

# Propositions of solutions for *Analysis I* by Terence Tao

Frédéric Santos

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## 1. Introduction

No exercises in this chapter.

## 2. Starting at the beginning: the natural numbers

EXERCISE 2.2.1. — *Prove that the addition is associative, i.e. that for any natural numbers  $a, b, c$ , we have  $(a + b) + c = a + (b + c)$ .*

Let's use induction on  $c$  while keeping  $a$  and  $b$  fixed.

- Base case for  $c = 0$ : let's prove that  $(a + b) + 0 = a + (b + 0)$ . The left hand side is equal to  $(a + b)$  according to Lemma 2.2.3. For the right hand side, if we apply the same lemma to the  $(b + 0)$  part, we get  $a + (b + 0) = a + b$ . Both sides are equal to  $a + b$ , and the base case is thus done.
- Now let's suppose inductively that  $(a + b) + c = a + (b + c)$ : we have to prove that  $(a + b) + c++ = a + (b + c++)$ . Using Lemma 2.2.3 on the right hand side leads to  $a + (b + c)++$ . Now consider the left hand side. Using still the same lemma, we get  $(a + b) + c++ = ((a + b) + c)++$ . By the inductive hypothesis, this is also equal to  $(a + (b + c))++$ . And, using the lemma 2.2.3 again, this also leads to  $a + b + c++$ . Therefore, both sides are equal to  $a + b + c++$ , and we have closed the induction.

EXERCISE 2.2.2. — *Let  $a$  be a positive number. Prove that there exists exactly one natural number  $b$  such that  $b++ = a$ .*

Let's use induction on  $a$ .

- Base case for  $a = 1$ : we know that  $b = 0$  matches this property, since  $0++ = 1$  by Definition 2.1.3. Furthermore, there is only one solution. Suppose that is another natural number  $b$  such that  $b++ = 1$ . Then, we would have  $b++ = 0++$ , which would imply  $b = 0$  by Axiom 2.4. The base case is demonstrated.
- Let's suppose inductively that there is exactly one natural number  $b$  such that  $b++ = a$ . We have to prove that there is exactly one natural number  $b'$  such that  $b'++ = a++$ . By the induction hypothesis, and taking  $b' = b++$ , we have  $b'++ = (b++)++ = a++$ . So there exists a solution, with  $b' = b++ = a$ . Uniqueness is given by Axiom 2.4.: if  $b'++ = a++$ , then we necessarily have  $b' = a$ .

EXERCISE 2.2.3. — Let  $a, b, c$  be natural numbers. Prove the following properties of order for natural numbers:

- (a) Reflexivity:  $a \geq a$ . This is true since  $a = 0 + a$  by Definition 2.2.1. By commutativity of addition, we can also write  $a = a + 0$ . So there is indeed a natural number  $n$  (with  $n = 0$ ) such that  $a = a + n$ , i.e.  $a \geq a$ .
- (b) Transitivity: if  $a \geq b$  and  $b \geq c$ , then  $a \geq c$ . From the part  $a \geq b$ , there exists a natural number  $n$  such that  $a = b + n$  according to Definition 2.2.11. A similar consideration for the part  $b \geq c$  leads to  $b = c + m$ ,  $m$  being a natural number. Combining together those two equalities, we can write  $a = b + n = (c + m) + n = c + (m + n)$  by associativity (see Exercise 2.2.1). Then,  $n + m$  being a natural number<sup>1</sup>, the transitivity is demonstrated.
- (c) Anti-symmetry: if  $a \geq b$  and  $b \geq a$ , then  $a = b$ . From the part  $a \geq b$ , there exists a natural number  $n$  such that  $a = b + n$ . Similarly, there exists a natural number  $m$  such that  $b = a + m$ . Combining those two equalities leads to  $a = b + n = (a + m) + n = a + (m + n)$ . By cancellation law (Proposition 2.2.6), we can conclude that  $0 = m + n$ . According to Corollary 2.2.9, this leads to  $m = n = 0$ . Therefore, both  $m$  and  $n$  are null, meaning that  $a = b + 0 = b$ .
- (d) Preservation of order:  $a \geq b$  iff  $a + c \geq b + c$ . First, let's prove that  $a + c \geq b + c \implies a \geq b$ . If  $a + c \geq b + c$ , there exists a natural number  $n$  such that  $a + c = b + c + n$ . By cancellation law (Proposition 2.2.6)<sup>2</sup>, we conclude that  $a = b + n$ , i.e.  $a \geq b$ , thus demonstrating the first implication. Conversely, let's suppose that  $a \geq b$ . There exists a natural number  $m$  such that  $a = b + m$ . Therefore,  $a + c = b + m + c$  for any natural number  $c$ . Still by associativity and commutativity, we can rewrite this as  $a + c = (b + c) + m$ , i.e.  $a + c \geq b + c$ .
- (e)  $a < b$  iff  $a ++ \leq b$ . First, let's prove that  $a ++ \leq b \implies a < b$ . By definition of ordering, there exists a natural number  $n$  such that  $b = (a++) + n$ . By definition of addition, we can re-write:  $b = (a++ + n)++$ . Then, by commutativity and yet again by definition of addition,  $b = (n + a++)++ = (n++) + (a++)$ . Thus, there exists a natural number  $n++$  such that  $b = n++ + a$ , which means that  $b \geq a$ . But we still have to prove that  $a \neq b$ . Let's suppose that  $a = b$ : in this case, by cancellation law, we would have  $n++ = 0$ , which is impossible according to Axiom 2.3 (0 is not the successor of any natural number). Thus,  $a \neq b$  et  $b \geq a$ : we have showed that  $a < b$ .  
Conversely, let's prove that  $a < b \implies a ++ \leq b$ . Starting from that strict inequality, there exists a *positive*<sup>3</sup> natural number  $n$  such that  $b = a + n$ . By Lemma 2.2.10, since  $n$  is positive, it has one unique antecessor  $m$ , so that  $n$  can be written  $m++$ . Thus,  $b = a + (m++) = (a + m)++ = (m + a)++ = m + (a++) = (a++) + m$ . And,  $m$  being a natural number, this corresponds to the statement  $b \geq a$ .
- (f)  $a < b$  iff  $b = a + d$  for some positive number  $d$ . First, let's prove the first implication,  $a < b \implies b = a + d$  with  $d \neq 0$ . Since  $a < b$ , we have in particular  $a \leq b$ , and

<sup>1</sup>This is a trivial induction from the definition of addition.

<sup>2</sup>And also associativity and commutativity that we do not detail explicitly here.

<sup>3</sup>We make use here of the statement (f) demonstrated below. There is no circularity here, since proving (f) will not make use of (e).

there exists a natural number  $d$  such that  $b = a + d$ . For the sake of contradiction, let's suppose that  $d = 0$ . We would have  $b = a$ , which would contradict the condition  $a \neq b$  of the strict inequality. Thus,  $d$  is a positive number, which demonstrates the left-to-right implication.

Conversely, let's suppose that  $b = a + d$ , with  $d \neq 0$ . This expression gives immediately  $a \leq b$ . But if  $a = b$ , by cancellation law, this would lead to  $0 = d$ , a contradiction with the fact that  $d$  is a positive number. Thus,  $a \neq b$  and  $a \leq b$ , which demonstrates  $a < b$ .

EXERCISE 2.2.4. — *Demonstrate three lemmas used to prove the trichotomy of order for natural numbers.*

- (a) Show that we have  $0 \leq b$  for any natural number  $b$ . This is obvious since, by definition of addition,  $0 + b = b$  for any natural number  $b$ . This is precisely the definition of  $0 \leq b$ .
- (b) Show that if  $a > b$ , then  $a++ > b$ . If  $a > b$ , then  $a = b + d$ ,  $d$  being a positive natural number. Let's recall that  $a++ = a + 1$ . Thus,  $a++ = a + 1 = b + d + 1 = b + (d + 1)$  by associativity of addition. Furthermore,  $d + 1$  is a positive natural number (by Proposition 2.2.8). Thus,  $a++ > b$ .
- (c) Show that if  $a = b$ , then  $a++ > b$ . Once again, let's use the fact that  $a++ = a + 1$ . Thus,  $a++ = a + 1 = b + 1$ , and 1 is a positive natural number. This is the definition of  $a++ > b$ .

EXERCISE 2.2.5. — *Prove the strong principle of induction, formulated as follows: Let  $m_0$  be a natural number, and let  $P(m)$  be a property pertaining to an arbitrary natural number  $m$ . Suppose that for each  $m \geq m_0$ , we have the following implication: if  $P(m')$  is true for all natural numbers  $m_0 \leq m' < m$ , then  $P(m)$  is also true. (In particular, this means that  $P(m_0)$  is true, since in this case the hypothesis is vacuous.) Then we can conclude that  $P(m)$  is true for all natural numbers  $m \geq m_0$ .*

First let's introduce a small lemma (similar to Proposition 2.2.12(e)).

**Lemma.** *For any natural number  $a$  and  $b$ ,  $a < b++$  iff  $a \leq b$ .*

*Proof.* If  $a < b++$ , then  $b++ = a + n$  for a given positive natural  $n$ . By Lemma 2.2.10, there exists one natural number  $m$  such as  $n = m++$ . Thus  $b++ = a + m++$ , which can be rewritten  $b++ = (a + m)++$  by Lemma 2.2.3<sup>4</sup>. By Axiom 2.4., this is equivalent to  $b = a + n$ , which can also be written  $a \leq b$ .

Conversely, if  $a \leq b$ , there exists a natural number  $m$  such as  $b = a + m$ . Thus,  $b++ = (a + m)++ = a + (m++)$  by Definition of addition (2.2.1). And,  $m++$  being a positive number, this means that  $b > a$  according to Proposition 2.2.12(f).  $\square$

Now we can prove the main proposition. Let  $Q(n)$  be the property “ $P(m)$  is true for all  $m$  such that  $m_0 \leq m < n$ ”. Let's induct on  $n$ .

- (Although this is not necessary,) we could consider two types of base cases. If  $n < m_0$ ,  $Q(n)$  is the proposition “ $P(m)$  is true for all  $m$  such that  $m_0 \leq m < n$ ”, but there is no such natural number  $m$ . Thus,  $Q(n)$  is vacuously true. If  $n = m_0$ ,  $P(m_0)$  is true by hypothesis, thus  $Q(m_0)$  is also true.

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<sup>4</sup>We could also rewrite  $b + 1 = a + m + 1$  and then use the cancellation law.

- Now let's suppose inductively that  $Q(n)$  is true, and show that  $Q(n++)$  is also true. If  $Q(n)$  is true,  $P(m)$  is true for all  $m$  such that  $m_0 \leq m < n$ . By hypothesis, this implies that  $P(n)$  is true. Thus,  $P(m)$  is true for any natural number  $m$  such that  $m_0 \leq m \leq n$ , i.e. such that  $m_0 \leq m < n++$  according to the lemma introduced above. This is precisely  $Q(n++)$ , and this closes the induction.

Thus,  $Q(n)$  is true for all natural numbers  $n$ , which means in particular that  $P(m)$  is true for any natural number  $m \geq m_0$ . This demonstrates the principle of strong induction.

EXERCISE 2.2.6. — *Let  $n$  be a natural number, and let  $P(m)$  be a property pertaining to the natural numbers such that whenever  $P(m++)$  is true, then  $P(m)$  is true. Suppose that  $P(n)$  is also true. Prove that  $P(m)$  is true for all natural numbers  $m \leq n$ ; this is known as the principle of backwards induction.*

Terence Tao suggests to use induction on  $n$ . So let  $Q(n)$  be the following property: “if  $P(n)$  is true, then  $P(m)$  is true for all  $m \leq n$ ”. The goal is to prove  $Q(n)$  for all natural numbers  $n$ .

- Base case  $n = 0$ : here,  $Q(n)$  means that if  $P(0)$  is true, then  $P(m)$  is true for any  $m \leq 0$ . By Definition 2.2.11, if  $m \leq 0$ , there exists a natural number  $d$  such that  $0 = m + d$ . But, by Corollary 2.2.9, this implies that both  $m = 0$  and  $d = 0$ . Thus, the only number  $m$  such that  $m \leq 0$  is 0 itself. Therefore,  $Q(0)$  is simply the tautology “if  $P(0)$  is true, then  $P(0)$  is true”—a statement that we can safely accept. The base case is the, demonstrated.
- Let's suppose inductively that  $Q(n)$  is true: we must show that  $Q(n++)$  is also true. If  $P(n++)$  is true, then by definition of  $P$ ,  $P(n)$  is also true. Then, by induction hypothesis,  $P(m)$  is true for all  $m \leq n$ . We have showed that  $P(n++)$  implies  $P(m)$  for all  $m \leq n++$ <sup>5</sup>, which is precisely  $Q(n++)$ . This closes the induction.

EXERCISE 2.3.1. — *Show that multiplication is commutative, i.e., if  $n$  and  $m$  are natural numbers, show that  $n \times m = m \times n$ .*

We will use an induction of  $n$  while keeping  $m$  fixed. However, this is not a trivial result, and even the base case is not straightforward. We will first introduce some lemmas.

**Lemma.** *For any natural number  $n$ ,  $n \times 0 = 0$ .*

*Proof.* Let's induct on  $n$ . For the base case  $n = 0$ , we know by Definition 2.3.1 of multiplication that  $0 \times 0 = 0$ , since  $0 \times m = 0$  for any natural number  $m$ .

