow that $g \circ h^{-1} : C \rightarrow B$ is an injection. Thus we follow that there exists an injection from B to C and vice-versa, thus implying that $|B| =_c |C|$, as desired.

5.4.17

Prove that $|A \times B| =_c |B \times A|$

We can define a bijection $f(\langle a, b \rangle) = \langle b, a \rangle$, which will give us desired result.

5.4.18

Suppose that $|A| \leq_c |B|$, $|B| \leq_c |C|$ and $|C| \leq_c |A|$. Prove that $|A| =_c |B| =_c |C|$

We can use the same argument as in 5.4.19.

5.4.19

Let $f : A \rightarrow K$ and $g : B \rightarrow L$ be bijections. Let $h : A \times B \rightarrow K \times L$ be defined by $h(\langle a, b \rangle) = \langle f(a), g(b) \rangle$ for all $\langle a, b \rangle \in A \times B$. Prove that h is a bijection.

Suppose that $\langle k, l \rangle \in K \times L$. We follow that $k \in K$ and $l \in L$, thus there exist $a \in A, b \in B$ such that $f(a) = k$ and $g(b) = l$ by the fact that f, g are both bijective and therefore surjective. Thus there exists $\langle a, b \rangle \in A \times B$ such that $h(\langle a, b \rangle) = \langle k, l \rangle$. Thus h is surjective.

Suppose that $\langle a, b \rangle \neq \langle a', b' \rangle$. We follow that $a \neq a'$ or $b \neq b'$. Thus by injectiveness of f, g we follow that $f(a) \neq f(a')$ or $g(b) \neq g(b')$, which imply that $\langle f(a), g(b) \rangle \neq \langle f(a'), g(b') \rangle$. Thus we follow that h is injective, as desired.

5.4.20

Prove that $G(g^{-1} \circ h \circ f) = h$ where the functions G, g^{-1}, h, f are as in the proof of Theorem 5.4.6(3)

We follow that

$$G(g^{-1} \circ h \circ f) = g \circ g^{-1} \circ h \circ f \circ f^{-1}$$

We can follow that both $g \circ g^{-1}$ and $f \circ f^{-1}$ are identity functions on L and K respectively. Thus we follow that since $h : K \rightarrow L$

$$G(g^{-1} \circ h \circ f) = g \circ g^{-1} \circ h \circ f \circ f^{-1} = h$$

as desired.

5.4.21

Suppose A is nonempty. Let $c \in B$ and $d \in B$ be distinct. Using a diagonal argument, show that there is no function $F : A \rightarrow B^A$ that is onto B^A . Now find a one-to-one function $G : A \rightarrow B^A$. Conclude that $|A| <_c |B^A|$.

Define a function $f : \mathcal{P}(A) \rightarrow B^A$ by the rule

$$(f(X))(a) = \begin{cases} c & \text{if } a \in X \\ d & \text{if } a \notin X \end{cases}$$

Suppose that $X_1 \neq X_2 \in \mathcal{P}(A)$. Then we follow that there exists $a \in X_1$ such that $a \notin X_2$ (or vice versa, both cases are equivalent). Thus $(f(X_1))(a) \neq (f(X_2))(a)$. Now we can follow that $X_1 \neq X_2 \Rightarrow f(X_1) \neq f(X_2)$. Thus f is injective. Therefore we can follow that

$$|\mathcal{P}(A)| \leq_c |B^A|$$

Since $|A| <_c |\mathcal{P}(A)|$, we conclude that there could be no surjections between A and B^A , as desired. From this argument alone we can follow that there exists an injection $h : A \rightarrow B^A$,

but I haven't used the diagonal argument, because I can't figure out where I'm supposed to put it here, so I'll provide a direct injection anyways.

Since A is nonempty, we follow that there exists $a \in A$. Thus we follow that for each $a \in A$ we can define a function $f : A \rightarrow B$ by

$$f(x) = \begin{cases} x = a \Rightarrow c \\ x \neq a \Rightarrow d \end{cases}$$

we can follow that the map which sends A to produced function is injective, thus we can conclude that $|A| \leq_c |B^A|$. Keeping in mind our previous result we can follow that

$$|A| <_c |B^A|$$

, as desired.

5.4.22

Prove that $|\omega^\omega| =_c |\mathcal{P}(\omega)|$. Conclude that $|\omega^\omega| =_c |R|$.

We know that there exists bijective function $p : \omega \times \omega \rightarrow \omega$. Thus we follow that there exists $p^{-1} : \omega \rightarrow \omega \times \omega$. For $f \in \omega^\omega$ define $A : \omega^\omega \rightarrow \mathcal{P}(\omega)$

$$A_f = \{p(i, j) : \langle i, j \rangle \in f\}$$

Then we follow that

$$f_1 \neq f_2 \Rightarrow \langle i, j \rangle \in f_1 \wedge \langle i, j \rangle \notin f_2 \Rightarrow p(i, j) \in A_{f_1} \wedge p(i, j) \notin A_{f_2} \Rightarrow A_{f_1} \neq A_{f_2}$$

Thus given function is injective. Thus $|\omega^\omega| \leq_c |\mathcal{P}(\omega)|$.

We know that $|\mathcal{P}(\omega)| =_c |\{0, 1\}^\omega|$, and since $\{0, 1\}^\omega \subseteq \omega^\omega$, we follow that $|\mathcal{P}(\omega)| \leq_c |\omega^\omega|$.

Thus we follow by Schroder-Bernstein that $|\mathcal{P}(\omega)| =_c |\omega^\omega|$, as desired.

5.4.23

Prove Theorem 5.4.7(1)

Suppose that $A \cap B = \emptyset$. Then we follow that for $\langle f, g \rangle \in K^A \times K^B$ we can define a function $h_{f,g} : A \cup B \rightarrow K$ by

$$h(x) = \begin{cases} x \in A \Rightarrow f(x) \\ x \in B \Rightarrow g(x) \end{cases}$$

Since $A \cap B = \emptyset$ we follow that the function is well defined. Thus we can define $H : K^A \times K^B \rightarrow K^{A \cup B}$ by this rule. We can follow that the function is injective and surjective pretty easily, thus we follow that

$$|K^A \times K^B| =_c |K^{A \cup B}|$$

as desired.

5.4.24

Prove Theorem 5.4.7(2)

Let $f \in K^A \times L^A$. We follow that $f = \langle g, h \rangle$. Thus we can define $k : A \times (K \times L)$ by

$$k(x) = \langle g(x), h(x) \rangle$$

We can follow that this function is bijective pretty easily.

5.4.25

skip.

5.4.26

Prove that $|(\omega^\omega)^\omega| =_c |\omega^\omega|$

We follow that $|\omega \times \omega| =_c |\omega|$. Thus $|\omega^{\omega \times \omega}| =_c |\omega^\omega|$. Since $|(\omega^\omega)^\omega| = |\omega^{\omega \times \omega}|$, we follow that $|(\omega^\omega)^\omega| = |\omega^\omega|$, as desired

5.4.27

Prove that

$$|(\omega^\omega)^{(\omega^\omega)}| =_c |\omega^{(\omega^\omega)}|$$

and

$$|(\{0, 1\}^\omega)^{\omega^\omega}| =_c |\{0, 1\}^{(\omega^\omega)}|$$

We can follow that

$$|\omega^\omega \times \omega| =_c |\omega^\omega|$$

thus we follow that since $|A| =_c |A|$ for any set A

$$|A^{(\omega^\omega \times \omega)}| =_c |A^{(\omega^\omega)}|$$

and since

$$|A^{(\omega^\omega \times \omega)}| =_c |(A^\omega)^{(\omega^\omega)}|$$

we follow that

$$|A^{(\omega^\omega)}| =_c |(A^\omega)^{(\omega^\omega)}|$$

Substituting ω or $\{0, 1\}$ for A we get the desired result.

5.4.31

Let A and B be nonempty sets. Using the AC, prove that there exists a one-to-one $f : A \rightarrow B$ iff there exists $g : B \rightarrow A$ that is onto A .

Suppose that $f : A \rightarrow B$ is injective. Because A is nonempty, we follow that there exists $a \in A$. We follow that a function $f' : A \rightarrow \text{ran}(A)$ defined by $f'(x) = f(x)$ is bijective, therefore we can define $g : B \rightarrow A$ by

$$g(x) = \begin{cases} x \in \text{ran}(A) \Rightarrow f^{-1}(x) \\ x \notin \text{ran}(A) \Rightarrow a \end{cases}$$

Suppose that $x \in A$. We follow that

$$g(f^{-1}(x)) = x$$

. Thus we follow that g is surjective.