Now let's suppose that  $n \times 0 = 0$ . Thus,  $n++ \times 0 = (n \times 0) + 0$  by Definition 2.3.1. But by induction hypothesis,  $n \times 0 = 0$ , so that  $n++ \times 0 = 0 + 0 = 0$ . This closes the induction.  $\square$

**Lemma.** *For all natural numbers  $m$  and  $n$ , we have  $m \times n++ = (m \times n) + m$ .*

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<sup>5</sup>Actually, we use here yet another lemma, similar to the one introduced for the previous exercise. We use the fact that  $m \leq n++$  is equivalent to  $m = n++$  or  $m \leq n$ , which is easy to prove, but is not part of the “standard” results presented in the textbook.

*Proof.* Let's induct on  $m$ . The base case  $m = 0$  is easy to prove:  $0 \times n++ = 0$  by Definition 2.3.1 of multiplication, and  $(0 \times n) + 0 = 0$ .

Now suppose inductively that  $m \times n++ = (m \times n) + m$ , and we must show that

$$m++ \times n++ = (m++ \times n) + m++ \quad (1)$$

We begin by the left hand side: by Definition 2.3.1,  $m++ \times n++ = (m \times n++) + n++$ . By induction hypothesis, this is equal to  $(m \times n) + m + n++$ .

Then, apply the definition of multiplication to the right hand side:  $(m++ \times n) + m++ = (m \times n) + n + m++$ . The Lemma 2.2.3 and the commutativity of addition leads to  $(m \times n) + n + m++ = (m \times n) + (n + m)++ = (m \times n) + (m + n)++ = (m \times n) + m + n++$ , which is equal to the left hand side.

Thus, both sides of equation (1) are equal, and we can close the induction.  $\square$

Now it is easier to prove the main result ( $n \times m = m \times n$ ), by an induction on  $n$ .

- Base case  $n = 0$ : we already know by Definition 2.3.1 that  $0 \times m = 0$ . The first lemma introduced in this exercise also provides  $m \times 0 = 0$ . Thus, the base case is proved, since  $0 \times m = m \times 0 (= 0)$ .
- Now we suppose inductively that  $n \times m = m \times n$ , and we must prove that:

$$n++ \times m = m \times n++ \quad (2)$$

By Definition 2.3.1 of multiplication, the left hand side is equal to  $(n \times m) + m$ .

Using the lemma introduced above, the right hand side is equal to  $(m \times n) + m$ . By induction hypothesis, this is also equal to  $(n \times m) + m$ , which closes the induction.

**EXERCISE 2.3.2.** — *Show that positive natural numbers have no zero divisors, i.e. that  $nm = 0$  iff  $n = 0$  or  $m = 0$ . In particular, if  $n$  and  $m$  are both positive, then  $nm$  is also positive.*

We will prove the second statement first. Suppose, for the sake of contradiction, that  $nm = 0$  and that both  $n$  and  $m$  are positive numbers. Since they are positive, by Lemma 2.2.10, there exists two (unique) natural numbers  $a$  and  $b$  such that  $n = a++$  and  $m = b++$ . Thus, the hypothesis  $nm = 0$  can also be written  $(a++) \times (b++) = 0$ . But, by Definition 2.3.1 of multiplication,  $(a++) \times (b++) = (a \times b++) + b++$ . Thus, we should have  $(a \times b++) + b++ = 0$ . By Corollary 2.2.9, this implies that both  $(a \times b++) = 0$  and  $b++ = 0$ , which is impossible since zero is the successor of no natural number (Axiom 2.3).

Thus, we have proved that if  $n$  and  $m$  are both positive, then  $nm$  is also positive. The main statement can now be proved more easily.

- The right-to-left implication is straightforward: if  $n = 0$ , then by Definition of multiplication,  $n \times m = 0 \times m = 0$ . Since multiplication is commutative, we have the same result if  $m = 0$ .
- The left-to-right implication is exactly the contrapositive of the statement we have just proved above.

EXERCISE 2.3.3. — *Show that multiplication is associative, i.e., for any natural numbers  $a, b, c$ , we have  $(a \times b) \times c = a \times (b \times c)$ .*

We will induct on  $c$  while keeping  $a$  and  $b$  fixed.

- Base case: for  $c = 0$ , we must prove that  $(a \times b) \times 0 = a \times (b \times 0)$ . The left hand side is equal to 0 by definition (and commutativity) of multiplication<sup>6</sup>. The right hand side is equal to  $a0$ , which is also 0. Both sides are null, and the base case is proved.
- Suppose inductively that  $(a \times b) \times c = a \times (b \times c)$ , and let's prove that  $(a \times b) \times c++ = a \times (b \times c++)$ . By definition (and commutativity) of multiplication, the left hand side is equal to  $(a \times b) \times c + (a \times b)$ . The right hand side is equal to  $a \times (b \times c + b)$ , and by distributive law (i.e., Proposition 2.3.4), this is also  $a \times (b \times c) + a \times b$ . But then, by inductive hypothesis, this can be rewritten  $(a \times b) \times c + a \times b$ , which is equal to the left hand side. The induction is closed.

EXERCISE 2.3.4. — *Prove the identity  $(a + b)^2 = a^2 + 2ab + b^2$  for all natural numbers  $a, b$ .*

By distribution law (i.e., Proposition 2.3.4) and commutativity of multiplication, we have:

$$\begin{aligned}(a + b)^2 &= (a + b)(a + b) = (a + b)a + (a + b)b \\ &= a \times a + b \times a + a \times b + b \times b \\ &= a^2 + a \times b + a \times b + b^2 \\ &= a^2 + 2ab + b^2\end{aligned}$$

(For the last step, we recall that, by Definition 2.3.1,  $2 \times m = m + m$  for any natural number  $m$ .)

EXERCISE 2.3.5. — *Euclidean algorithm. Let  $n$  be a natural number, and let  $q$  be a positive number. Prove that there exists natural numbers  $m, r$  such that  $0 \leq r < q$  and  $n = mq + r$ .*

We will induct on  $n$  while remaining  $q$  fixed.

- Base case: if  $n = 0$ , there exists an obvious solution, namely  $m = 0$  and  $r = 0$ .
- Suppose inductively that there exists  $m, r$  such that  $n = mq + r$  with  $0 \leq r < q$ , and let's prove that there exists  $m', r'$  such that  $n + 1 = m'q + r'$ , with  $0 \leq r' < q$ .

By the induction hypothesis, we have  $n + 1 = mq + r + 1$ . Since  $r < q$ , we have  $r + 1 \leq q$  (this is Proposition 2.2.12). Thus, we have two cases here:

1. If  $r + 1 < q$ , then  $n + 1 = mq + (r + 1)$ , with  $0 \leq r + 1 < q$ , so that choosing  $m' = m$  and  $r' = r + 1$  is convenient.
2. If  $r + 1 = q$ , then  $n + 1 = mq + q = (m + 1)q$  according to the distributive law (Proposition 2.3.4). Thus, choosing  $m' = m + 1$  and  $r' = 0$  is convenient.

This closes the induction.

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<sup>6</sup>Actually, we use the second lemma introduced for the resolution of Exercise 2.3.1.

### 3. Set theory

EXERCISE 3.1.2. — *Using only Definition 3.1.4, Axiom 3.1, Axiom 3.2, and Axiom 3.3, prove that the sets  $\emptyset$ ,  $\{\emptyset\}$ ,  $\{\{\emptyset\}\}$ , and  $\{\emptyset, \{\emptyset\}\}$  are all distinct (i.e., no two of them are equal to each other).*

As a general reminder, we recall that sets are objects (Axiom 3.1) and the empty set  $\emptyset$  is such that no object is an element of  $\emptyset$ , thus  $\emptyset \notin \emptyset$ .

1. First let's show that  $\emptyset$  is different from all other sets.  $\emptyset$  is an element of  $\{\emptyset\}$  and  $\{\emptyset, \{\emptyset\}\}$ , and  $\{\emptyset\}$  is an element of  $\{\{\emptyset\}\}$ . But none of those two objects are elements of  $\emptyset$  (by Axiom 3.2), thus  $\emptyset$  is different from all three other sets.
2. Then let's show that  $\{\emptyset\} \neq \{\{\emptyset\}\}$ . By Axiom 3.3, the singleton  $\{\emptyset\}$  is such that  $x \in \{\emptyset\} \iff x = \emptyset$ . Similarly, the singleton  $\{\{\emptyset\}\}$  is such that  $x \in \{\{\emptyset\}\} \iff x = \{\emptyset\}$ . But we already know that  $\emptyset \neq \{\emptyset\}$  so there exists an object,  $\emptyset$ , which is a element of  $\{\emptyset\}$  but not an element of  $\{\{\emptyset\}\}$ . Those sets are not equal.
3. Now let's show that  $\{\emptyset\} \neq \{\emptyset, \{\emptyset\}\}$ . By Axiom 3.3, the pair  $\{\emptyset, \{\emptyset\}\}$  is such that  $x$  is an element of this set iff  $x = \emptyset$  or  $x = \{\emptyset\}$ . Thus,  $\{\emptyset\}$  is an element of  $\{\emptyset, \{\emptyset\}\}$ , but is not an element of  $\{\emptyset\}$  (if it was, we should have  $\emptyset = \{\emptyset\}$ , which would be a contradiction with the first point of this proof). Those two sets are thus different.
4. Finally, we also have  $\{\{\emptyset\}\} \neq \{\emptyset, \{\emptyset\}\}$ . Indeed, we have  $\emptyset \in \{\emptyset, \{\emptyset\}\}$  by Axiom 3.3. However,  $\emptyset \in \{\{\emptyset\}\} \iff \emptyset = \{\emptyset\}$  by definition of a singleton, and we know this latest statement is false by the first point of this proof. Those two sets are also different.

EXERCISE 3.1.3. — *Prove the remaining claims in Lemma 3.1.13.*

Those claims are the following:

1.  $\{a, b\} = \{a\} \cup \{b\}$ . By Axiom 3.3, the pair  $\{a, b\}$  is such that  $x \in \{a, b\} \iff x = a$  or  $x = b$ . Let's consider three cases:
  - if  $x = a$ ,  $x \in \{a\}$  by Axiom 3.3, thus  $x \in \{a\} \cup \{b\}$  by Axiom 3.4
  - if  $x = b$ ,  $x \in \{b\}$  by Axiom 3.3, thus  $x \in \{a\} \cup \{b\}$  by Axiom 3.4
  - if  $x \neq a$  and  $x \neq b$ ,  $x \notin \{a\}$  and  $x \notin \{b\}$  by Axiom 3.3, so that  $x \notin \{a\} \cup \{b\}$

Thus,  $\{a, b\}$  and  $\{a\} \cup \{b\}$  have the same elements, and are equal.

2.  $A \cup B = B \cup A$  for all sets  $A$  and  $B$ . Indeed,  $x \in A \cup B \iff x \in A$  or  $x \in B$ . If  $x \in A$ , then  $x \in B \cup A$  by Axiom 3.4. A similar argument holds if  $x \in B$ . Thus, in both cases,  $x \in B \cup A$ . We can show in a similar fashion that any element of  $B \cup A$  is in  $A \cup B$ .
3.  $A \cup \emptyset = \emptyset \cup A = A$ . Since we've just showed that union is commutative, proving  $A \cup \emptyset = A$  is sufficient. If  $x \in A$ , then  $x \in A \cup \emptyset$ . The converse is also true: if  $x \in A \cup \emptyset$ , then  $x \in A$  or  $x \in \emptyset$ . But there is no element in  $\emptyset$ , so that we have necessarily  $x \in A$ . Thus,  $A \cup \emptyset$  and  $A$  have the same elements: they are equal.

EXERCISE 3.1.4. — *Prove the remaining claims from Proposition 3.1.18.*

Let  $A, B, C$  be sets. Those claims are the following:

1. If  $A \subseteq B$  and  $B \subseteq A$ , then  $B = A$ . According to Definition 3.1.4, two sets  $A$  and  $B$  are equal iff every element of  $A$  is an element of  $B$ , and vice versa. This is precisely the present claim.
2. If  $A \subsetneq B$  and  $B \subsetneq C$ , then  $A \subsetneq C$ . Let  $x$  be an element of  $A$ . Since  $A \subsetneq B$ ,  $x$  is also an element of  $B$ . And since  $B \subsetneq C$ ,  $x$  is also an element of  $C$ . This holds for any  $x$  in  $A$ , and thus it demonstrates that  $A \subset C$ . Furthermore, since  $A \subsetneq B$ , there exists an element  $y \in B$  which is not an element of  $A$ . As  $B \subsetneq C$ ,  $y$  is also an element of  $C$ . Thus we have  $y$ , an element of  $C$  which is not in  $A$ . Combined to the previous result  $A \subset C$ , this demonstrates  $A \subsetneq C$ .

EXERCISE 3.1.5. — *Let  $A, B$  be sets. Show that the three statements  $A \subseteq B$ ,  $A \cup B = B$  and  $A \cap B = A$  are logically equivalent (i.e., any one of them implies the other two).*

1. First, we prove that  $A \subseteq B \implies A \cup B = B$ . The first inclusion  $B \subseteq A \cup B$  is trivial, since any element of a set  $B$  is always either in  $A$  or  $B$ . For the converse inclusion, let  $x$  be an element of  $A \cup B$ , and let's prove that  $x \in B$ . By Axiom 3.4, we have  $x \in A$  or  $x \in B$ . If  $x \in B$ , the result holds. If  $x \in A$ , then we also have  $x \in B$  since  $A \subseteq B$ . Thus, any element of  $A \cup B$  is an element of  $B$ , which demonstrates the equality  $A \cup B = B$ .
2. Then, we prove that  $A \cup B = B \implies A \cap B = A$ . The first inclusion is trivial: if  $x \in A \cap B$ , then we always have  $x \in A$ . Now let's prove the converse inclusion: let  $x$  be an element of  $A$ ; we must show that  $x \in A \cap B$ . If  $x \in A$ , then  $x \in A \cup B$ . But, by hypothesis,  $A \cup B = B$ , thus  $x \in B$ . So,  $x \in A$  and  $x \in B$ , i.e.  $x \in A \cap B$ . This demonstrates the implication.
3. Finally, we prove that  $A \cap B = A \implies A \subseteq B$ . Let  $x \in A$ . Since  $A \cap B = A$ , we have  $x \in A \cap B$ . It follows that  $x \in B$ . We have proved that any element  $x \in A$  is also an element of  $B$ , i.e.  $A \subseteq B$ .

EXERCISE 3.1.8. — *Let  $A, B$  be sets. Prove the absorption laws  $A \cap (A \cup B) = A$  and  $A \cup (A \cap B) = A$ .*

1. The first inclusion  $A \cap (A \cup B) \subseteq A$  is trivial: if  $x \in A \cap (A \cup B)$  then in particular  $x \in A$  by Definition 3.1.23 of an intersection<sup>7</sup>. Thus, we have  $A \cap (A \cup B) \subseteq A$ .

For the converse inclusion, let  $x$  be an element of  $A$ . Then by definition  $x \in A$ , and we have also  $x \in A \cup B$  since  $x \in A$ . Thus,  $x \in A \cap (A \cup B)$ , which proves the converse inclusion.

Consequently,  $A = A \cap (A \cup B)$ .

2. First we show that  $A \cup (A \cap B) \subseteq A$ . Let  $x \in A \cup (A \cap B)$ . By Definition of an union, we have either  $x \in A$ , or  $x \in A \cap B$ . In both cases<sup>8</sup>, we have  $x \in A$ , so that the inclusion is proved.

<sup>7</sup>This intersection is not empty since  $A$  and  $A \cup B$  are not disjoint.

<sup>8</sup>If  $A$  and  $B$  are disjoint, then the first case  $x \in A$  necessarily holds, since  $x \in A \cup B$  is impossible.



Conversely, let  $x \in A$ . Then in particular, we have  $x \in A \cup (A \cap B)$  by Definition of an union, because  $x \in A$ . Thus,  $x \in A \cup (A \cap B)$ .

We have proved that  $A \cup (A \cap B) = A$ .

EXERCISE 3.1.9. — *Let  $A, B, X$  be sets such that  $A \cup B = X$  and  $A \cap B = \emptyset$ . Show that  $A = X \setminus B$  and  $B = X \setminus A$ .*

The two sets  $A$  and  $B$  play a symmetrical role here, so that proving one of these two assertions is sufficient. For instance, we prove that  $A = X \setminus B$ .

- Let  $x$  be an element of  $A$ . Since  $x \in A$ , we also have  $x \in A \cup B$  by definition of an union. But  $A \cup B = X$ , and then  $x \in X$ . On the other hand, we cannot have  $x \in B$ , because  $x \in A$  and the sets  $A, B$  are disjoint. Thus,  $x \in X$  and  $x \notin B$ , which means that  $x \in X \setminus B$ . We have proved that  $A \subseteq X \setminus B$ .
- Conversely, let  $x$  be an element of  $X \setminus B$ . By definition, this means that  $x \in X$ , i.e.  $x \in A \cup B$ , and  $x \notin B$ . Since  $x \in A \cup B$ , we have either  $x \in A$  or  $x \in B$ , but we know that the latter is impossible. Thus, we have necessarily  $x \in A$ . We have proved that  $X \setminus B \subseteq A$ .
- We can conclude that  $X \setminus B = A$ .

EXERCISE 3.1.11. — *Prove that the axiom of replacement (Axiom 3.6) implies the axiom of specification (Axiom 3.5).*

Let's recall the axiom of replacement. Let  $A$  be a set. For every  $x \in A$ , and for every (abstract) object  $y$ , let  $P(x, y)$  be a statement pertaining to both  $x$  and  $y$ , such that for any  $x \in A$  there is at most one  $y$  for which  $P(x, y)$  is true. Then there exists a set  $\{y : P(x, y) \text{ is true for some } x \in A\}$ , such that for any object  $z$ ,

$$z \in \{y : P(x, y) \text{ is true for some } x \in A\} \iff P(x, z) \text{ is true for some } x \in A$$

Now, let  $A$  be a set,  $x$  an element of  $A$ , and  $y$  an object. We accept the axiom of replacement, and show that it implies the axiom of specification.

Let  $Q(x, y)$  be the property " $x = y$  and  $P(x)$ ". According to the axiom of replacement, there exists a set  $\{y : Q(x, y) \text{ is true for some } x \in A\}$  such that:

$$\begin{aligned} & z \in \{y : Q(x, y) \text{ is true for some } x \in A\} \\ \iff & Q(x, z) \text{ is true for some } x \in A \\ \iff & x = z \text{ and } P(x) \text{ is true for some } x \in A \\ \iff & x = z \text{ and } P(z) \text{ is true for some } x \in A \text{ (by axiom of substitution)} \\ \iff & z \in A \text{ and } P(z) \text{ is true} \end{aligned}$$

Thus, we have proved the existence of a set (the set  $\{y : Q(x, y) \text{ is true for some } x \in A\}$ ) satisfying the axiom of specification:  $z$  belongs to this set iff  $z \in A$  and  $P(z)$  is true.

EXERCISE 3.3.1. — *Show that the definition of equality in Definition 3.3.7 is reflexive, symmetric and transitive. Also verify the substitution property: if  $f_1, f_2 : X \rightarrow Y$  and  $g_1, g_2 : Y \rightarrow Z$  are functions such that  $f_1 f_2$  and  $g_1 = g_2$ , then  $g_1 \circ f_1 = g_2 \circ f_2$ .*

1. Definition 3.3.7 says that two functions  $f$  and  $g$  are equal if they have same domain  $X$  and range  $Y$ , and if, for all  $x \in X$ ,  $f(x) = g(x)$ . This definition of equality is obviously reflexive, symmetric and transitive if we assume that the objects in the domain  $X$  and the range  $Y$  verify themselves the axioms of equality.
2. Since  $f_1 = f_2$ , they have same domain  $X$  and same range  $Y$ . This is also the case for  $g_1$  and  $g_2$ , with domain  $Y$  and range  $Z$ . Thus,  $g_1 \circ f_1$  has domain  $X$  and range  $Z$ , and so has  $g_2 \circ f_2$ . Furthermore, we have, for all  $x \in X$ :

$$\begin{aligned} g_2 \circ f_2(x) &= g_2 \circ f_1(x) \text{ (since } f_1 = f_2) \\ &= g_1 \circ f_1(x) \text{ (since } g_1 = g_2) \end{aligned}$$

which closes the demonstration.

EXERCISE 3.3.2. — *Let  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$  be functions. Show that if  $f$  and  $g$  are both injective, then so is  $g \circ f$ . Similarly, show that if  $f$  and  $g$  are both surjective, then so is  $g \circ f$ .*

First let's note that  $g \circ f : X \rightarrow Z$ .

1. Suppose that  $f$  and  $g$  are both injective, and let  $x, x' \in X$ . We have successively :

$$\begin{aligned} g \circ f(x) &= g \circ f(x') \\ g(f(x)) &= g(f(x')) \\ f(x) &= f(x') \text{ because } g \text{ is injective} \\ x &= x' \text{ because } f \text{ is injective} \end{aligned}$$

We have showed that  $g \circ f(x) = g \circ f(x') \Rightarrow x = x'$  for all  $x, x' \in X$ , i.e. that  $g \circ f$  is injective.

2. Suppose that  $f$  and  $g$  are both surjective, and let be  $z \in Z$ . Since  $g$  is surjective, there exists  $y \in Y$  such that  $z = g(y)$ . And since  $f$  is surjective, there exists  $x \in X$  such that  $y = f(x)$ . Thus, combining those two results, there exists  $x \in X$  such that  $z = g(f(x))$ . This means precisely that  $g \circ f$  is surjective.

EXERCISE 3.3.3. — *When is the empty function injective? surjective? bijective?*

Let  $f$  be the empty function, i.e.  $f : \emptyset \rightarrow Y$  for a certain range  $Y$ .

1.  $f$  is injective iff  $x \neq x' \Rightarrow f(x) \neq f(x')$ . This can be considered as vacuously true since there are no such  $x$  and  $x'$ .  $f$  can be considered as always injective, for any range  $Y$ .
2.  $f$  is surjective iff for any  $y \in Y$ , there exists  $x \in \emptyset$  such that  $y = f(x)$ . We can clearly see that this assertion is false if  $Y \neq \emptyset$ , since any  $y \in Y$  will have no antecedent in  $\emptyset$ . Conversely, if  $Y = \emptyset$ , the assertion is vacuously true, since there is no element in  $Y$ . Thus,  $f$  is surjective iff  $Y = \emptyset$ .
3. Since  $f$  is always injective, and is surjective iff  $Y = \emptyset$ , it is clear that  $f$  is bijective iff  $Y = \emptyset$ .

EXERCISE 3.3.4. — Let  $f : X \rightarrow Y$ ,  $\tilde{f} : X \rightarrow Y$ ,  $g : Y \rightarrow Z$ ,  $\tilde{g} : Y \rightarrow Z$  be functions. Show that if  $g \circ f = g \circ \tilde{f}$  and  $g$  is injective, then  $f = \tilde{f}$ . Is this statement true if  $g$  is not injective? Also, show that if  $g \circ f = \tilde{g} \circ f$  and  $f$  is surjective, then  $g = \tilde{g}$ . Is this statement true if  $f$  is not surjective?

This exercise introduces some cancellation laws for composition.

1. First, note that  $f$  and  $\tilde{f}$  have same domain and range, which is the first condition for two functions to be equal (by Definition 3.3.7). Then, suppose that  $g \circ f = g \circ \tilde{f}$  and  $g$  is injective. For the sake of contradiction, suppose that there exists  $x \in X$  such that  $f(x) \neq \tilde{f}(x)$ . Since  $g$  is injective, we would thus have  $g(f(x)) \neq g(\tilde{f}(x))$ , which would be a contradiction to the hypothesis  $g \circ f = g \circ \tilde{f}$ . Thus, there is no  $x$  such that  $f(x) \neq \tilde{f}(x)$ , or in other words,  $f = \tilde{f}$ .

This property is false if  $g$  is not injective. As a counterexample, one can think of  $f : \mathbb{R} \rightarrow \mathbb{R}$  with  $f(x) = x$ ,  $\tilde{f} : \mathbb{R} \rightarrow \mathbb{R}$  with  $\tilde{f}(x) = -x$ , and  $g : \mathbb{R} \rightarrow \mathbb{R}_+$  with  $g(x) = |x|$ .

2. As previously, first note that  $g$  and  $\tilde{g}$  have same domain and range. Let be  $y, y' \in Y$ . Since  $f$  is surjective, there exist  $x, x' \in X$  such that  $y = f(x)$  and  $y' = f(x')$  respectively. Since  $g \circ f = g \circ \tilde{f}$ , we have  $g(f(x)) = g(\tilde{f}(x))$ , i.e.  $g(y) = g(y')$ . We have showed that, for any  $y, y' \in Y$ , we have  $g(y) = g(y')$ , which means that  $g = \tilde{g}$ .

This statement is false if  $f$  is not surjective. For instance, let  $f$  be a constant function, e.g.  $f : \mathbb{R} \rightarrow \mathbb{R}$  with  $f(x) = 1$  for all  $x$ . Let  $g, \tilde{g} : \mathbb{R} \rightarrow \mathbb{R}$  with  $g(x) = 0$  and  $\tilde{g}(x) = -x + 1$ . We have  $g(1) = \tilde{g}(1)$ , i.e.  $g(f(x)) = \tilde{g}(f(x))$  for all  $x \in X$ , but we obviously do not have  $g = \tilde{g}$ .

EXERCISE 3.3.5. — Let  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$  be functions. Show that if  $g \circ f$  is injective, then  $f$  must be injective. Is it true that  $g$  must also be injective? Show that if  $g \circ f$  is surjective, then  $g$  must be surjective. Is it true that  $f$  must be surjective?

1. If  $g \circ f$  is injective, then for any given objects  $x, x' \in X$ , we have  $g(f(x)) = g(f(x')) \implies x = x'$ . For the sake of contradiction, suppose that  $f$  is not injective. In this case, there exist two elements  $a, a' \in X$  such that  $a \neq a'$  and  $f(a) = f(a')$ . We would thus have  $g(f(a)) = g(f(a'))$  (axiom of substitution) and  $a \neq a'$ , which is incompatible with the hypothesis that  $g \circ f$  is injective.

Thus,  $g \circ f$  injective implies that  $f$  is injective.

However,  $g$  does not need to be injective. For instance, let's consider  $X = \{1, 2\}$  and  $Y = Z = \{1, 2, 3\}$ . Let's define the function  $f$  as the mapping  $f(1) = 1$ ,  $f(2) = 2$ . Let's define the function  $g$  as the mapping  $g(1) = 1$ ,  $g(2) = 2$ ,  $g(3) = 2$ . Here,  $f$  is injective, so is  $g \circ f$ , but  $g$  is not injective.