Conversely, suppose that there exists surjective $g : B \rightarrow A$. Let $\langle G_i : i \in A \rangle$ be indexed function, where

$$G(i) = g^{-1}[\{i\}]$$

Because g is surjective, we follow that for every $a \in A$ there exists $y \in B$ such that $g(y) = a$. Thus we follow that $g^{-1}[\{a\}] \neq \emptyset$, and therefore $\langle G_i : i \in A \rangle$ has nonempty terms. We can also follow that since g is a function,

$$(\forall i_1, i_2 \in A)(i_1 \neq i_2 \Rightarrow g^{-1}[\{i_1\}] \cap g^{-1}[\{i_2\}] = \emptyset)$$

We follow from AC that there exists a function $\langle h_i : i \in A \rangle$ such that $h_i \in G(i)$. Since $G(i) \subseteq A$ we can state that $\text{ran}(h) \subseteq A$, thus we're justified to define a function $f : A \rightarrow B$ by $f(x) = h(x)$. Let $x_1, x_2 \in A$ be such that $x_1 \neq x_2$. Suppose that $f(x_1) = f(x_2)$. Then we follow that $g^{-1}[\{x_1\}] \cap g^{-1}[\{x_2\}] \neq \emptyset$, which is a contradiction. Therefore we can follow that f is injective, as desired.

5.4.39

Let A be a set and let $H : \mathcal{P}(A) \rightarrow \mathcal{P}(A)$. Suppose for all C and D in $\mathcal{P}(A)$ we have that $H(C) \subseteq H(D)$ whenever $C \subseteq D$. Let

$$S = \{D : D \subseteq A \wedge H(D) \subseteq D\}$$

and let $X = \bigcap S$. Prove that $H(X) = X$. Moreover, suppose $Y \subseteq X$ satisfies $H(Y) \subseteq Y$. Prove that $X = Y$.

We follow that

$$(\forall D \in S)(\bigcap S \subseteq D)$$

Thus we follow that

$$(\forall D \in S)(X \subseteq D)$$

therefore by definition of H we follow that

$$(\forall D \in S)(H(X) \subseteq H(D))$$

And since $D \in S$, we follow that $H(D) \subseteq D$, therefore

$$(\forall D \in S)(H(X) \subseteq D)$$

thus

$$H(X) \subseteq \bigcap S$$

thus $H(X) \subseteq X$. Thus we follow that $X \in S$. By the definition of H we follow that $H(X) \subseteq X$ implies that $H(H(X)) \subseteq H(X)$. Thus we follow that $H(X) \in S$ by definition of S . Thus we follow that $\bigcap S \subseteq H(X)$. Therefore $X \subseteq H(X)$. Therefore by double inclusion we follow that $H(X) = X$.

Suppose that $Y \subseteq X$ is such that $H(Y) \subseteq Y$. We follow that since $X \subseteq A$ and by given conditions $Y \in S$. Thus $\bigcap S \subseteq Y$. Therefore $X \subseteq Y$. Therefore by double inclusion $X = Y$, as desired.

Chapter 6

Transfinite Recursion

6.1 Well-Ordering

6.1.1

Let R be the set of real number and let \leq be the standart order on R . Suppose $f : \omega \rightarrow R$ is such that for all $n, m \in \omega$, if $n \in m$, then $f(n) < f(m)$. Let $A = \{f(i) : i \in \omega\}$.

(a) Let i and j be in ω . Prove that if $f(i) < f(j)$, then $i \in j$.

We follow that if $j \in i$, then $f(j) < f(i)$, which is not the case. We also follow that if $i = j$, then $f(j) = f(i)$, therefore we follow by trichotomy that $i \in j$, as desired.

(b) Prove that \leq is a well-ordering on A .

Suppose that $Q \subseteq A$ and $Q \neq \emptyset$. Let $Q_i = f^{-1}[Q]$. We follow that $Q_i \subseteq \omega$ and $Q_i \neq \emptyset$, therefore by well-ordering of ω we follow that there exists least element $q \in Q$. Let $a_m = f(q)$ and let there be arbitrary $a' \in A$. For a' there exists $j \in Q_i$ such that $f(j) = a'$. Because q is the least element of Q_i we follow that $q \leq a'$, therefore by definition of f , $f(q) \leq f(a')$. Thus we follow that $f(q)$ is the least element of Q . Therefore we follow that every nonempty subset of A has a least element, therefore \leq is a well-ordering on A , as desired.

6.1.2

Let $A = \omega \cup \{\omega\}$, and for all $x, y \in A$ define the relation \leq on A by $x \leq y$ if and only if $x \in y$ or $x = y$. Show that \leq is a well-ordering on A .

Suppose that $x, y, z \in A$.

We can follow that $x = x$, therefore $x \leq x$.

Suppose that $x \leq y$ and $y \leq z$. If none of x, y, z are equal to ω , then we follow transitive properties from ordering on ω , therefore $x \leq z$. If $z = \omega \wedge x, y \neq \omega$, then we follow that $x \in z \Rightarrow x \leq z$. If $z = y = \omega$ and $x \neq \omega$, then we follow that $z \in z \Rightarrow x \leq z$. If

$x = y = z = \omega$, then we follow that $x \leq \omega$. All of the other cases are impossible, therefore we follow transitive property.

Suppose that $x \leq y$ and $y \leq x$. Suppose that $y \in x$. Then we follow that if $x = y$, then $y \in y$, which is impossible. If $x \in y$, then we also have impossible case. Thus we conclude that $x = y$, which gives us antisymmetry.

Suppose that $x, y \in A$. If $x, y \neq \omega$, then we follow that $x \leq y$ or $y \leq x$ by standard order on ω . If $y = \omega$ and $x \neq \omega$, then we follow that $x \in y$, therefore $x \leq y$. If $y = x = \omega$, then we follow that $y \leq x$. This gives us total ordering.

Suppose that $B \subseteq A$ and $B \neq \emptyset$. If $B = \{\omega\}$, then we follow that ω is the least (and only) element of B . If $B \neq \{\omega\}$ then we follow that $B' = B \setminus \{\omega\}$ is nonempty. We follow that $B' \subseteq \omega$, therefore there exists a least element b of B' . Therefore we follow that

$$(\forall x \in B')(b \leq x)$$

Since $B' \subseteq \omega$, we follow that $b \in \omega$. Thus

$$(\forall x \in B)(b \leq x)$$

therefore b is the least element of B . Therefore we follow that for all subsets of A we've got that it has a least element. Therefore \leq is a well-ordering on A , as desired.

6.1.3

Supposes that \preceq is a well-ordering on A and that $f : A \rightarrow A$ is such that if $x \prec y$ then $f(x) \prec f(y)$ whenever $x, y \in A$.

(a) Show that f is injective.

Suppose that $x \neq y \in A$. We follow that $x \prec y$ or $y \prec x$ (by trichotomy). Thus we follow that $f(x) \prec f(y)$ or $f(y) \prec f(x)$. Therefore $f(x) \neq f(y)$. Therefore f is injective, as desired.

(b) Prove that $x \preceq f(x)$ for all $x \in A$.

Suppose that

$$f(x) \prec x$$

then we follow that

$$f(f(x)) \prec f(x)$$

by definition of f . This gives us the idea to define a function $p : \omega \rightarrow A$ by

$$p(0) = x$$

$$p(n^+) = f(p(n))$$

Now define

$$I = \{n \in \omega : p(n) \prec p(n^+)\}$$

we follow that $0 \in I$ by our assumption that $f(x) \prec x$. Suppose that $n \in I$. Then we follow that $p(n) \prec (n^+)$. Therefore by definition of f

$$f(p(n)) \prec f(p(n^+))$$

$$p(n^+) \prec p((n^+)^+)$$

thus we follow that $n \in I \Rightarrow n^+ \in I$. Therefore $I = \omega$, and therefore we've got a function $p : \omega \rightarrow A$ such that $p(n) \prec p(n^+)$, which gives us a contradiction by 6.1.2.

6.1.4

Let A be an infinite set with the well-ordering \preceq . Now let $h : \omega \rightarrow A$ be the function defined in the proof of Theorem 6.1.3. Let $y \in A$. Prove that for all $n \in \omega$, if $y \prec h(n)$, then $y = h(i)$ for some $i \in n$.