2. If  $g \circ f$  is surjective, then for all  $z \in Z$ , there exists  $x \in X$  such that  $z = g(f(x))$ . For the sake of contradiction, suppose that  $g$  is not surjective: then, there exists  $z \in Z$  such that for all  $y \in Y$ ,  $z \neq g(y)$ . In particular, for all  $x \in X$ , since  $f(x) \in Y$ , we would have  $g(f(x)) \neq z$ , which would be a contradiction with  $g \circ f$  surjective.

However,  $f$  does not need to be surjective. For instance, let's consider  $X = Y = \{1, 2\}$  and  $Z = \{1\}$ . Let  $f$  be the mapping  $f(1) = f(2) = 1$ , and  $g$  be the mapping  $g(1) = g(2) = 1$ . Here,  $g \circ f$  is surjective, but  $f$  is not.

EXERCISE 3.3.6. — Let  $f : X \rightarrow Y$  be a bijective function, and let  $f^{-1} : Y \rightarrow X$  be its inverse. Verify the cancellation laws  $f^{-1}(f(x)) = x$  for all  $x \in X$  and  $f(f^{-1}(y)) = y$  for all  $y \in Y$ . Conclude that  $f^{-1}$  is also invertible and has  $f$  as its inverse.

Recall that, by definition, for all  $y \in Y$ ,  $f^{-1}(y)$  is the only element  $x \in X$  such that  $f(x) = y$ .

1. Let  $a$  be an element of  $X$ , we thus have  $f(a) \in Y$ . Let's apply the definition to the element  $y = f(a) \in Y$ : by definition,  $f^{-1}(f(a))$  is the only element  $x \in X$  such that  $f(x) = f(a)$ . Since  $f$  is bijective, this implies  $x = a$ . We thus have proved that  $f^{-1}(f(a)) = a$ .
2. The proof for  $f(f^{-1}(y)) = y$  is similar.
3. To prove that  $f^{-1}$  is also invertible, we need to prove that  $f^{-1}$  is bijective, i.e. injective and surjective.

For any given  $y \in Y$ , since  $f$  is bijective, there exists exactly one  $x \in X$  such that  $y = f(x)$ . Similarly, for any given  $y' \in Y$ , there exists exactly one  $x' \in X$  such that  $y' = f(x')$ . In other words,  $f^{-1}(y) = x$  and  $f^{-1}(y') = x'$ . Suppose that  $f^{-1}(y) = f^{-1}(y')$ . This can be written  $x = x'$ , which necessarily implies  $f(x) = f(x')$  since  $f$  is a function (and by axiom of substitution). And this can also be written  $y = y'$ . We thus have proved that for any  $y, y' \in Y$ ,  $f^{-1}(y) = f^{-1}(y') \implies y = y'$ . Thus,  $f^{-1}$  is injective.

Furthermore, for any given  $x \in X$ , let's denote  $y = f(x)$ . Since  $f$  is bijective, this means that  $f^{-1}(y) = x$ . Thus, any  $x \in X$  has a predecessor  $y \in Y$  for  $f^{-1}$ , i.e.  $f^{-1}$  is surjective.

EXERCISE 3.3.7. — Let  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$  be functions. Show that if  $f$  and  $g$  are bijective, then so is  $g \circ f$ , and we have  $(g \circ f)^{-1} = f^{-1} \circ g^{-1}$ .

The first point is an immediate consequence of Exercise 3.3.2. We just have to show that  $(g \circ f)^{-1} = f^{-1} \circ g^{-1}$ .

Let be any given element  $z \in Z$ . Since  $g$  is bijective, there exists one single element  $y \in Y$  such that  $z = g(y)$ , i.e.  $y = g^{-1}(z)$ . And since  $f$  is also bijective, there exists exactly one single element  $x \in X$  such that  $y = f(x)$ , i.e.  $x = f^{-1}(y) = f^{-1}(g^{-1}(z))$ .

Thus, for every  $z \in Z$ , there exists exactly one  $x \in X$  such that  $g \circ f(x) = z$ , and this element is  $f^{-1}(g^{-1}(z))$ . This means exactly that  $(g \circ f)^{-1} = f^{-1} \circ g^{-1}$ .

EXERCISE 3.4.1. — Let  $f : X \rightarrow Y$  be a bijective function, and let  $f^{-1} : Y \rightarrow X$  be its inverse. Let  $V$  be any subset of  $Y$ . Prove that the forward image of  $V$  under  $f^{-1}$  is the same as the inverse image of  $V$  under  $f$ ; thus the fact that both sets are denoted as  $f^{-1}$  will not lead to any inconsistency.

Since “ $f^{-1}(V)$ ” may refer to two different things here, let's first introduce some notations to avoid any confusion :

- Let  $F$  be the *forward image* of  $V$  under  $f^{-1}$ , i.e.  $F = \{f^{-1}(y) \mid y \in V\}$ .
- Let  $I$  be the *inverse image* of  $V$  under  $f$ , i.e.  $I = \{x \in X \mid f(x) \in V\}$ .

In this exercise we must show that  $F = I$ , so as to ensure that the two definitions of  $f^{-1}$  are equivalent. So, we will prove that  $F \subseteq I$  and  $I \subseteq F$ .

1. Let be  $x \in F$ . Thus, there exists  $y \in V$  such that  $x = f^{-1}(y)$ . By definition, this is equivalent to  $f(x) = y$ . But since  $y \in V$ , we can say that  $f(x) \in V$ . Thus, we have both  $x \in X$  (because  $F \subseteq X$ ) and  $f(x) \in V$ , which means that  $x \in I$ .
2. Conversely, let be  $x \in I$ . By definition, this means that  $x \in X$  and that  $f(x) \in V$ , i.e. there exists a certain element  $y \in V$  such that  $y = f(x) \in V$ . This latter statement is equivalent to  $x = f^{-1}(y)$ . Thus, we have  $x \in X$  and  $x = f^{-1}(y)$  for a certain  $y \in V$ , which means that  $x \in F$ .

EXERCISE 3.4.2. — Let  $f : X \rightarrow Y$  be a function, let  $S$  be a subset of  $X$  and let  $U$  be a subset of  $Y$ . What, in general, can one say about  $f^{-1}(f(S))$  and  $S$ ? What about  $f(f^{-1}(U))$  and  $U$ ?

This exercise gives a first taste of Exercise 3.4.5 below.

1. First consider  $f^{-1}(f(S))$  and  $S$ .
  - Do we have  $f^{-1}(f(S)) \subset S$ ? Generally, no. As a counterexample, let's consider  $f(x) = x^2$  with  $X = Y = \mathbb{R}$  and  $S = \{0, 2\}$ . We have  $f^{-1}(f(S)) = f^{-1}(\{0, 4\}) = \{-2, 0, 2\}$ . In this set, we have an element,  $-2$ , which is not an element of  $S$ .
  - Do we have  $S \subset f^{-1}(f(S))$ ? Yes. Let be  $x \in S$ . Then, by definition,  $f(x) \in f(S)$ . So,  $x \in X$  and is such that  $f(x) \in f(S)$ : this is precisely the definition of  $x \in f^{-1}(f(S))$ .
  - Conclusion: generally speaking,  $S$  and  $f^{-1}(f(S))$  are not equal, but  $S \subset f^{-1}(f(S))$ .
2. Now consider  $f(f^{-1}(U))$  and  $U$ .
  - Do we have  $U \subset f(f^{-1}(U))$ ? Generally, no. As a counterexample, let's consider  $f(x) = \sqrt{x}$  with  $X = \mathbb{R}_+$ ,  $Y = \mathbb{R}$  and  $U = [-1, 1]$ . We have  $f(f^{-1}(U)) = f([0, 1]) = [0, 1]$ , which is clearly not a subset of  $U$ .
  - Do we have  $f(f^{-1}(U)) \subset U$ ? Yes. Let be  $y \in f(f^{-1}(U))$ . By definition, there exists  $x \in f^{-1}(U)$  such that  $y = f(x)$ . But if  $x \in f^{-1}(U)$ , we have  $f(x) \in U$ . And since  $y = f(x)$ , this means that  $y \in U$ .
  - Conclusion: generally speaking,  $U \neq f(f^{-1}(U))$ , but  $f(f^{-1}(U)) \subset U$ .

EXERCISE 3.4.3. — Let  $A, B$  be two subsets of  $X$ , and let be  $f : X \rightarrow Y$ . Show that  $f(A \cap B) \subseteq f(A) \cap f(B)$ , that  $f(A) \setminus f(B) \subseteq f(A \setminus B)$ , and  $f(A \cup B) = f(A) \cup f(B)$ . Is it true that, for the first two statements, the  $\subseteq$  relation can be improved to  $=$ ?

Let's prove the three statements successively:

1. If  $y \in f(A \cap B)$ , then there exists  $x \in A \cap B$  such that  $f(x) = y$ . Since  $x \in A \cap B$ , we have both  $x \in A$  and  $x \in B$ , which implies  $y = f(x) \in f(A)$  and  $y = f(x) \in f(B)$  respectively. Thus,  $y \in f(A) \cap f(B)$ , and we have proved that  $f(A \cap B) \subseteq f(A) \cap f(B)$ .  
However, the converse inclusion is false in general. For instance, let's consider the two sets  $A = \{1, 2\}$ ,  $B = \{2, 3\}$  and the (non injective) function  $f$  defined as the mapping  $f(1) = 1$ ,  $f(2) = 2$ ,  $f(3) = 1$ . We have  $f(A) = \{1, 2\}$ ,  $f(B) = \{1, 2\}$ , thus  $f(A) \cap f(B) = \{1, 2\}$ . This is not a subset of  $f(A \cap B) = f(\{2\}) = \{2\}$ .

2. If  $y \in f(A) \setminus f(B)$ , then there exists  $x_0 \in A$  such that  $y = f(x_0)$ , but we have  $f(b) \neq y$  for all  $b \in B$ . Suppose that  $x_0 \in B$ : in this case,  $f(x_0) \neq y$ , a contradiction. Thus,  $y = f(x_0)$  with  $x_0 \in A \setminus B$ , which proves that  $f(A) \setminus f(B) \subseteq f(A \setminus B)$ .

However, the converse inclusion is false in general. For instance, let's consider the two sets  $A = \{1, 2, 3\}$ ,  $B = \{3\}$  and the function  $f$  defined as the mapping  $f(1) = 1$ ,  $f(2) = 2$ ,  $f(3) = 1$ . We have  $f(A \setminus B) = \{1, 2\}$  but  $f(A) \setminus f(B) = \{2\}$ .

3. If  $y \in f(A \cup B)$ , then there exists  $x \in A \cup B$  such that  $y = f(x)$ . If  $x \in A$ , then  $f(x) \in f(A)$ , which implies  $x \in f(A) \cup f(B)$ . There is an identical result if  $x \in B$ . Thus,  $f(A \cup B) \subseteq f(A) \cup f(B)$ .

Conversely, if  $y \in f(A) \cup f(B)$ , then we have either  $y \in f(A)$  or  $y \in f(B)$  (or both). In the first case, there exists  $x \in A$  such that  $y = f(x)$ . But since  $x \in A$ , we also have  $x \in A \cup B$ , so that  $y \in f(A \cup B)$ . The same result holds if  $y \in B$ . Thus, in both cases,  $y \in f(A \cup B)$ .

EXERCISE 3.4.4. — Let be  $f : X \rightarrow Y$  a function, and let  $A, B$  be subsets of  $Y$ . Show that  $f^{-1}(A \cup B) = f^{-1}(A) \cup f^{-1}(B)$ , that  $f^{-1}(A \cap B) = f^{-1}(A) \cap f^{-1}(B)$ , and that  $f^{-1}(A \setminus B) = f^{-1}(A) \setminus f^{-1}(B)$ .

We prove only the first statement here; since only very small adjustments are required in its proof to prove the last two ones.

- Let be  $x \in f^{-1}(A \cup B)$ . By definition,  $f(x) \in A \cup B$ , so that we have either  $f(x) \in A$  or  $f(x) \in B$ .

If  $f(x) \in A$ , then  $x \in f^{-1}(A)$  by definition. This implies that  $x \in f^{-1}(A) \cup f^{-1}(B)$ .

The same conclusion holds if  $f(x) \in B$ . Thus, we have demonstrated that  $f^{-1}(A \cup B) \subseteq f^{-1}(A) \cup f^{-1}(B)$ .

- For the converse inclusion, let be  $x \in f^{-1}(A) \cup f^{-1}(B)$ . We have either  $x \in f^{-1}(A)$  or  $x \in f^{-1}(B)$ .

If  $x \in f^{-1}(A)$ , then  $f(x) \in A$ , and since  $A \subset A \cup B$ , we have  $f(x) \in A \cup B$ . This implies  $x \in f^{-1}(A \cup B)$ .

The same conclusion holds if  $x \in f^{-1}(B)$ . Thus,  $f^{-1}(A) \cup f^{-1}(B) \subseteq f^{-1}(A \cup B)$ .

- This proves the equality  $f^{-1}(A \cup B) = f^{-1}(A) \cup f^{-1}(B)$ .

EXERCISE 3.4.5. — Let  $f : X \rightarrow Y$  be a function. Show that  $f^{-1}(f(S)) = S$  for every  $S \subseteq Y$  iff  $f$  is surjective. Show that  $f(f^{-1}(S)) = S$  for every  $S \subseteq X$  iff  $f$  is injective.