Let

$$I = \{n \in \omega : \underline{L}_{h(n)} \subseteq \text{ran}(h)\}$$

we follow that for $h(0) = p$ and

$$\underline{L}_{h(0)} = \underline{L}_p = \{p\}$$

thus $0 \in I$. Suppose that $j \in I$. We follow that $\underline{L}_{h(j)} \subseteq \text{ran}(h)$. From the inductive proof in the theorem we follow that

$$\underline{L}_{h(j^+)} = \underline{L}_{h(j)} \cup \{h(j^+)\}$$

Since $\{h(j^+)\}, \underline{L}_{h(j)} \subseteq \text{ran}(h)$, we follow that $\underline{L}_{h(j^+)} \subseteq \text{ran}(h)$, therefore $I = \omega$.

From this we follow that if $y \prec h(n)$, then $y \in \underline{L}_{h(j^+)}$, therefore $(\exists i \in \omega)(y = h(i))$, as desired.

6.1.5

Suppose that \preceq is a well-ordering on W and let $C \subseteq W$. Show that \preceq_C is a well-ordering on C .

We can follow that \preceq_C is a total order from one of the exercises in the section 3.4. Suppose that $X \subseteq C$. Then we follow that $X \subseteq W$. Therefore it has a \preceq -least element x . Since $x \in X$, we follow that $x \in C$. Suppose that $y \in X$. Then we follow that $x \preceq y$. Because $y \in X$ we follow that $y \in C$. Therefore we follow that $x \preceq_C y$. Therefore x is a \preceq_C -least element of X . Thus we conclude that every nonempty subset of C has a \preceq_C -least element. Therefore \preceq_C is a well-order on C , as desired.

6.1.6

Prove Theorem 6.1.4

Let \preceq' be a well-ordering on the set B . Suppose that $h : A \rightarrow B$ is injective. Define the relation \preceq on A by $x \preceq y$ iff $h(x) \preceq' h(y)$ for all $x, y \in A$. Then we follow that \preceq is a total order by some exercise (or theorem) in chapter 3 (if not, then it's pretty evident).

Suppose that X is nonempty and $X \subseteq A$. We follow that $h[X] \subseteq B$ and it is nonempty as well. By well-ordering of \preceq' we follow that there exists $x \in h[X]$ that is \preceq' -least element of $h[X]$. Because h is injective, we follow that there exists only one $y \in X$ such that $h(x) = y$. Let $z \in X$ be arbitrary. Then we follow that

$$h(x) \preceq' h(z)$$

therefore

$$x \preceq z$$

thus we follow that x is the \preceq -least element of X . Thus we follow that every nonempty subset of A has a \preceq -least element, thus we can conclude that \preceq is a well-order on A , as desired.

6.1.7

Prove that every finite set has a well-ordering

We follow that by 6.1.4 and the fact that \leq is a well-order for any $n \in \omega$.

6.1.8

Prove that every countably infinite set has a well-ordering

We follow that by 6.1.4 and the fact that \leq is a well-order for ω .

6.2 Transfinite Recursion Theorem**6.2.1**

Complete the proof of Theorem 6.2.1 by showing that the function H satisfies $H(u) = F(H|s(u))$ for all $u \in W$. Also, show that H is the only such function.

Assume that

$$H(u) \neq F(H|s(u))$$

for some $u \in W$.

Let w is the \preceq -lowest element of W such that

$$H(w) \neq F(H|s(w))$$

We know that $g_w = G(w)$ is such that

$$g_w(w) = F(g_w|s(w))$$

From claim 3 we follow that

$$(\forall x \in s(w))(g_w(x) = g_x(x))$$

By using definition of H we get

$$(\forall x \in s(w))(g_w(x) = H(x))$$

therefore

$$g_w|s(w) = H|s(w)$$

thus

$$g_w(w) = F(g_w|s(w))$$

$$g_w(w) = F(H|s(w))$$

$$H(w) = F(H|s(w))$$

which is a contradiction.

Now suppose that there exist two functions $H_1 \neq H_2$ such that

$$H_1(w) = F(H_1|s(w))$$

$$H_2(w) = F(H_2|s(w))$$

we follow that there exists lowest $w \in W$ such that $H_1(w) \neq H_2(w)$. Thus

$$H_1|s(w) = H_2|s(w)$$

And since F is a function we follow that

$$F(H_1|s(w)) = F(H_2|s(w))$$

thus

$$H_1(w) = H_2(w)$$

which is a contradiction.

6.2.2

Show that Theorem 6.2.5 implies Theorem 6.2.1

Let $F : A^{<W} \rightarrow A$. If $A = \emptyset$, then we follow that $A^{<W} = \emptyset$, therefore $H = \emptyset$, which presents a trivial case. Because of it, suppose that A is nonempty. Because A is nonempty, we follow that there exists certain $a \in A$. Define

$$\phi(x, y) = (x \in A^{<W} \wedge F(x) = y) \vee (x \notin A^{<W} \wedge y = a)$$

For every set x we follow that $x \in A^{<W}$ or $x \notin A^{<W}$. Thus we follow that two clauses of ϕ are mutually exclusive. If $x \in A^{<W}$, then we follow that there exists a unique $y \in A$ such that $F(x) = y$ by the virtue of the fact that F is a function. If $x \notin A^{<W}$, we follow that $y = a$ is the only possibility.

Applying 6.2.5 to set W with corresponding well-order \prec , we follow that there exists a unique function H with domain W such that

$$\phi(H|s(u), H(u))$$

From the definition of ϕ we follow that

$$\forall x (\phi(x, y) \Rightarrow y \in A)$$

therefore for all $u \in W$ we've got that $H(u) \in A$. Therefore we're justified to state that $H : W \rightarrow A$.

Therefore we conclude that there exists $H : W \rightarrow A$ such that

$$H(u) = F(H|s(u))$$

which gives us the result of theorem 6.2.1, as desired.

6.2.3

Let \preceq be a well-ordering on a set W and A be a set. Define $l : A^{precW} \rightarrow W$ by $l(g)$ equals the \preceq -least $u \in W$ such that $u \notin \text{dom}(g)$. Let $G : A^{<W} \times W \rightarrow A$ be a function. Show that Theorem 6.2.1 implies there exists a function $H : W \rightarrow A$ such that

$$H(u) = G(H|s(u), u)$$

for all $u \in W$.

Define a relations F by

$$\langle u, y \rangle \in F \Leftrightarrow G(\langle u, l(u) \rangle) = y$$

We can follow that for arbitrary $u \in A^{<W}$ there exists a unique tuple $\langle u, l(u) \rangle$, and for this tuple theree exists a unique $y \in A$ such that $G(\langle u, l(u) \rangle) = y$. Thus we follow that F is a

function from $A^{<W}$ to A . Thus we follow that there exists a unique $H : W \rightarrow A$ such that for all $u \in W$

$$H(u) = F(H|s(u))$$

by definition of F we follow that

$$H(u) = G(H|s(u), l(H|s(u)))$$

We follow that $H|s(u) : s(u) \rightarrow A$. Therefore definition of l gives us that

$$l(H|s(u)) = u$$

thus

$$H(u) = G(H|s(u), u)$$

as desired.

6.2.4

Suppose that \preceq is a well-ordering on a set W and $F : A^{<W} \rightarrow A$ is a function. Let $H : W \rightarrow A$ be as in Theorem 6.2.1

(a) Let $u, v \in W$. Prove that if $s(u) = s(v)$, then $u = v$.

Suppose that $u \neq v$. Then we follow that $u \prec v$ or $v \prec u$. Assume the former (both cases are similar). Then we follow that $u \in s(v)$. Thus $u \in s(u)$, thus $u \prec u$, therefore $u \neq u$, which is a contradiction.

(b) Suppose that F is one-to-one. Prove that H is also one-to-one.

Suppose that $u \neq v \in W$. We follow that $s(u) \neq s(v)$. Thus $H|s(v) \neq H|s(u)$ (we're talking about restrictions and not ranges, thus this implication is valid). Now we can follow that injectivity of F implies that $F(H|s(v)) \neq F(H|s(u))$. Therefore we conclude by applying definition of H that $H(v) \neq H(u)$. Therefore we can follow that H is injective, as desired.

6.2.5

Let \preceq be a well-ordering on W and \preceq^* be a well-ordering on A . Assume for each $g \in A^{<W}$, there is a $y \in A$ such that $g(x) \prec^* y$ for all $x \in \text{dom}(g)$. Show that there is an $H : W \rightarrow A$ so that for all $v \in W$ and $u \in W$, if $v \prec u$, then $H(v) \prec^* H(u)$.