This exercise is a continuation of Exercise 3.4.2. Let's recall its results, that will reduce the amount of things to be proven here:

- we always have  $f^{-1}(f(S)) \subseteq S$  for every  $S \subseteq Y$ , thus we just have to prove that  $f$  is surjective iff  $S \subseteq f^{-1}(f(S))$  for every  $S \subseteq Y$ .
- we always have  $S \subseteq f(f^{-1}(S))$  for every  $S \subseteq X$ , thus we just have to prove that  $f$  is injective iff then  $f(f^{-1}(S)) \subseteq S$  for every  $S \subseteq X$ .

Let's prove those two statements.

1. Let  $f$  be surjective: let's show that  $S \subseteq f(f^{-1}(S))$  for all  $S \subseteq Y$ . Let  $S$  be a subset of  $Y$ , and  $y \in S$ <sup>9</sup>. Since  $f$  is surjective, there exists  $x \in X$  such that  $y = f(x)$ . Recall that  $y \in S$ : this means that  $f(x) \in S$ , i.e.  $x \in f^{-1}(S)$ . Thus,  $y = f(x) \in f(f^{-1}(S))$ . We have proved that, if  $f$  is surjective,  $y \in S \Rightarrow y \in f(f^{-1}(S))$ , i.e.  $S \subseteq f(f^{-1}(S))$ .

Conversely, suppose that  $S \subseteq f(f^{-1}(S))$  for every  $S \subseteq Y$  and let's show that  $f$  is surjective. Let's choose  $S = Y$ : by hypothesis, we have  $Y \subseteq f(f^{-1}(Y))$ . Then, let be  $y \in Y$ . There exists  $x \in f^{-1}(Y) \subseteq X$  such that  $y = f(x)$ . This means precisely that  $f$  is surjective.

The first equivalence is proved.

2. Let  $f$  be injective, and  $S \subseteq X$ . Let be  $x \in f^{-1}(f(S))$ . Thus, by definition,  $f(x) \in f(S)$ . This means that there exists  $x' \in f(S)$  such that  $f(x) = f(x')$ . And since  $f$  is injective,  $x = x' \in S$ . Thus, if  $f$  is injective,  $f^{-1}(f(S)) \subseteq S$  for every  $S \subseteq X$ .

Conversely, suppose that  $f^{-1}(f(S)) \subseteq S$  for every  $S \subseteq X$ . In particular, this is true for any singleton  $S = \{x_0\}$ , with  $x_0 \in S$ . In such a case, we obtain  $f^{-1}(f(\{x_0\})) = \{x_0\}$ . For any element  $x \in X$ , if  $x \neq x_0$ , we have  $x \notin \{x_0\}$  by definition of a singleton, thus  $x \notin f^{-1}(f(\{x_0\}))$ , and thus  $f(x) \neq f(x_0)$ . This means that  $f$  is injective.

The second equivalence is proved.

**EXERCISE 3.4.6.** — *Prove lemma 3.4.9. (Hint: start with the set  $\{0,1\}^X$  and apply the replacement axiom, replacing each function  $f$  with the object  $f^{-1}(\{1\})$ .)*

First, let's recall the main propositions involved in this exercise:

- **Replacement axiom.** Let  $A$  be a set. For any object  $x \in A$ , and any object  $y$ , suppose we have a statement  $P(x, y)$  pertaining to  $x$  and  $y$ , such that for each  $x \in A$  there is at most one  $y$  for which  $P(x, y)$  is true. Then there exists a set  $\{y \mid P(x, y) \text{ is true for some } x \in A\}$ , such that for any object  $z$ ,

$$z \in \{y \mid P(x, y) \text{ is true for some } x \in A\} \iff P(x, z) \text{ is true for some } x \in A$$

- **Power set axiom.** Let  $X$  and  $Y$  be sets. There there exists a set, denoted  $Y^X$ , which consists of all the function from  $X$  to  $Y$ :

$$f \in Y^X \iff (f \text{ is a function from } X \text{ to } Y)$$

- **Lemma 3.4.9.** Let  $X$  be a set. Then the set  $\{Y \mid Y \text{ is a subset of } X\}$  is a set.

The aim is to prove this lemma using the two axioms recalled here.

1. Let  $X$  be a set, and  $Y = \{0, 1\}$ . Per the power set axiom,  $\{0, 1\}^X$  is a set, and it contains all the functions  $f : X \rightarrow \{0, 1\}$ .
2. Let  $A$  be a subset of  $X$ . One can define the function  $f_A : X \rightarrow \{0, 1\}$ , such that for all  $x \in X$ ,  $f(x) = 1$  if  $x \in A$ , and  $f(x) = 0$  otherwise. We can even say more:

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<sup>9</sup>If  $S$  is empty, the statement is vacuously true, so that we can suppose  $S \neq \emptyset$ .

- If  $A$  is a subset of  $X$ , then there exists an element  $f \in \{0,1\}^X$  such that  $A = f^{-1}(\{1\})$ : this is precisely  $f_A$  as defined above.
- Conversely, if  $f \in \{0,1\}^X$ , then  $A = f^{-1}(\{1\})$  is by definition a subset of  $X$ .

Thus, the two statements “ $A$  is a subset of  $X$ ” and “there exists  $f \in \{0,1\}^X$  such that  $A = f^{-1}(\{1\})$ ” are equivalent.

3. Finally, let be  $A \subset X$  and  $f \in \{0,1\}^X$ . Let’s define  $P(f, A)$  the statement “ $A = f^{-1}(\{1\})$ ”. For each  $f$ , there is at most one  $A$  (in fact, *exactly* one  $A$ ) such that  $P(f, A)$  is true. Thus, per the axiom of replacement, there exists a set:

$$\mathcal{P} = \{A \mid A = f^{-1}(\{1\}) \text{ for some } f \in \{0,1\}^X\}$$

And, thanks to the equivalence demonstrated in 2.:

$$\mathcal{P} = \{A \mid A \text{ is a subset of } X\}$$

is a well-defined set, which we wanted to prove.

EXERCISE 3.4.7. — *Let  $X, Y$  be sets. Define a partial function from  $X$  to  $Y$  to be any function  $f : X' \rightarrow Y'$  with  $X' \subseteq X$  and  $Y' \subseteq Y$ . Show that the collection of all partial functions from  $X$  to  $Y$  is itself a set.*

- Let be  $X' \subseteq X$  and  $Y' \subseteq Y$ . If both  $X'$  and  $Y'$  are fixed, then per the power set axiom (3.10), there exists a set  $Y'^{X'}$  which consists of all the functions from  $X'$  to  $Y'$ .
- By lemma 3.4.9, there exist a set  $2^X$  which consists of all the subsets of  $X$ , and a set  $2^Y$  which consists of all the subsets of  $Y$ .
- Now we *fix* an element  $X'$  of  $2^X$ . Let be  $Y'$  an element of the set  $2^Y$ ,  $A$  a set, and  $P$  the property “ $P(Y', A): A = Y'^{X'}$ ”. Per the replacement axiom, there exists exactly one (and thus, at most one) set:

$$\begin{aligned} \{A \mid P(Y', A) \text{ is true for some } Y' \in 2^Y\} &= \{A \mid A = Y'^{X'} \text{ for some } Y' \in 2^Y\} \\ &= \{Y'^{X'} \mid Y' \in 2^Y\} \end{aligned}$$

- Each element of this set is itself a set. Thus we can apply the axiom of union (3.11): there exists a set  $\bigcup \{Y'^{X'} \mid Y' \in 2^Y\}$  whose elements are those objects which are elements of elements of  $\{Y'^{X'} \mid Y' \in 2^Y\}$ , i.e.:

$$\bigcup \{Y'^{X'} \mid Y' \in 2^Y\} = \{f \mid f : X' \rightarrow Y' \text{ for some } Y' \in 2^Y\}$$

This set is obtained for one given *fixed* subset  $X' \subseteq X$ , so let’s denote this set:

$$S_{X'} = \{f \mid f : X' \rightarrow Y' \text{ for some } Y' \in 2^Y\}$$

- Now we apply once again the union set (3.11), especially in its second formulation. If we denote  $I = 2^X$ , then for each element  $X' \in I$  we do have one set  $S_{X'}$ , which is defined above. Thus, there exists a set  $\bigcup_{X' \in 2^X} S_{X'} := \bigcup \{S_{X'} \mid X' \in 2^X\}$ . And, for every function  $f$ , we have  $f \in \bigcup \{S_{X'} \mid X' \in 2^X\}$  iff there exists  $X' \in 2^X$  such that  $f \in S_{X'}$ , i.e. if there exists  $X' \subset X$  and  $Y' \subset Y$  such that  $f : X' \rightarrow Y'$ .



- Consequently, we have proved that there exists a set which consists of the collection of all partial functions from  $X$  to  $Y$ .

EXERCISE 3.4.8. — *Prove that Axiom 3.4 can be deduced from Axiom 3.1, Axiom 3.3 and Axiom 3.11.*

Let's recall very briefly the four axioms involved here :

- Axiom 3.4 (to be proved) says that if  $A$  and  $B$  are sets, then there exists a union set  $A \cup B$  such that  $x \in A \cup B$  iff  $x \in A$  or  $x \in B$ .
- Axiom 3.1 essentially says that sets are objects.
- Axiom 3.3 says that singletons are pair sets do exist.
- Axiom 3.11: let  $A$  be a set, whose all elements are themselves sets. Then there exists a set  $\bigcup A$  whose elements are those objects which are elements of elements of  $A$ , i.e.,  $x \in \bigcup A$  iff  $x \in S$  for some  $S \in A$ .

Here is a sketch of proof for Axiom 3.4. Let  $A$  and  $B$  be sets. According to Axiom 3.1,  $A$  and  $B$  are themselves objects: they can be elements of other sets. Consequently, according to Axiom 3.3, it makes sense to talk about the singleton sets  $\{A\}$  and  $\{B\}$ , and the set  $\{A, B\}$ .

Now we consider this latter set, which we denote  $\mathcal{A} = \{A, B\}$ . According to axiom 3.11, there exists a set  $\bigcup \mathcal{A}$  whose elements those objects which are the elements of  $\mathcal{A}$ , i.e.,  $x \in \bigcup \mathcal{A}$  iff there exists  $S \in \mathcal{A}$  such that  $x \in S$ . But  $\mathcal{A}$  is a pair set with only two elements, so that  $S$  must necessarily be equal to  $A$  or  $B$ .

This leads to the following conclusion: if  $A$  and  $B$  are sets, then there exists a set  $\mathcal{A}$  such that  $x \in \mathcal{A}$  iff  $x \in A$  or  $x \in B$ . This is precisely the Axiom 3.4.

EXERCISE 3.5.1. — *Suppose we define the ordered pair  $(x, y)$  for any objects  $x$  and  $y$  by the formula  $(x, y) := \{\{x\}, \{x, y\}\}$ . Show that this definition obeys the property (3.5), and also whenever  $X$  and  $Y$  are sets, the cartesian product  $X \times Y$  is also a set.*

Recall that property (3.5) says that  $(x, y) = (x', y')$  iff  $x = x'$  and  $y = y'$ . The proof below is heavily inspired by the sketch given by Paul Halmos in his famous book, *Naive Set Theory*. (The proof below is just immensely more verbose.)

1. First, we go back to Remark 3.1.9 by Terence Tao (page 37). In this remark, Tao says that for any object  $a$ , the pair set  $\{a, a\}$  is in fact the singleton  $\{a\}$ . Tao asks *why?* to the reader. This is easy to prove using the Definition 3.1.4 (equality of sets): both sets have the same elements, thus they are equal. This fact is a crucial point for the current proof.

Indeed, first note that for any object  $x$ , the ordered pair  $(x, x)$  will be (by definition) equal to  $\{\{x\}, \{x, x\}\}$ . Applying twice the Remark 3.1.9 made by Terence Tao, we can conclude that  $(x, x) = \{\{x\}\}$  for any object  $x$ .

Conversely, if any ordered pair  $(x, y)$  is a singleton, this means that  $\{\{x\}, \{x, y\}\}$  is a singleton. This implies that both elements of this pair set are equal, i.e.  $\{x\} = \{x, y\}$ . Thus, (by Definition 3.1.4,)  $y \in \{x\}$ , i.e.  $x = y$ .

This gives a handy conclusion, that we can write as a lemma:

**Lemma.** *An ordered pair  $(x, y)$  is a singleton if and only if  $x = y$  (and in this case, this singleton is  $\{\{x\}\} = \{\{y\}\}$ ).*

We can now prove more easily that property (3.5) is met.

2. Let's prove that the property (3.5) is satisfied.

- First, let be two ordered pairs  $(a, b) = \{\{a\}, \{a, b\}\}$  and  $(x, y) = \{\{x\}, \{x, y\}\}$ . If  $a = x$  and  $y = b$ , then we obviously have  $\{\{a\}, \{a, b\}\} = \{\{x\}, \{x, y\}\}$ .
- For the reciprocal, suppose that  $(a, b) = (x, y)$ , and let's show that  $a = x$  and  $b = y$ . We will consider two distinct cases.

(a) First consider the case where  $a = b$  (note that this also covers the case  $x = y$ , since they play symmetrical roles). Thus  $(a, b) = \{\{a\}\}$ . Since  $(a, b) = (x, y)$ , we have  $\{\{x\}, \{x, y\}\} = \{\{a\}\}$ .

This means that  $\{x\} \in \{\{a\}\}$ , i.e.  $a = x$ .

But we also have  $\{x, y\} \in \{\{a\}\}$ , i.e.  $\{x, y\} = \{a\}$ . This means in particular that  $\{x, y\}$  is a singleton, which is only possible if  $x = y$  according to the lemma introduced above.

Thus,  $a = b$  by hypothesis, and  $a = x$ , and  $x = y$ . This finally means that all four elements are equal:  $a = b = x = y$ .

We can insist: if we have either  $a = b$  or  $x = y$ , then all four elements are equal, and property (3.5) is met.

(b) The other case is  $a \neq b$  (which also implies  $x \neq y$ , otherwise all four elements would be equal). Since  $(a, b) = (x, y)$ , we have  $\{a\} \in \{\{x\}, \{x, y\}\}$ , so that we have either  $\{a\} = \{x\}$  or  $\{a\} = \{x, y\}$ . The latter case can be excluded:  $\{a\} = \{x, y\}$  would mean that  $\{x, y\}$  is a singleton, thus  $x = y$ , a contradiction with our hypothesis. Thus, the only possibility is  $\{a\} = \{x\}$ , i.e.  $a = x$ .

We also have  $\{a, b\} \in \{\{x\}, \{x, y\}\}$ , and for the same reason, the only possibility is  $\{a, b\} = \{x, y\}$ . But we have showed that  $a = x$ , so that  $\{a, b\} = \{a, y\}$ .

The conclusion is  $y = b$ .

- Conclusion: in both cases,  $(a, b)$  implies both  $a = x$  and  $y = b$ , which is our initial goal. Property (3.5) is met.

3. Finally, if we adopt this definition,  $X \times Y$  is a set. Indeed, for every  $x \in X$  and  $y \in Y$ , both  $x$  and  $y$  are elements of  $X \cup Y$ . Thus, the singleton  $\{x\}$  and the pair set  $\{x, y\}$  are elements of the power set of  $X \cup Y$  (which is indeed a set, by Lemma 3.4.9: see Exercise 3.4.6). In other words, if  $\mathcal{P}(A)$  denotes the power set of a set  $A$ , we have  $\{x\} \in \mathcal{P}(X \cup Y)$  and  $\{x, y\} \in \mathcal{P}(X \cup Y)$ .

Thus, for every objects  $x \in X$  and  $y \in Y$ ,  $\{\{x\}, \{x, y\}\} \subset \mathcal{P}(X \cup Y)$ . This latter statement is equivalent to  $\{\{x\}, \{x, y\}\} \in \mathcal{P}(\mathcal{P}(X \cup Y))$ , which is also a well-defined set by a (recursive) application of Lemma 3.4.9.

Then, for any element  $S \in \mathcal{P}(\mathcal{P}(X \cup Y))$ , let  $P(S)$  be the property “There exists  $x \in X$  and  $y \in Y$  such that  $S = \{\{x\}, \{x, y\}\}$ ”. By the axiom of specification (Axiom 3.5), there exists a set  $\{S \in \mathcal{P}(\mathcal{P}(X \cup Y)) \mid P(S) \text{ is true}\}$ : this set is precisely the cartesian product  $X \times Y$  we were looking for.

## 4. Integers and rationals

EXERCISE 4.1.1. — *Verify that the definition of equality on the integers is both reflexive and symmetric.*

Recall the Definition 4.1.1 of equality on integers: two integers  $a \text{---} b$  and  $c \text{---} d$  are equal iff  $a + d = c + b$ . This defines a binary relation on  $\mathbb{Z}$ , denoted “ $=$ ”. Let’s show that this relation is reflexive and symmetric.

- Reflexivity: let  $a$  and  $b$  be natural numbers, so that  $a \text{---} b$  is an integer. We know that, on natural numbers, equality is reflexive, i.e.  $a + b = a + b$ . This equality means precisely that  $a \text{---} b = a \text{---} b$ .
- Symmetry: let  $a, b, c, d$  be natural numbers. If  $a \text{---} b = c \text{---} d$ , do we also have  $c \text{---} d = a \text{---} b$ ?

$$\begin{aligned}
 a \text{---} b &= c \text{---} d \\
 \iff a + d &= c + b \\
 \iff c + b &= a + d \text{ (equality is symmetric on naturals)} \\
 \iff c \text{---} d &= a \text{---} b
 \end{aligned}$$

EXERCISE 4.1.2. — *Show that the definition of negation on the integers is well-defined in the sense that if  $(a \text{---} b) = (a' \text{---} b')$ , then  $-(a \text{---} b) = -(a' \text{---} b')$  (so equal integers have equal negations).*

Since  $a \text{---} b = a' \text{---} b'$ , we have  $a + b' = a' + b$ .

Also, by Definition 4.1.4 of negation, we have:

$$\begin{aligned}
 -(a \text{---} b) &= b \text{---} a \\
 -(a' \text{---} b') &= b' \text{---} a'
 \end{aligned}$$

Then, we have successively:

$$\begin{aligned}
 b + a' &= a' + b \text{ (addition is commutative on naturals, Prop. 2.2.4)} \\
 &= a + b' \text{ (initial hypothesis)} \\
 &= b' + a \text{ (by commutativity on naturals once again)}
 \end{aligned}$$

and this equality  $b + a' = b' + a$  precisely means that  $b \text{---} a = b' \text{---} a'$ , i.e. that  $-(a \text{---} b) = -(a' \text{---} b')$ .

EXERCISE 4.1.3. — *Show that  $(-1) \times a = -a$  for every integer  $a$ .*

Since  $a$  is an integer, there exist two natural numbers  $n$  and  $m$  such that  $a = m \text{---} n$ .

On the one hand, by Definition 4.1.4,  $-a = n \text{---} m$ .

On the other hand, using once again Definition 4.1.4 and Definition 4.1.2,

$$\begin{aligned}
 (-1) \times a &= (0 \text{---} 1) \times (m \text{---} n) \\
 &= (0 \times m + 1 \times n) \text{---} (0 \times n + 1 \times m) \\
 &= n \text{---} m
 \end{aligned}$$

Thus, we have indeed  $(-1) \times a = -a$ .

EXERCISE 4.1.4. — *Prove the remaining identities in Proposition 4.1.6.*

Let  $x = a - b$ ,  $y = c - d$  and  $z = e - f$  be three integers. Those identities are the following:

1.  $x + y = y + x$ , i.e., we must prove that addition is commutative on the integers. We have:

$$\begin{aligned} x + y &= (a - b) + (c - d) \\ &= (a + c) - (b + d) \text{ (by Definition 4.1.2)} \\ &= (c + a) - (d + b) \text{ (addition is commutative on naturals)} \\ &= (c - d) + (a - b) \text{ (by Definition 4.1.2 again)} \\ &= y + x \end{aligned}$$

2.  $(x + y) + z = x + (y + z)$ , i.e. prove that addition is associative on the integers. This is a very similar proof, and this is a direct consequence of associativity of addition on the naturals.

3.  $x + 0 = 0 + x = x$ . We have already showed that addition is commutative on the integers, so we just have to prove that  $x + 0 = x$ .

$$\begin{aligned} x + 0 &= (a - b) + (0 - 0) \\ &= (a + 0) - (b + 0) \\ &= a - b = x. \end{aligned}$$

4.  $x + (-x) = (-x) + x = 0$ . Once again, thanks to the previous result about commutativity, we just have to prove that  $x + (-x) = 0$ .

$$\begin{aligned} x + (-x) &= (a - b) + (b - a) \text{ (by Definition 4.1.4)} \\ &= (a + b) - (b + a) \text{ (by Definition 4.1.2)} \\ &= (a + b) - (a + b) \text{ (addition is commutative on naturals)} \\ &= 0 \text{ (because } m - m = 0 - 0 \text{ for all integer } m) \end{aligned}$$

5.  $xy = yx$ , i.e. multiplication is commutative on the integers.

$$\begin{aligned} xy &= (a - b) \times (c - d) \\ &= (ac + bd) - (ad + bc) \text{ (by Definition 4.1.2)} \\ &= (ca + db) - (da + cb) \text{ (multiplication is commutative on the naturals)} \\ &= yx \text{ (by Definition 4.1.2)} \end{aligned}$$

6.  $(xy)z = x(yz)$ , i.e. multiplication is associative on the integers. This is actually the only identity proved in the main text by Terence Tao.

7.  $x1 = 1x = x$ . The equality between the first two terms is a direct consequence of commutativity of multiplication on the integers. We just have to prove that  $x1 = x$ . And indeed,  $x1 = (a - b) \times (1 - 0) = (a1 + b0) - (b1 + a0) = a - b = x$ .
8.  $x(y + z) = xy + xz$ , i.e. show distributivity on the integers. On the left side, we have:

$$\begin{aligned} x(y + z) &= (a - b)((c - d) + (e - f)) \\ &= (a - b)((c + e) - (d + f)) \\ &= (a(c + e) + b(d + f)) - (a(d + f) + b(c + e)) \\ &= ((ac + ae + bd + bf)) - ((ad + af + bc + be)) \end{aligned}$$

and then on the left side:

$$\begin{aligned} xy + xz &= (a - b)(c - d) + (a - b)(e - f) \\ &= ((ac + bd) - (ad + bc)) + ((ae + bf) - (af + be)) \\ &= ((ac + ae + bd + bf)) - ((ad + af + bc + be)) \end{aligned}$$

9.  $(y + z)x = yx + zx$ . This latter identity is a direct consequence of commutativity of multiplication on the integers, and distributivity on the integers, both being already proved earlier in this exercise.

EXERCISE 4.1.5. — *Prove Proposition 4.1.8, i.e.: let  $x$  and  $y$  be integers such that  $xy = 0$ , then either  $x = 0$  or  $y = 0$  (or both).*

We will use here Lemma 4.1.5 (trichotomy of integers, which says that any integer is either zero, or equal to a positive natural number, or the negation of a positive natural number), and Lemma 2.3.3 (which provides an equivalent of Proposition 4.1.8 for natural numbers only). We will prove the proposition for (all) three possible cases:  $x = 0$ ,  $x$  is a positive natural number,  $-x$  is a positive natural number.

$y$  will be considered as a fixed integer,  $y = c - d$  with  $c, d$  natural numbers.

1. First let's take the case  $x = 0$ . There is nothing to prove here, the proposition is obviously true.
2. Then let's take the case where  $x$  is a positive natural number (and, consequently, is not equal to zero). In this case, as an integer,  $x$  can be written  $n - 0$  with  $n$  a positive natural number.

$$\text{We have } xy = (n - 0) \times (c - d) = (nc + 0d) - (nd + 0c) = nc - nd.$$

Thus,  $xy = 0$  iff  $nc - nd = 0 - 0$ , and by Definition 4.1.1, this means that  $nc = nd$ . But since all three  $n, c, d$  are natural numbers, we can use the cancellation law for natural numbers and conclude that  $c = d$ .

This means that  $y = c - c = 0 - 0 = 0$ . Thus, in this case, if  $xy = 0$  with  $x$  non-zero, we have showed that  $y$  is necessarily equal to 0.

3. Finally, let's take the case where  $x$  is the opposite of a positive natural number  $n$ , i.e.  $x = 0 - n$ . A very similar proof also leads to  $c = d$ , and to  $y = 0$ .

EXERCISE 4.1.6. — *Prove Corollary 4.1.9, i.e. if  $a, b, c$  are integers such that  $ac = bc$  and  $c$  is non-zero, then  $a = b$ .*

If  $ac = bc$ , then  $ac + (-bc) = bc + (-bc) = 0$ . Thus,  $ac - bc = 0$ .

Let's use the property of distributivity (Proposition 4.1.6): we obtain  $(a - b)c = 0$ . According to Proposition 4.1.8 (see also the previous exercise), this implies either  $c = 0$  or  $a - b = 0$ . The first option ( $c = 0$ ) must be discarded since it does not fit the initial hypothesis. The only possibility is thus  $a - b = 0$ , and adding  $b$  to both sides finally leads to  $a = b$ .

EXERCISE 4.1.7. — *Prove Lemma 4.1.11.*

The statements to prove are the following:

1. Show that  $a > b$  if and only if  $a - b$  is a positive natural number.

First suppose that  $a > b$ . This means (Definition 4.1.10) that there exists a natural number  $n$  such that  $a = b + n$ , and  $a \neq b$ . Then, we add to both sides the opposite of  $b$ , and we get  $a + (-b) = b + n + (-b)$ , i.e.  $a - b = n$ . In this latest equality,  $n$  cannot be zero, otherwise we would have  $a = b$ , which is excluded. The first implication is proved.

Then suppose that  $a - b = n$  with  $n$  a positive natural number. Adding  $b$  to both sides leads to  $a = b + n$ , i.e.  $a \geq b$ . We cannot have  $a = b$ , because this would be a contradiction with the fact that  $n \neq 0$ . Thus,  $a > b$ .

2. Show that addition preserves order, i.e. if  $a > b$ , then  $a + c > b + c$ .

Suppose that  $a > b$ . According to the previous point, this means that  $a - b = n$ , with  $n$  a positive natural number. Then, we get successively:

$$\begin{aligned} a &= b + n && \text{(by adding } b \text{ to both sides)} \\ a + c &= b + c + n && \text{(by adding } c \text{ to both sides)} \\ a + c - b - c &= n && \text{(by adding } (-b) + (-c) \text{ to both sides)} \\ a + c - (b + c) &= n && \text{(by using the distributive law and Exercise 4.1.3)} \end{aligned}$$

Using again the previous point, since  $(a + c) - (b + c)$  is equal to a positive natural number, we can conclude that  $a + c > b + c$ .