Define $F : A^{<W} \rightarrow A$ by

$$F(g) = \prec^* \text{- lowest element of } \{y \in A : (\forall x \in \text{dom}(g))(g(x) \prec^* y)\}$$

We can follow pretty easily that this thing is a function. 6.2.1 gives us that there exists $H : W \rightarrow A$ such that

$$H(u) = F(H|s(u))$$

Now let v, u be such that $v \prec u$. We follow that $v \in s(u)$. Therefore we can follow that $H(u) = F(H|s(u))$. By definition of F we follow that $(\forall x \in s(u))(H(x) \prec H(u))$. Since $v \in s(u)$ we follow that $H(v) \prec H(u)$, as desired.

6.2.6

Let A be a set. Suppose that $A \subseteq C$ where C is a transitive set. Prove that $\overline{A} \subseteq C$. Thus, \overline{A} is the "smallest" transitive set for which A is a subset.

Suppose that $A \subseteq C$ and C is a transitive set. Let

$$I = \{n \in \omega : F(n) \subseteq C\}$$

we follow that $F(0) = A \subseteq C$ by premise of the exercise. Let $n \in I$. We follow that $F(n) \subseteq C$. We follow that

$$(\forall x \in F(n))(x \in C)$$

because C is transitive, we follow

$$(\forall x \in F(n))(x \subseteq C)$$

let $y \in F(n^+)$. We follow that $y \in \bigcup F(n)$. Thus

$$(\exists X \in F(n))(y \in X)$$

thus $y \in C$. Therefore $\bigcup F(n) \subseteq C$. Therefore $F(n^+) \subseteq C$. Therefore $n \in I \Rightarrow n^+ \in I$. Therefore $I = \omega$. Thus we follow that

$$(\forall n \in \omega)(F(n) \subseteq C)$$

Suppose that $x \in \overline{A}$. We follow that there exists $n \in \omega$ such that $x \in F(n)$. Because $F(n) \subseteq C$, we follow that $x \in C$. Thus we follow that $\overline{A} \subseteq C$, as desired.

Given that \overline{A} is transitive, we follow that \overline{A} is the smallest transitive set for which A is a subset.

6.2.7

Let B be a set. Conclude from Exercise 6 that $\overline{\{B\}}$ is the smallest transitive set that contains B as an element.

Suppose that C is a transitive set that contains B as an element. We follow that C contains $\{B\}$ as a subset. Therefore we follow that $\overline{\{B\}} \subseteq C$ by previous exercise. Therefore for all transitive set C

$$B \in C \Rightarrow \overline{\{B\}} \subseteq C$$

We follow that $B \in \overline{\{B\}}$ and $\overline{\{B\}}$ imply that $\overline{\{B\}}$ is the smallest transitive subset such that B is an element this set.

6.2.8

Let A be a set. Using the replacement axiom, one can show that $\{\bar{x} : x \in A\}$ is a set. Establish the following:

(a) Prove that if $x \in A$, then $\bar{x} \subseteq \bar{A}$.

We follow that $x \in A$ and $A \subseteq \bar{A}$ implies that $x \in \bar{A}$. Since \bar{A} is transitive, we follow that $x \subseteq \bar{A}$. Since \bar{A} is transitive, exercise 6 implies that $\bar{x} \subseteq \bar{A}$.

(b) Prove that $A \cup \bigcup \{\bar{x} : x \in A\} \subseteq \bar{A}$

We can follow that $A \subseteq \bar{A}$. For every $x \in A$ we follow that $\bar{x} \subseteq \bar{A}$. Suppose that $y \in \bigcup \{\bar{x} : x \in A\}$. We follow that there exists $x \in A$ such that $y \in \bar{x}$. Thus $y \in \bar{A}$. Therefore $\bigcup \{\bar{x} : x \in A\} \subseteq \bar{A}$. Therefore we follow that $A \cup \bigcup \{\bar{x} : x \in A\} \subseteq \bar{A}$.

(c) Prove that $A \cup \bigcup \{\bar{x} : x \in A\}$ is a transitive set.

Suppose that $y \in A \cup \bigcup \{\bar{x} : x \in A\}$. If $y \in A$, then $\bar{y} \in \{\bar{x} : x \in A\}$. Therefore $\bar{y} \subseteq \bigcup \{\bar{x} : x \in A\}$. Since \bar{y} is transitive and $y \in \bar{y}$, we follow that $y \subseteq \bigcup \{\bar{x} : x \in A\}$.

If $y \in \bigcup \{\bar{x} : x \in A\}$. We follow that there exists $x' \in A$ such that $y \in \bar{x}'$. Thus $y \subseteq \bar{x}'$. Therefore $\bigcup \bar{y} \in \{\bar{x} : x \in A\}$. Thus we follow that $y \subseteq A \cup \bigcup \{\bar{x} : x \in A\}$.

From those conclusion we follow that presented set is transitive.

(d) Prove that $A \cup \bigcup \{\bar{x} : x \in A\} = \bar{A}$

We follow that $A \subseteq A \cup \bigcup \{\bar{x} : x \in A\}$ and $A \cup \bigcup \{\bar{x} : x \in A\}$ is transitive, therefore we follow that $\bar{A} \subseteq A \cup \bigcup \{\bar{x} : x \in A\}$. From part (a) we get double inclusion, which gives us equality.

6.2.9

Let A be a set. Using the proof of Theorem 6.2.8 as a model, prove that there is a function F with domain ω such that

1. $F(0) = A$

2. $F(n^+) = \{F(n)\}$ for all $n \in \omega$.

Let $C = F[\omega]$. Prove that $A \in C$ and for all X , if $X \in C$, then $\{X\} \in C$.

We can define

$$y = \begin{cases} A & \text{if } f = \emptyset \\ \{F(n)\} & \text{if } f \text{ is a function with domain } k^+ \text{ for some } k \in \omega \\ \emptyset & \text{otherwise} \end{cases}$$

and define $\phi(f, y)$ based on this definition. Then we follow that there exists a function F with domain ω such that the required conditions hold.

Let $C = F[\omega]$. We follow that $F(0) \in C$, therefore $A \in C$.

If $X \in C$, then we follow that there exists $n \in \omega$ such that $F(n) = X$. Thus $F(n^+) = \{X\}$. Since $n^+ \in \omega$, we follow that $F(n^+) \in F[\omega]$, therefore $\{X\} \in F[\omega]$, as desired.

6.2.10

Let A be a set. Using the proof of Theorem 6.2.8 as a model, prove that there is a function F with domain ω such that

1. $F(0) = A$

2. $F(n^+) = \mathcal{P}(F(n))$ for all $n \in \omega$.

Let $C = F[\omega]$. Prove that $A \in C$ and for all X , if $X \in C$, then $\mathcal{P}(X) \in C$.

We can define

$$y = \begin{cases} A & \text{if } f = \emptyset \\ \mathcal{P}(F(n)) & \text{if } f \text{ is a function with domain } k^+ \text{ for some } k \in \omega \\ \emptyset & \text{otherwise} \end{cases}$$

and define $\phi(f, y)$ based on this definition. Then we follow that there exists a function F with domain ω such that the required conditions hold.

Let $C = F[\omega]$. We follow that $F(0) \in C$, therefore $A \in C$.

If $X \in C$, then we follow that there exists $n \in \omega$ such that $F(n) = X$. Thus $F(n^+) = \mathcal{P}(X)$. Since $n^+ \in \omega$, we follow that $F(n^+) \in F[\omega]$, therefore $\mathcal{P}(X) \in F[\omega]$, as desired.

Chapter 7

The Axiom of Choice (Revisited)

7.1 Zorn's Lemma

7.1.1

Let $\langle A_i : i \in I \rangle$ be an indexed function so that $A_i \neq \emptyset$ for all $i \in I$. Without appealing to the axiom of choice, prove that if $\bigcup_{i \in I} A_i$ is countably infinite, then there is a function $f : I \rightarrow \bigcup_{i \in I} A_i$, such that $f(i) \in A_i$, for all $i \in I$.

Because $\bigcup_{i \in I} A_i$ is countably infinite and all of A_i are nonempty, we can follow that $|I| \leq_c |\omega|$, $|A_i| \leq_c |\omega|$ and $|\bigcup_{i \in I} A_i| =_c |\omega|$ (we can follow that if one of those is not true, then we've got a contradiction of the fact that $|\bigcup_{i \in I} A_i| =_c |\omega|$).

Thus we follow that there exists a bijection $g : \omega \rightarrow \bigcup_{i \in I} A_i$. We can follow that for every i there exists $g^{-1}[A_i] \subseteq \omega$. Because each A_i is nonempty and g is a bijection, we follow that $g^{-1}[A_i]$ is nonempty for all $i \in I$. Define $f' : I \rightarrow \omega$ by

$$f'(i) = \leq\text{-least element of } g^{-1}[A_i]$$

since the least element of a subset is unique, we follow that the function is well-defined. thus we follow that for $f = g \circ f' : I \rightarrow \bigcup_{i \in I} A_i$ we've got

$$f(i) \in A_i$$

for all $i \in I$, as desired.

7.1.2

Let $R \subseteq A \times B$ and let $R(x, y)$ denote $\langle x, y \rangle \in R$. Now suppose that for all $x \in A$, there is a $y \in B$ such that $R(x, y)$. Using the axiom of choice, show that there is a function $f : A \rightarrow B$ such that $R(x, f(x))$ for all $x \in A$

Because for every $x \in A$ there exists $y \in B$ such that $R(x, y)$, we follow that for $x \in A$ we can define a function $Q : A \rightarrow \mathcal{P}(B)$ by

$$Q(x) = \{y \in B : R(x, y)\}$$

Because for every x there exists y such that $R(x, y)$ we follow that

$$(\forall x \in A)(Q(x) \neq \emptyset)$$

thus we can follow that Q_x is an indexed function with nonempty terms. Thus AC implies that there exists $q : A \rightarrow \bigcup \mathcal{P}(B)$ such that $q(x) \in Q(x)$. Since $\bigcup \mathcal{P}(B) = B$, we follow that $q : A \rightarrow B$ and by the fact that $q(x) \in Q(x)$, we follow that $R(x, q(x))$, as desired.

7.1.3

RW: Let $R \subseteq A \times A$ and let $R(x, y)$ denote $\langle x, y \rangle \in R$. Suppose that $A \neq \emptyset$ and for all $x \in A$, there is a $y \in A$ such that $R(x, y)$. Show that there is a function $h : \omega \rightarrow A$ such that $R(h(n), h(n^+))$ for all $n \in \omega$

By previous exercise we follow that there exists $f : A \rightarrow A$ such that $R(x, f(x))$ for all $x \in A$. Let $a \in A$ be arbitrary (it exists because $A \neq \emptyset$). We follow by 4.2.1 that we can define $h : \omega \rightarrow A$ by

$$h(0) = a$$

$$h(n^+) = f(h(n))$$

Suppose that $k \in \omega$. Let $b = h(k)$. By proven properties of f and the fact that $b \in A$ we follow that

$$R(b, f(b))$$

by substituting b for its definition we follow that

$$R(h(k), f(h(k)))$$

and by definition of k we follow that

$$R(h(k), h(k^+))$$

Since $k \in \omega$ is arbitrary, we follow the desired conclusion.

7.1.4

Prove 7.1.4

Let \preceq be a partial order on A , and let C be a chain in A . Suppose that $C' \subseteq C$ is a cofinal chain.

Suppose that $x \in C_p$. We follow that

$$(\forall c \in C)(c \prec x)$$

Since $C' \subseteq C$, we follow that

$$(\forall c \in C')(c \prec x)$$

thus $x \in C'_p$ by definition. Therefore we conclude that $C'_p \subseteq C_p$.

Suppose that $x \in C'_p$. We follow that

$$(\forall c \in C')(c \prec x)$$

Let $y \in C$. By the fact that C' is cofinal we follow that there exists $q \in C'$ such that $y \prec q$. Because $q \in C'$, we follow that $q \prec x$. Thus we follow by transitivity that $y \prec x$. Because $y \in C$ is arbitrary, we conclude that

$$(\forall c \in C)(c \prec x)$$

therefore $x \in C_p$. Therefore we follow that $C'_p \subseteq C_p$. Thus by double inclusion we have $C_p = C'_p$, as desired.

7.1.5

Let (F, \subseteq) be a partially ordered set where F is a set (of sets). Suppose that for every chain $C \subseteq F$ we have that $\bigcup C \in F$.

(a) Let $C \subseteq F$ be a chain. Prove that $\bigcup C$ is an upper bound for C .

Suppose $X \in C$. Suppose that $x \in X$. We follow that $x \in \bigcup C$ and thus $X \subseteq \bigcup C$. Therefore

$$(\forall X \in C)(X \subseteq \bigcup C)$$

and by the properties of F we follow that $\bigcup C$. Thus we conclude that $\bigcup C$ is an upper bound for C by definition.

(b) Using Zorn's Lemma, show that there exists an $M \in F$ that is maximal, that is, M is not the proper subset of any $A \in F$.

By previous point we can follow that every chain C of F has an upper bound. Thus Zorn's Lemma implies that F has a maximal element M . Definition of a maximal element implies the desired result.

7.1.6

Let $f : A \rightarrow B$ and $F = \{X \subseteq A : (f|X) : X \rightarrow B \text{ is one-to-one}\}$. Consider the partially ordered set (F, \subseteq) .

The fact that F is nonempty is followed from the fact that $(f|\emptyset)$ is injective. Also, if f is restricted to a singleton, then it is also injective.

(a) Using Zorn's Lemma, show that there is an $M \in F$ that is maximal

Suppose that C is a chain in F . We want to show that C has an upper bound. If $f : A \rightarrow B$ is injective, then we follow that A is an upper bound for any subset of F .

Suppose that C is a chain in F . Suppose that $x \neq y \in \bigcup C$. We follow that there exist two sets $X, Y \in C$ such that $x \in X$ and $y \in Y$. Because C is a chain we follow that $X \subseteq Y$ or $Y \subseteq X$. Assume the former. Then we follow that $x, y \in Y$, and by the fact that $Y \in F$, we follow that $f(x) \neq f(y)$. Therefore $f|_{\bigcup C}$ is injective. Therefore $\bigcup C \in F$. Thus we follow that if C is a chain in F , then $\bigcup C \in F$. Using previous exercise (which uses Zorn's Lemma) we can conclude that F has a maximal element.

(probably a typo in the text of the exercise) (b) Prove that if f is onto B , then $(f|M) : M \rightarrow B$ is a bijection.

Suppose that $(f|M) : X \rightarrow B$ is not a bijection. Since $M \in F$, we follow that $(f|M) : M \rightarrow B$ is injective. Thus we follow that $(f|M) : M \rightarrow B$ is not surjective. Therefore there exists $b \in B$ such that $b \notin f[M]$. Because $f : A \rightarrow B$ is surjective, we can conclude that there exists $x \in A$ such that $f(x) = b$. Therefore $(f|M \cup \{x\}) : M \cup \{x\} \rightarrow B$ is injective and thus $M \cup \{x\} \in F$. Because $M \subseteq M \cup \{x\}$, we follow that M is not a maximal element, which is a contradiction.

7.1.7

Let (A, \preceq) be a poset. Let $F = \{D \in \mathcal{P}(A) : D \text{ is a chain in } A\}$. Consider the partially ordered set (F, \subseteq) .

(a) Let C be a chain in F . Show that $\bigcup C$ is a chain in A .

Suppose that $x, y \in \bigcup C$. We follow that there exist sets $X, Y \in C$ such that $x \in X$ and $y \in Y$. Since C is a chain we follow that $X \subseteq Y$ or $Y \subseteq X$. Assume the former. Then we follow that $x, y \in Y$. Thus $x \preceq y$ or $y \preceq x$ by the fact that Y is a chain. Therefore we conclude that $\bigcup C$ is a chain in A .

The remaining part (and this part as well) is practically identical to 7.1.5, therefore I'll skip the details.

7.1.8

Let P be the set of nonzero natural numbers. Then $(P, |)$ is a poset where $|$ is a divisibility relation on P . Define a partial order \preceq on P such that $| \subseteq \preceq$ and $2 \preceq 3$.

I think that standard \leq will do. It is a partial order (every total order is a partial order), if $x|y$, then $x \leq y$, therefore $| \subseteq \leq$, and we've got that $2 \leq 3$. Don't know if I'm missing something obvious, but I think that's it.