3. Show that positive multiplication preserves order, i.e. if  $a > b$  and  $c$  is positive, then  $ac > bc$ .

Since  $a > b$ , according to the first point of this exercise, we have  $a - b = n$ , with  $n$  a positive natural number. According to the distributive law,  $(a - b)c = ac - bc$ . But we also have  $(a - b)c = nc$ , and  $nc$  is a positive natural number (as product of two positive numbers, see Lemma 2.3.3). Thus,  $ac - bc$  is equal to a positive number, which means that  $ac > bc$ .

4. Show that negation reverses order, i.e. if  $a > b$ , then  $-a < -b$ .

Here, we will need a small lemma, which says that for any natural number  $n$ , we have  $n = -(-n)$ . There are several ways to show this result: either by proving that  $(-1) \times (-1) = 1$  and using Exercise 4.1.3, or simply by noting that  $n + (-n) = 0$  for all  $n$ , which means that  $n$  is the opposite of  $-n$  (i.e.,  $n = -(-n)$ ).

Now this point is easy to prove.  $a > b$  means that  $a - b$  is a positive number, as shown earlier in this exercise. We want to prove that  $-a < -b$ , and proving this assertion requires to show that  $-b - (-a)$  is a positive number. But  $-b - (-a) = -b + a = a - b$ , which is a positive natural number. Thus we are done.

5. Show that order is transitive, i.e. if  $a > b$  and  $b > c$ , then  $a > c$ .

Still using the first point of this exercise, we have  $a - b = n$  and  $b - c = m$ , with  $n, m$  two positive natural numbers. We know that  $n + m$  is positive as the sum of two positive numbers, thus  $n + m = a - b + b - c = a - c$  is positive. This means that  $a > c$ .

6. Show order trichotomy, i.e.: exactly one of the statements  $a > b$ ,  $a < b$ , or  $a = b$  is true.

- If  $a = b$ , then obviously (exactly) one of those statements is true.
- Now consider the case  $a \neq b$ , and let's show that we have either  $a > b$  or  $a < b$  (and cannot have both).

Let's consider the integer  $a - b$ . By trichotomy of integers (Lemma 4.1.5), we know that we have either  $a - b = 0$  (which is excluded here), or  $a - b = n$  with  $n$  positive, or  $a - b = -n$  with  $n$  positive.

If  $a - b = n$ , then  $a > b$  according to the first point of this exercise. If  $a - b = -n$ , then  $-n = -(a - b) = b - a$ , thus  $b > a$ .

Finally, we just have to show that we cannot have both  $a > b$  and  $b > a$  at the same time. If  $a > b$ , then the integer  $a - b$  is positive. If  $b > a$ , then  $b - a$  is positive, i.e.  $-(b - a) = a - b$  is the opposite of a positive natural. Thus,  $a - b$  is both positive and the opposite of a positive number, which is excluded by the trichotomy of integers.

EXERCISE 4.1.8. — *Show that the principle of induction (Axiom 2.5) does not apply directly to the integers. More precisely, give an example of a property  $P(n)$  pertaining to an integer  $n$  such that  $P(0)$  is true, and that  $P(n)$  implies  $P(n++)$  for all integers  $n$ , but that  $P(n)$  is not true for all integers  $n$ .*

According to Lemma 4.1.5, an integer is either equal to 0, or equal to a positive natural number, or equal to the negation of a positive natural number.

Let's define  $P(n)$  as the property "The integer  $n$  is a natural number, i.e. is either equal to 0 or equal to a positive natural number". Obviously,  $P(0)$  is true. Furthermore, if  $n$  is a natural number, then  $n++$  is also a natural number (Axiom 2.2), so that if  $P(n)$  is true, then  $P(n++)$  is true. Thus,  $P(n)$  matches the required conditions.

However,  $P(-1)$  is obviously false.

EXERCISE 4.2.1. — *Show that the definition of equality for the rational numbers is reflexive, symmetric, and transitive.*

This exercise resembles Exercise 4.1.1, and the same approach applies. Recall the Definition 4.2.1: two rational numbers  $a // b$  and  $c // d$  are equal iff  $ad = bc$ . This defines a binary relation on  $\mathbb{Q}$ , denoted " $=$ ". Let's show that this relation is reflexive, symmetric and transitive.

Hereafter,  $a, b, c, d, e, f$  are integers (and  $b, d, f$  are non-zero).

- Reflexivity: here we must prove that  $a // b = a // b$ . This is the case iff  $ab = ba$ , which is true because of (commutativity of multiplication on  $\mathbb{Z}$  and) reflexivity of equality on  $\mathbb{Z}$ .
- Symmetry: here we must prove that if  $a // b = c // d$ , we also have  $c // d = a // b$ . We have successively:

$$\begin{aligned}
& a // b = c // d \\
\iff & ad = bc \\
\iff & da = cb \text{ (}\times \text{ is commutative on } \mathbb{Z}\text{)} \\
\iff & cb = da \text{ (= is symmetric on } \mathbb{Z}\text{)} \\
\iff & c // d = a // b
\end{aligned}$$

- Transitivity: here we must prove that if  $a // b = c // d$  and  $c // d = e // f$ , then  $a // b = e // f$ . I.e., we must prove that if  $ad = bc$  and  $cf = de$ , then  $af = be$ .

Let's multiply by  $e$  both sides of the equality  $ad = bc$ : we get  $ade = bce$ . Since  $de = cf$ , we also get  $acf = bce$ .

In this latest equality, using the cancellation law (Corollary 4.1.9) for  $c$  would lead to  $af = be$ , which would close the proof. However, unlike  $b$ ,  $d$  or  $f$ , the integer  $c$  may be equal to 0, and in this case we cannot use the cancellation law. There are thus two different cases:

- If  $c \neq 0$ , we simply use the cancellation law: since  $acf = bce$ , then  $af = be$ , which means that  $a // b = e // f$ .
- If  $c = 0$ , then  $bc = 0$ . But since  $ad = bc$ , we also have  $ad = 0$ , and we know that  $d \neq 0$ . According to Proposition 4.1.8, this leads to  $a = 0$ . A similar reasoning leads to  $e = 0$ . Thus,  $a = c = e = 0$ , and  $0 = af = be$ , which means  $a // b = e // f$ .

EXERCISE 4.2.2. — *Prove the remaining components of Lemma 4.2.3.*

Let  $a // b = a' // b'$  be two rationals; let  $c // d = c' // d'$  be two rationals. The remaining claims are the following:

- Prove that  $-(a' // b') = -(a // b)$ . This equality holds iff  $(-a') // b' = (-a) // b$ , i.e. iff  $(-a')b = b'(-a)$ . We have successively:

$$\begin{aligned}
(-a')b &= (-1)a'b \text{ (see Exercise 4.1.3)} \\
&= (-1)ab' \text{ (because } a // b = a' // b'\text{)} \\
&= (-a)b' \text{ (using Exercise 4.1.3 one again)}
\end{aligned}$$

Thus we are done.

- Prove that  $(a // b) \times (c // d) = (a' // b') \times (c // d)$ . To prove this equality, we must show that  $(ac) // (bd) = (a'c) // (b'd)$ . By definition of equality between rationals, this holds iff  $acb'd = bda'c$ . Since  $ab' = ba'$ , the claim follows (using commutativity of multiplication on integers<sup>10</sup>).

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<sup>10</sup>This kind of precision about very basic properties of naturals and integers will not be mentioned anymore.



- Prove that  $(a // b) \times (c // d) = (a // b) \times (c' // d')$ . To prove this equality, we must show that  $(ac) // (bd) = (ac') // (bd')$ . By definition of equality between rationals, this holds iff  $acbd' = bdac'$ . Since  $cd' = dc'$ , the claim follows.

EXERCISE 4.2.3. — *Prove the remaining components of Proposition 4.2.4.*

Let  $x = a // b$ ,  $y = c // d$ , and  $z = e // f$  be rational numbers, with  $a, c, e$  integers, and  $b, d, f$  non-zero integers. The remaining claims are the following:

1.  $x + y = y + x$ , i.e. addition is commutative for the rationals.

On the one hand, we have  $x + y = a // b + c // d = (ad + bc) // bd$ .

On the other hand,  $y + x = c // d + a // b = (cb + da) // db = (ad + bc) // bd$  using the commutativity of addition and multiplication on the integers. Thus, the two expressions are equal.

2.  $(x + y) + z = x + (y + z)$ : already proved in the book.
3.  $x + 0 = 0 + x = x$ . By the first point of this exercise, we already know that  $x + 0 = 0 + x$ , so we have just to show that  $x + 0 = x$ . We have  $x + 0 = a // b + 0 // 1 = (a1 + b0) // (b1) = a // b = x$ , which is the required result.
4.  $x + (-x) = (-x) + x = 0$ . Once again, the part  $x + (-x) = (-x) + x$  comes from the first point of this exercise, so we just have to prove that  $x + (-x) = 0$ . We have  $x + (-x) = a // b + -(a // b) = a // b + (-a) // b = (ab - ba) // b^2 = 0 // b^2$ . But we know that  $0 // m = 0 // 1 = 0$  for all non-zero integer  $m$ , since  $0 \times 1 = m \times 0$ . Thus,  $x + (-x) = 0 // b^2 = 0$ , as required.
5.  $xy = yx$ , i.e. multiplication is commutative on the rationals. Indeed,  $xy = (a // b) \times (c // d) = (ac) // (bd)$  by definition. On the other hand,  $yx = (c // d) \times (a // b) = (ca) // (db) = (ac) // (bd)$  by commutativity of multiplication on the integers. Thus,  $xy = yx$ .
6.  $(xy)z = x(yz)$ , i.e. multiplication is associative on the rationals. We have  $(xy)z = (ace) // (bdf) = x(yz)$  by associativity of multiplication on the integers.
7.  $x1 = 1x = x$ . Once again, we already know that  $x1 = 1x$ , thanks to the fifth point of this exercise. So we just have to show that  $x1 = x$ . We have  $x1 = (a // b) \times (1 // 1) = (a1) // (b1) = a // b = x$ .
8.  $x(y + z) = xy + xz$ , i.e. distributivity of multiplication for the rationals. On the one hand, we have:

$$\begin{aligned} x(y + z) &= (a // b)(c // d + e // f) \\ &= (a // b)((cf + de) // (df)) \\ &= (acf + ade) // (bdf) \end{aligned}$$

On the other hand<sup>11</sup>:

$$\begin{aligned}
 xy + xz &= (a // b)(c // d) + (a // b)(e // f) \\
 &= (ac) // (bd) + (ae) // (bf) \\
 &= (acbf + bdae) // (b^2df) \\
 &= (acf + ade) // (bdf)
 \end{aligned}$$

Thus we have indeed  $x(y + z) = xy + xz$ .

9.  $(y + z)x = yx + zx$ . This can be deduced immediately from commutativity of multiplication and the eighth point of this exercise.
10. For all  $x \neq 0$ ,  $xx^{-1} = x^{-1}x = 1$ . Once again, the part  $xx^{-1} = x^{-1}x$  comes from the fifth point of this exercise, so that we just have to show that  $xx^{-1} = 1$ .

$$\begin{aligned}
 xx^{-1} &= (a // b) \times (b // a) \\
 &= (ab) // (ba) \\
 &= 1 // 1 = 1
 \end{aligned}$$

EXERCISE 4.2.4. — *Prove Lemma 4.2.7. (trichotomy of rationals), i.e., if  $x$  is a rational number, then exactly one of the following three statements is true: (a)  $x$  is equal to 0, (b)  $x$  is a positive rational number, or (c)  $x$  is a negative rational number.*

Following the hint given by Terence Tao, we'll first prove that *at least* one of those statements is true, and then that *at most* one of them is true. Let be  $x = a // b$ , where  $a$  is an integer and  $b$  a non-zero integer.

1. Let's prove that at least one of those statements is true.

First, an obvious case: if  $a = 0$ , then  $x = a // b = 0$ , thus one of the statements is true. Now consider the case where  $a \neq 0$ . By the trichotomy of integers,  $a$  can be either positive or negative. Similarly,  $b$  can also be either positive or negative (it cannot be null, by definition). Thus, there are four main cases:

- $a > 0$  and  $b > 0$ . Here, by Definition 4.2.6,  $x = a // b$  is positive.
- $a > 0$  and  $b < 0$ . Here,  $b = -m$ , with  $m$  a positive natural number. Thus,  $x = a // (-m)$ . But  $a // (-m) = (-a) // m$  (this is easy to verify:  $am = (-a)(-m)$ ). This means that  $x = (-a) // m$ , with both  $a$  and  $m$  positive, i.e.  $x$  is negative.
- $a < 0$  and  $b > 0$ . Here,  $x = a // b$  is negative by Definition 4.2.6.
- $a < 0$  and  $b < 0$ . Here, we can say that  $a = -n$  and  $b = -m$ , with  $n, m$  positive natural numbers. Thus,  $x = (-n) // (-m) = n // m$  (once again, this latest equality is easy to verify). Thus,  $x$  is positive.

Conclusion: if all four cases, at least one of the three properties is true.

2. Now prove that at most one of those statements is true.

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<sup>11</sup>We use implicitly here the fact that  $(nm) // n = m // 1$  for all integers  $n, m$  with  $m \neq 0$ , which is straightforward to prove.