7.1.9

Using Theorem 7.1.10, show there is a total order \preceq on $\mathcal{P}(\omega)$ such that for all $x, y \in \mathcal{P}(\omega)$, if $x \subseteq y$, then $x \preceq y$. Show that $\preceq \neq \subseteq$ on $\mathcal{P}(\omega)$.

By straightforward application of 7.1.10 on a partial order \subseteq we get $\preceq \subseteq \mathcal{P}(\omega) \times \mathcal{P}(\omega)$ such that $(\subseteq) \subseteq (\preceq)$ (parentheses are used for clarity). This gives us the desired result.

We can follow that $\{2\} \not\preceq \{3\}$ and $\{3\} \not\preceq \{2\}$, but given that \preceq is a total order we follow that $\{2\} \preceq \{3\}$ or $\{3\} \preceq \{2\}$. Assume the former. Then we follow that $\langle \{2\}, \{3\} \rangle \in \preceq$ and $\langle \{2\}, \{3\} \rangle \notin (\subseteq)$, which tells us that $\subseteq \neq \preceq$, as desired.

7.1.10

Let $\langle A_i : i \in I \rangle$ be an indexed function with nonempty terms, and let

$$F = \{g : g \text{ is a function} \wedge \text{dom}(g) \subseteq I \wedge (\forall i \in \text{dom}(g))(g(i) \in A_i)\}$$

Thus, (F, \subseteq) is a partially ordered set. Assuming Zorn's Lemma, prove the AC as follows:

Let $C \subseteq F$ be a chain. Prove that $\bigcup C$ is in F and is an upper bound for C .

We can follow that since $C \subseteq F$, we can state that $\bigcup C \subseteq I \times \text{ran}(A)$. Suppose that $x, y \in \bigcup C$ are such that $x = \langle u, v \rangle$, $y = \langle o, w \rangle$. We follow that there exist $X, Y \in C$ such that $x \in X$ and $y \in Y$. By the fact that C is a chain we follow that $X \subseteq Y$ or $Y \subseteq X$. Assume the former. Then we follow that $x, y \in Y$. Since $Y \in C \subseteq F$, we follow that it is a function, and thus if $u = o$, then $v = w$. Thus we follow that $\bigcap C$ is a function. We can also follow that because $Y \in F$ we've got that $\text{dom}(Y) \subseteq I$, and thus $u, o \in I$, therefore $\text{dom} \bigcup C \subseteq I$. By the same token we've got the last condition of inclusion in F , therefore we can conclude that $\bigcup C \in F$.

Now exercise 7.1.5 can be applied to state that provided result implies that $\bigcup C$ is an upper bound of C whenever C is a chain.

(b) Conclude, via Zorn's Lemma, that F has a maximal element h .

Conditions that are proven in previous point are sufficient to apply Zorn's Lemma and get the desired result.

(c) Show that $\text{dom}(h) = I$ and $(\forall i \in I)(h(i) \in A_i)$. Thus $\langle h_i : i \in I \rangle$ is a choice function.

Because $h \in F$, we follow that $\text{dom}(h) \subseteq I$. Suppose that $I \not\subseteq \text{dom}(h)$. Let $i \in I \setminus \text{dom}(h)$. Now let $a \in A_i$. We can follow that $f : \{\langle i, a \rangle\}$ is a function, that satisfies all of the conditions of F , and therefore $f \in F$. We can follow that because $i \in I \setminus \text{dom}(h)$, we can state that $h \cup f \in F$. Thus we follow that $h \subseteq (h \cup f)$ and thus h is not a maximal element, which is a contradiction.

Therefore we conclude that $\text{dom}(h) = I$. The latter requirement is satisfied by the fact that $\text{dom}(h) = I$ and the last requirement for inclusion for F .

7.2 Filters and Ultrafilters

7.2.1

Let $S \subseteq X$ where S is nonempty. Let $F = \{A \subseteq X : S \subseteq A\}$. Prove that F is a filter on X .

Because F is a set of subsets of X we follow that $F \subseteq \mathcal{P}(X)$.

Since $S \subseteq X$, we follow that $X \in F$. Because S is nonempty, we follow that $S \not\subseteq \emptyset$, and thus $\emptyset \notin F$.

Suppose that $q, w \in F$. We follow that $S \subseteq q$ and $S \subseteq w$. Thus $S \subseteq q \cap w$. Therefore we follow that $q \cap w \in F$.

Suppose that $Y \in F$ and there exists $Z \subseteq X$ such that $Y \subseteq Z$ (i.e. $Y \subseteq Z \subseteq X$). We follow that since $S \subseteq Y$ by transitivity of \subseteq we get that $S \subseteq Z \subseteq X$. Thus we follow that $Z \in F$.

Therefore we conclude that F satisfies all of the requirements of a filter and thus is a filter on X , as desired.

7.2.2

Let F be a filter on X . Prove that F is closed under finite intersections. Conclude that F has the finite intersection property.

Let

$$I = \{n \in \omega : S \subseteq F \wedge |S| = n^+ \Rightarrow \bigcap S \in F\}$$

Suppose that $S \subseteq F$ and $|S| = 1 = (0)^+$. We follow that S is a singleton, whose element is an element of F , and thus $\bigcap S \in F$. Thus we conclude that $0 \in I$.

Suppose that $n \in I$. Let $S \subseteq F$ be such that $|S| = (n^+)^+$. We follow that there exists $a \in S$ and thus

$$S = (S \setminus \{a\}) \cup \{a\}$$

since $|S \setminus \{a\}| = n^+$ we follow that $\bigcap S \setminus \{a\} \in F$. Thus we follow that

$$\bigcap S = \bigcap S \setminus \{a\} \cap \{a\}$$

where on the right hand side we've got an intersection of two elements of F . Thus we follow that this intersection is in F (by the second property of a filter). Thus we conclude that $n^+ \in I$. Therefore we follow that $n \in I \Rightarrow n^+ \in I$, thus $I = \omega$. Therefore we can conclude that if S is a finite nonempty subset of F , then its intersection is also in F , and thus F is closed under finite intersections.

Given that F is closed under finite intersections, we follow that intersection of a finite subset of F is in F . Given that $\emptyset \notin F$, we conclude that intersection of a finite subset of F is nonempty, and thus F possesses finite intersection property, as desired.

7.2.3

Let $a \in X$ and $b \in X$ where $a \neq b$. Prove that the filter generated by $\{a, b\}$ is not maximal.

Let us denote the filter generated by $\{a, b\}$ as S . Let S' be the principal filter, generated by $\{a\}$. We follow that $\{a\} \in S'$, but $\{a\} \notin S$, thus $S' \neq S$. Suppose that $x \in S$. We follow that $\{a, b\} \subseteq x$. Thus $\{a\} \subseteq x$. Thus $x \in S'$. Therefore we follow that $S \subseteq S'$. Provided that $S \neq S'$, we conclude that S is not a maximal filter, as desired.

7.2.4

Let F be a filter on a nonempty set X . Let $A \in F$. Prove that $\mathcal{P}(A) \cap F$ is a filter on A .

Since $A \in F$ and $A \in \mathcal{P}(A)$, we follow that $A \in F \cap \mathcal{P}(A)$.

Suppose that $Z \in F \cap \mathcal{P}(A)$ and there exists Y such that $Z \subseteq Y \subseteq A$. Since $A \in F$, we follow that $A \in \mathcal{P}(X)$, and thus $A \subseteq X$. Thus $Z \subseteq Y \subseteq X$. Because $Z \in F$, we follow that $Y \in F$, and given that $Y \subseteq A$ we conclude that $Y \in F \cap \mathcal{P}(A)$.

Suppose that $X, Y \in F \cap \mathcal{P}(A)$. We follow that $X \cap Y \in F$. We also follow that

$$X \in \mathcal{P}(A) \wedge Y \in \mathcal{P}(A) \Rightarrow X \subseteq A \wedge Y \subseteq A \wedge X \cap Y \subseteq A \Rightarrow X \cap Y \in \mathcal{P}(A)$$

Thus we follow that $X, Y \in F \cap \mathcal{P}(A) \Rightarrow X \cap Y \in F \cap \mathcal{P}(A)$. Therefore we conclude that $F \cap \mathcal{P}(A)$ is a filter on A , as desired.

7.2.5

Suppose that X is an infinite set, and let A be a cofinite subset of X . Prove the following two items:

(a) If $A \subseteq B \subseteq X$, then B is a cofinite subset of X .

Lemme expand this exercise a bit and prove that set of cofinite sets constitutes a filter.

Let us prove that

$$F = \{S \subseteq X : X \setminus S \text{ is finite}\}$$

is a filter. We follow that $X \in F$ since $X \setminus X = \emptyset$. We've proven in the chapter the second property of the filter. We can also follow that if $A \subseteq B \subseteq X$, then $X \setminus B \subseteq X \setminus A$, and since all of the subsets of finite sets are finite, we follow that $X \setminus B$ is finite and thus B is cofinite as well. Thus F is a filter.

(b) If C is a cofinite subset of A , then C is a cofinite subset of X .

Because C is a subset of A we follow that

$$A \setminus (A \setminus C) = C$$

If C is a cofinite subset of A , then $A \setminus C$ is finite, thus $((A \setminus C) \cap C)$ is finite and thus $((A \setminus C) \cap C) \cup (X \setminus A)$ is finite. Thus we conclude that

$$((A \setminus C) \cap C) \cup (X \setminus A) = X \setminus (A \setminus (A \setminus C)) = X \setminus C$$

therefore $X \setminus C$ is finite and thus C is cofinite subset of X , as desired.

7.2.6

Let F be the filter of cofinite subsets of ω . Show that F is not an ultrafilter.

Let o be the set of odd numbers. Then we follow that $\omega \setminus o$ is infinite, thus $o \notin F$. We can also follow that $\omega \setminus (\omega \setminus o)$ is also infinite, and thus neither o nor $\omega \setminus o$ are in F . Thus we conclude that F is not an ultrafilter.

7.2.[7,8]

Prove Lemma 7.2.4

There's probably a typo in the text of the exercise.

Lemma 7.2.4 states that *if U is an ultrafilter on X , then*

(a) *For all $A \subseteq X$ and $B \subseteq X$, if $A \cup B \in U$, then either $A \in U$ or $B \in U$.*

(b) *Let F be a filter on X . If $U \subseteq F$, then $U = F$.*

Suppose that $A \subseteq X$, $B \subseteq X$ and $A \cup B \in U$. Suppose that neither A nor B are in U . We follow that since U is an ultrafilter, that $X \setminus A \in U$ and $X \setminus B \in U$. Thus $(X \setminus A) \cap (X \setminus B) \in U$. Therefore by DML

$$(X \setminus A) \cap (X \setminus B) = X \setminus (A \cup B) \in U$$

thus we follow that both $X \setminus (A \cup B)$ and $A \cup B$ are in U . Thus $(X \setminus (A \cup B)) \cap (A \cup B) = \emptyset \in U$, which is a contradiction of the fact that U is a filter. Thus we conclude that $A \in U$ or $B \in U$.

Suppose that F is a filter on X such that $U \subseteq F$. Suppose that $x \in F$. We follow that $x \subseteq X$, and thus $x \in U$ or $X \setminus x \in U$. If latter holds, then $X \setminus x \in U \subseteq F$, thus $X \setminus x, x \in F$ and therefore $(X \setminus x) \cap x = \emptyset \in F$, which is a contradiction. Thus we conclude that former holds and thus we've got that $F = U$ by double inclusion.

7.2.9

Let X be an infinite set and let F be the filter of all cofinite subsets of X . Suppose G is a filter on X such that $F \subseteq G$.

(a) *Prove that every $A \in G$ is infinite.*

Suppose that A is not infinite (i.e. finite). Then we follow that $X \setminus (X \setminus A) = A$ is finite, thus $X \setminus A \in F$. Thus $X \setminus A \in G$. Therefore $(X \setminus A) \cap A = \emptyset \in G$, which is a contradiction.

(b) *Prove that G is nonprincipal.*

Suppose that it is principal. Then we follow that there exists $a \in X$ such that $\{a\} \in G$. Thus G has finite elements, which is a contradiction.

(c) *Conclude that there is a nonprincipal ultrafilter on X .*

7.2.9 implies that there exists ultrafilter U on X such that $F \subseteq U$.

7.2.10

Let F be a nonempty set of filters on X . Prove that $\bigcap F$ is a filter on X .

For completeness' sake let us state that because

$$(\forall f \in F)(f \subseteq \mathcal{P}(X))$$

thus we follow that $\bigcap F \subseteq \mathcal{P}(X)$.

We can follow that since

$$(\forall f \in F)(X \in f \wedge \emptyset \notin f)$$

that $X \in \bigcap F$ and $\emptyset \notin \bigcap F$.

Suppose that $Y \in \bigcap F$ and there exists Z such that $Y \subseteq Z \subseteq X$. We follow that since $Y \in \bigcap F$ that

$$(\forall f \in F)(Y \in f)$$

thus $Y \subseteq Z \subseteq X$ implies that

$$(\forall f \in F)(Y \in f \wedge Y \subseteq Z \subseteq X)$$

thus

$$(\forall f \in F)(Z \in f)$$

therefore $Z \in \bigcap F$.

Suppose that $Y, Z \in \bigcap F$ are arbitrary. We follow that

$$(\forall f \in F)(Y, Z \in f)$$

since every f is a filter we follow that

$$(\forall f \in F)(Y \cap Z \in f)$$

thus $Y \cap Z \in \bigcap F$. Therefore we can conclude that $\bigcap F$ satisfies all of the properties of a filter, and thus it is a filter, as desired.

7.2.11

Let F be a filter on X and let $a \in X$.

(a) Prove that if $\{a\} \in F$, then $a \in A$ for all $A \in F$

Suppose that $A \in F$ is arbitrary. We follow that since $\{a\} \in F$ that

$$\{a\} \cap A \in F$$

if $a \notin A$, we follow that $\{a\} \cap A = \emptyset \in F$, which is a contradiction. Therefore we conclude the desired result.

(b) Suppose that F is an ultrafilter on X and $\{a\} \in F$. Conclude that F is the principal filter on X

Suppose that $S \subseteq X$ is such that $\{a\} \subseteq S$. We follow that since F is an ultrafilter that $S \in F$ or $X \setminus S \in F$. The latter is impossible by the fact that $a \notin X \setminus S$, and previous point states otherwise. Thus we conclude that

$$(\forall S \in \mathcal{P}(X))(\{a\} \subseteq S \Rightarrow S \in F)$$

thus F contains a principal filter of a .

Previous point proves that principal filter of a contains F . Therefore we conclude that F is a principal filter of a on X by double inclusion.

7.2.12

Let U be an ultrafilter on X .

(a) Suppose there is a finite set in U . Prove that $\{a\} \in U$ for some $a \in X$.

Let G be a finite set in U . Suppose that there is no $a \in X$ such that $\{a\} \in U$. We follow that

$$(\forall a \in X)(\{a\} \notin U)$$

thus

$$(\forall a \in X)(X \setminus \{a\} \notin U)$$

therefore

$$(\forall a \in G)(X \setminus \{a\} \notin U)$$

and since G is finite, we follow that $\{X \setminus \{a\} : a \in G\}$ is finite, thus

$$\bigcup \{X \setminus \{a\} : a \in G\} = X \setminus G$$

is also in U . Thus we follow that $(X \setminus G) \cap G = \emptyset \in U$, which is a contradiction.

(b) Conclude that if U is nonprincipal, then every $B \in U$ is infinite.

Previous point implies that if there exists finite $B \in U$, then U has $\{a\}$. From previous exercise we follow that because U is an ultrafilter that U is a principal filter. Thus we've got the desired result by the contrapositive.

7.2.13

Show that $\mathcal{P}(X) \setminus U = \{B \in \mathcal{P}(X) : X \setminus B \in U\}$, whenever U is an ultrafilter.

This thing directly follows from the definition of an ultrafilter:

$$y \in \mathcal{P}(X) \setminus U \Leftrightarrow y \in \mathcal{P}(X) \wedge y \notin U \Leftrightarrow y \in \mathcal{P}(X) \wedge X \setminus y \in U$$

7.2.14

Let F be a filter on X . Let $S = \{E \subseteq \mathcal{P}(X) : E \text{ is a filter on } X\}$. Note that $F \in S$. Consider the partially ordered set (S, \subseteq) .

(a) Let $C \subseteq S$ be a chain. Prove that $\bigcup C \in S$ and that $\bigcup C$ is an upper bound for C .

Because $C \subseteq S$ and S is a set of filters, we follow that

$$(\forall c \in C)(X \in c \wedge \emptyset \notin c)$$

thus we follow that $\emptyset \notin \bigcup C$ and $X \in \bigcup C$.

Suppose that $Z \in \bigcup C$ and there exist $Y \subseteq X$ such that $Z \subseteq Y \subseteq X$. We follow that since $Z \in \bigcup C$ we've got that there exists $c \in C$ such that $Z \in c$. Thus if $Z \subseteq Y \subseteq X$ we follow that $Y \in c$ as well, since c is a chain, and thus $Y \in \bigcup C$.

Suppose that $Y, Z \in \bigcup C$. We follow that there exist $c_1, c_2 \in C$ such that $Y \in c_1 \wedge Z \in c_2$. Since C is a chain under \subseteq , we follow that $c_1 \subseteq c_2$ or $c_2 \subseteq c_1$. Assume the former. Then we conclude that $Y, Z \in c_2$ and thus $Y \cap Z \in c_2$, thus $Y \cap Z \in \bigcup C$.

Thus we conclude that $\bigcup C$ is a filter, as desired. Suppose that $c \in C$. Then we follow $c \subseteq \bigcup C$, and thus $\bigcup C$ is an upper bound for C .

(b) Show, via Corollary 7.1.6 that S has a maximal element U such that $F \subseteq U$.

This result is directly implied by 7.1.6.

(c) Using Lemma 7.2.6 and Lemma 7.2.8, prove that U is an ultrafilter.

Suppose that U is not an ultrafilter. We follow that there exists $y \in \mathcal{P}(X)$ such that $y \notin U$ and $X \setminus y \notin U$. Lemma 7.2.8 implies that $U \cup \{y\}$ has FIP. 7.2.6 implies that there exists a filter H on X such that $U \cup \{y\} \subseteq H$. Since $y \notin U$ we follow that $U \neq U \cup \{y\}$ and thus $U \subset U \cup \{y\} \subseteq H$, thus $U \subset H$, therefore U is not a maximal element, which is a contradiction.

7.2.15

Let F be a filter on X . Prove that F is an ultrafilter if and only if F is maximal

Lemma 7.2.4(20) implies that every ultrafilter is maximal. Part (c) of previous exercise provides a proof that every maximal filter is an ultrafilter.

7.2.16

Let F be a filter on A . Let $B^A = \{f : f \text{ is a function from } A \text{ to } B\}$. Define the relation \sim on B^A by

$$f \sim g \iff \{x \in A : f(x) = g(x)\} \in F$$

for all $f, g \in B^A$. Prove that \sim is an equivalence relation in B^A .

Suppose that $f \in B^A$. Since f is a function, we follow that

$$(\forall x \in X)(f(x) = f(x))$$

thus

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

therefore we follow that $A \in F$ since F is a filter on A . Thus we follow that

$$(\forall f \in B^A)(f \sim f)$$

Suppose that f, g, h are such that $f \sim g$ and $g \sim h$. We follow that

$$\{x \in A : f(x) = g(x)\} \in F \wedge \{x \in A : g(x) = h(x)\} \in F$$

Since F is a filter we follow that their intersection is in F . Thus

$$\begin{aligned} \{x \in A : g(x) = h(x)\} \cap \{x \in A : f(x) = g(x)\} &\in F \Leftrightarrow \\ \Leftrightarrow \{x \in A : f(x) = g(x) \wedge g(x) = h(x)\} &\in F \Leftrightarrow \\ \Leftrightarrow \{x \in A : f(x) = h(x)\} \in F &\Leftrightarrow f \sim h \end{aligned}$$

thus we've got that

$$(\forall f, g, h \in B^A)(f \sim g \wedge g \sim h \Rightarrow f \sim h)$$

Suppose that $f, g \in B^A$ are such that $f \sim g$. We follow that

$$f \sim g \Leftrightarrow \{x \in A : f(x) = g(x)\} \in F \Leftrightarrow \{x \in A : g(x) = f(x)\} \in F \Leftrightarrow g \sim f$$

thus

$$(\forall f, g \in B^A)(f \sim g \Rightarrow g \sim f)$$

thus we conclude that \sim is reflexive, transitive and symmetric, and thus it constitutes an equivalence relation, as desired.

7.3 Well-Ordering Theorem

7.3.1

Let $\langle A_i : i \in I \rangle$ be an indexed function such that $A_i \neq \emptyset$ for all $i \in I$. By Theorem 7.3.1, the set $\bigcup_{i \in I} A_i$ has a well-ordering \preceq . Define a function f such that $\text{dom}(f) = I$ and $(\forall i \in I)(f(i) \in A_i)$. Thus, $\langle f(i) : i \in I \rangle$ is a choice function.

We follow that $A_j \subseteq \bigcup_{i \in I} A_i$, and thus there exists \preceq -least element of A_j .

Define $f : I \rightarrow \bigcup_{i \in I} A_i$ by

$$f(i) = \preceq \text{-least element of } A_i$$

we follow that $(\forall i \in I)(f(i) \in A_i)$, as desired.

7.3.2

Let \preceq be a total order on A . For each $u \in A$, let $s(u) = \{x \in A : x \prec u\}$. Suppose that for every $u \in A$ and X , if $X \subseteq s(u)$ is nonempty, then X has a \preceq -least element. Prove that \preceq is a well-ordering on A .

Let $Y \subseteq A$ be nonempty. Because it is nonempty we follow that there exists $u \in Y$. If $s(u) = \emptyset$, then we follow that for all $a \in A$ that $a = u$ or $u \prec a$, thus u is a \preceq -least element of both A and Y . Suppose that $s(u) \neq \emptyset$. If $Y \cap s(u) = \emptyset$, then we follow by trichotomy that for all $y \in Y$

$$u = y \vee u \prec y$$

thus once again, u is the \preceq -least element of Y . If $s(u) \cap Y$ is nonempty, then we follow that since $s(u) \cap Y \subseteq s(u)$ that it has a \preceq -least element x , and thus for all $y \in Y$ we've got that $x \preceq y$. Therefore we conclude that if X is a subset of A , then it has a \preceq -least element, which means that \preceq is a well-order on A , as desired.

7.3.3

Let \preceq be a well-order on C and let \preceq' be a well-ordering on D . Suppose that $\preceq \subseteq \preceq'$ and whenever $x \preceq y'$ and $y \preceq y$, then $x \preceq y$.

(a) Prove that $C \subseteq D$

Suppose that it isn't. Then we follow that there exists $c \in C$ such that $c \notin D$. Thus $c \preceq c$, therefore $c \preceq' c$, which contradicts the fact that \preceq' is a relation on D .

(b) Prove that $\preceq = \preceq' \cap (C \times C)$.

We follow that $\preceq \subseteq C \times C$ and $\preceq \subseteq \preceq'$, thus $\preceq \subseteq \preceq' \cap (C \times C)$. Suppose that $\langle x, y \rangle \in \preceq' \cap (C \times C)$ for some $x, y \in C$. We follow that $x \preceq' y$, and because \preceq is a total order we follow that $x \prec y$, $x = y$ or $y \prec x$. We follow that $y \prec x$ contradicts the $x \preceq' y$ since $\preceq \subseteq \preceq'$. Thus we follow that $x \preceq y$. Therefore we conclude that $\preceq' \cap (C \times C) \subseteq \preceq$. Double inclusion gives us the desired equality.

Prove that if $C \neq D$, then $C = \{z : z \prec' l\}$ for some $l \in D$.

Suppose that $C \neq D$. We follow that $D \setminus C$ is nonempty. Suppose that there exists $d \in D \setminus C$ such that $d \prec' c$ for some $c \in C$. We follow that $d \preceq' c$ and $c \preceq c$ by reflexivity of c . Thus by restrictions in the text of the exercise, we follow that $d \preceq c$. Therefore $d \in C$, which is a contradiction.

Thus we conclude that for all $d \in D \setminus C$, $c \preceq' d$ for all $c \in C$. Since $D \setminus C$ is nonempty, we follow that it's got a \preceq' -least element l . Since $l \in D \setminus C$, we conclude that $l \neq c$ for all $c \in C$. Thus we follow that $C \subseteq \{z : z \prec' l\}$. Suppose that $x \in \{z : z \prec' l\}$. We follow that if $x \in D \setminus C$, then both $l \preceq' x$ and $x \prec' l$ are true, which is a contradiction. Thus we follow that $x \in D \cap C$. Therefore we follow that $x \in \{z : z \prec' l\} \Rightarrow x \in C$, therefore $\{z : z \prec' l\} \subseteq C$. Double inclusion gives us that $\{z : z \prec' l\} = C$, as desired.