- Suppose, for the sake of contradiction, that we have both  $x = 0$  and  $x$  positive. On the one hand, “ $x = a // b = 0$ ” implies that  $a = 0$  (see Terence Tao’s remark, page 83). On the other hand, “ $x$  is positive” implies that  $a > 0$ . So we would have both  $a = 0$  and  $a$  positive, which is not compatible with the trichotomy of integers.
- A similar argument holds if we suppose both  $x = 0$  and  $x$  negative.
- Now suppose that we have both  $x$  positive and  $x$  negative, i.e.  $x = c // d = (-n) // m$ , with  $c, d, n, m$  positive natural numbers. Thus, we should have  $cm = (-n)d$ . On the one hand,  $cm$  is positive, as the multiplication of two positive natural numbers. On the other hand,  $(-n)d = -(nd)$  is negative. The equality  $cm = -nd$  is thus impossible.

Conclusion: all three statements are mutually exclusive.

EXERCISE 4.2.5. — *Prove Proposition 4.2.9.*

Let  $x, y, z$  be rational numbers. This proposition includes the following statements:

1. Prove that exactly one of the three statements  $x = y$ ,  $x < y$ , or  $x > y$  is true.

This statement is very close to Lemma 4.2.7, proved in the previous exercise. Let’s consider the rational number  $x - y$ . According to the trichotomy of rationals, this number can be either zero, positive or negative (exactly one of these statements is true).

If  $x - y = 0$ , then  $x = y$ . If  $x - y$  is positive, then  $x > y$ . And if  $x - y$  is negative, then  $x < y$ . Thus, the order trichotomy is a direct consequence of the ordering of rationals.

2. Prove that one has  $x < y$  if and only if  $y > x$ .

Since  $x < y$ , the rational number  $x - y$  is negative, and can be written  $(-a) // b$  for positive integers  $a, b$ . And since  $x - y = -a // b$ , we have  $a // b = y - x$ , i.e.  $y - x$  is positive, i.e.  $y > x$ .

3. Prove that if  $x < y$  and  $y < z$ , then  $x < z$ .

Since  $x < y$ ,  $x - y$  is negative. Similarly,  $y - z$  is negative. This means that  $x - y$  can be written  $(-a) // b$ , and  $y - z$  can be written  $(-c) // d$ , with  $a, b, c, d$  positive integers.

On the one hand, their sum is  $x - z$ . On the other hand, their sum is  $((-ad) + (-cb)) // (bd)$ . This latest expression is a negative rational, thus we have  $x < z$ .

4. Prove that if  $x < y$ , then  $x + z < y + z$ .

Suppose that  $x < y$ . Thus,  $x - y$  is negative. But we have, for any rational  $z$ ,  $x - y = (x + z) - (y + z)$ , and thus this latter expression is also negative. This means that  $x + z < y + z$ .

5. Prove that if  $x < y$  and  $z$  is positive, then  $xz < yz$ .

Since  $x < y$ , the rational number  $x - y$  is negative. Furthermore, we know (by Proposition 4.2.4) that  $xz - yz = (x - y)z$ . In the expression  $(x - y)z$ ,  $z$  is supposed to

be positive and  $x - y$  is negative, thus their product is negative<sup>12</sup>. This means that  $xz < yz$ .

EXERCISE 4.2.6. — *Show that if  $x, y, z$  are rational numbers such that  $x < y$  and  $z$  is negative, then  $xz > yz$ .*

If  $x < y$ , then  $x - y$  is negative. Thus,  $(x - y)z$  is the product of two negative rationals: it is a positive rational<sup>13</sup>.

But  $(x - y)z = xz - yz$  by Proposition 4.2.4. And since we have showed that this number is positive, we have  $xz > yz$ .

Note: in particular, this exercise says that if  $x > y$ , then  $-x < -y$  (with  $z = -1$ ).

EXERCISE 4.3.1. — *Prove Proposition 4.3.3.*

Let  $x, y, z$  be rational numbers. The statements to prove are the following:

1. Show that  $|x| \geq 0$  for all  $x$ , and that  $|x| = 0$  iff  $x = 0$ .

There are three cases:

- if  $x = 0$ , then  $|x| := 0$ , thus we have in particular  $|x| \geq 0$ .
- if  $x > 0$ , then  $|x| := x$ , thus  $|x| > 0$ . And in particular, this means that  $|x| \geq 0$ .
- if  $x < 0$ , then  $|x| := -x$ , thus  $|x| > 0$ . And in particular,  $|x| \geq 0$ .

We can note that the only case where  $|x| = 0$  is when  $x = 0$ . Thus, by trichotomy of rationals,  $|x| = 0$  iff  $x = 0$ .

2. Show that  $|x + y| \leq |x| + |y|$ .

- If  $x = 0$  or  $y = 0$ , this is immediate.
- If  $x > 0$  and  $y > 0$ ,  $x + y$  is positive, thus  $|x + y| = x + y = |x| + |y|$ .
- If  $x < 0$  and  $y < 0$ ,  $x + y$  is negative, thus  $|x + y| = -(x + y) = -x - y$ . On the other hand,  $|x| + |y| = -x - y$ .
- Finally, the case where  $x$  and  $y$  are of opposite signs. Say that  $x$  is positive and  $y$  negative, but they are exchangeable. On the one hand,  $|x| + |y| = x - y > 0$ . On the other hand,  $|x + y|$  can be either equal to  $x + y$  if  $x + y > 0$ , i.e. if  $x > -y$ ; or equal to  $-x - y$  if  $x + y < 0$ , i.e. if  $x < -y$ .

In the first case, since  $-y < 0 < y$  by hypothesis, we have  $|x + y| = x + y < x - y = |x| + |y|$ .

In the second case, since  $-x < 0 < x$  by hypothesis, we have  $|x + y| = -x - y < x - y = |x| + |y|$ .

Conclusion: in all cases, we have indeed  $|x + y| \leq |x| + |y|$ .

<sup>12</sup>This is never explicitly mentioned in the book. However, using Exercise 4.1.3, we know that for every integer  $a$ , we have  $-a = (-1) \times a$ . So let's consider the product  $n(-m)$  where  $n, m$  are positive integers: this product is  $(-1)nm = -(nm)$ , and thus is negative.

<sup>13</sup>Similarly, if  $x$  and  $y$  are negative, then  $-x$  and  $-y$  are positive, and their product  $(-x)(-y) = (-1)(-1)xy = xy$  is positive by definition. This can also be deduced from Proposition 4.2.9(e), by choosing  $x = 0$ .

3. Show that  $-y \leq x \leq y$  iff  $y \geq |x|$ . (Thus, in particular,  $-|x| \leq x \leq |x|$ .)

- First suppose that  $y \geq |x|$ . Note that, whatever could be the value of  $x$ , we have necessarily  $y \geq 0$  according to the first point of this exercise. Now we can split into three cases.

If  $x = 0$  then  $y \geq 0$  and the claim is immediate.

If  $x > 0$ , then  $|x| = x$ , and the part  $y \geq x$  is immediate. Furthermore, the other part  $-y \leq x$  is also immediate since  $-y$  is negative and  $x$  is positive.

If  $x < 0$ , then  $|x| = -x$ , thus we have  $y \geq -x$ , i.e.  $-y \leq x$  according to Exercise 4.2.6. Additionally, the part  $x \leq y$  is immediate since  $x$  is negative and  $y$  is positive.

- Conversely, suppose that  $-y \leq x \leq y$ . If  $x \geq 0$ , then  $|x| = x$ , thus the rightmost inequality gives  $x = |x| \leq y$ . In the other case, if  $x < 0$ , then  $|x| = -x$ . The leftmost inequality  $-y \leq x$  leads (according to Exercise 4.2.6) to  $y \geq -x$ , i.e.  $y \geq |x|$ .

4. Show that  $|xy| = |x| \times |y|$ . (In particular,  $|-x| = |x|$ .)

Once again, we can split into several cases, as in the second point of this exercise.

- If  $x = 0$  or  $y = 0$ , both sides of the equality are zero (cf. the first point of this exercise), thus the claim is immediate.
- If  $x > 0$  and  $y > 0$ , the product  $xy$  is also positive. Thus,  $|xy| = xy$ , and  $|x| \times |y| = xy$ , and the claim follows.
- If  $x < 0$  and  $y < 0$ , then the product  $xy$  is positive, and  $|xy| = xy$ . On the other hand,  $|x| \times |y| = (-x)(-y) = xy$ , and the claim follows.
- If  $x$  and  $y$  are of opposite signs (say  $x$  positive and  $y$  negative, but they are exchangeable), then  $xy$  is negative, and  $|xy| = -xy$ . On the other hand,  $|x| \times |y| = -xy$ , thus the claim follows.

5. Show that  $d(x, y) \leq 0$  for all  $x, y$ , and that  $d(x, y) = 0$  iff  $x = y$ .

We have  $d(x, y) = |x - y| \geq 0$  according to the first point of this exercise. Furthermore, still according to the first point,  $d(x, y) = |x - y| = 0$  iff  $x - y = 0$ , i.e.  $x = y$ .

6. Show that  $d(x, y) = d(y, x)$ .

We have  $d(x, y) = |x - y|$  and  $d(y, x) = |y - x|$  by definition. But  $|y - x| = |-(x - y)| = |x - y|$  according to the fourth point of this exercise.

7. Show that  $d(x, z) = d(x, y) + d(y, z)$ .

We have  $d(x, z) = |x - z| = |(x - y) + (y - z)| \leq |x - y| + |y - z|$  according to the second point of this exercise. The claim follows.

EXERCISE 4.3.2. — *Prove the remaining claims in Proposition 4.3.7.*

Let  $x, y, z, w$  be rational numbers.

1. If  $x = y$ , then  $d(x, y) = 0$  according to Proposition 4.3.3(e). Thus,  $d(x, y) \leq \varepsilon$  for any positive number  $\varepsilon$ .

Conversely, suppose that  $d(x, y) \leq \varepsilon$  for any  $\varepsilon > 0$ , and let's prove that  $x = y$ . Suppose, for the sake of contradiction, that  $x \neq y$ ; and let be  $\varepsilon = |x - y|/2$ . Since  $x \neq y$ , we have  $|x - y| > 0$ , thus  $\varepsilon$  is a positive number. Furthermore,  $d(x, y) = \varepsilon + \varepsilon$ , thus  $d(x, y) > \varepsilon$ , which is a contradiction.

2. This is a direct consequence from Proposition 4.3.3(f). Indeed, since  $d(x, y) = d(y, x)$ , we obviously have  $d(y, x) \leq \varepsilon$  when  $d(x, y) \leq \varepsilon$ .
3. Suppose that  $d(x, y) \leq \varepsilon$  and  $d(y, z) \leq \delta$ . Thus, by triangle inequality,  $d(x, z) \leq d(x, y) + d(y, z) \leq \varepsilon + \delta$ .
4. Suppose that  $d(x, y) \leq \varepsilon$  and  $d(z, w) \leq \delta$ . Thus,

$$\begin{aligned} d(x + z, y + w) &= |(x + z) - (y + w)| \\ &= |(x - y) + (z - w)| \\ &\leq |x - y| + |z - w| \\ &\leq \varepsilon + \delta \end{aligned}$$

which means that  $x + z$  and  $y + w$  are  $(\varepsilon + \delta)$ -close.

Similarly,  $d(x - z, y - w) = |(x - y) + (w - z)|$ , and using just the symmetry of distance, we can conclude that  $x - z$  and  $y - w$  are  $(\varepsilon + \delta)$ -close according to the previous result.

5. This is clear: we have  $d(x, y) \leq \varepsilon < \varepsilon'$ .
6. Since  $d(x, y) \leq \varepsilon$ , we have  $-\varepsilon \leq y - x \leq \varepsilon$ . Similarly, we have  $-\varepsilon \leq z - x \leq \varepsilon$ .  
 $y$  and  $z$  are exchangeable here, so we can suppose that  $y \leq w \leq z$ . From this inequality, we can get  $y - x \leq w - x \leq z - x$ . Extending this with the former inequalities, we have:

$$-\varepsilon \leq y - x \leq w - x \leq z - x \leq \varepsilon$$

and in particular  $-\varepsilon \leq w - x \leq \varepsilon$ , which means  $d(w, x) \leq \varepsilon$ .

7. We have  $d(x, y) = |x - y| \leq \varepsilon$ . Since  $z$  is positive, we have  $|z| > 0$ , thus  $|x - y||z| \leq \varepsilon|z|$ . But according to Proposition 4.3.3(d),  $|x - y|z = |(x - y)z| = |xz - yz|$ . Thus,  $|xz - yz| \leq \varepsilon|z|$ , i.e.,  $xz$  and  $yz$  are  $\varepsilon|z|$ -close.

EXERCISE 4.3.3. — *Prove Proposition 4.3.10.*

Let  $x, y$  be rationals, and  $n, m$  be natural numbers. The claims to prove are the following (they are re-ordered and re-numbered here):

1. Show that  $x^n x^m = x^{n+m}$ . We induct on  $n$  while keeping  $m$  fixed.

For the base case  $n = 0$ , we have on the one hand  $x^n x^m = x^0 x^m = 1 \cdot x^m = x^m$ . On the other hand,  $x^{n+m} = x^{0+m} = x^m$ . Thus, both sides are equal, and the base case is done.

Now suppose that  $x^n x^m = x^{n+m}$ , and let's show that  $x^{n+1} x^m = x^{(n+1)m}$ . We have:

$$\begin{aligned}
x^{n+1} x^m &= (x^n x) x^m && \text{(by Definition 4.3.9)} \\
&= x^n x^m x && \text{(by associativity and commutativity of multiplication)} \\
&= x^{n+m} x && \text{(by induction hypothesis)} \\
&= x^{n+m+1} && \text{(by Definition 4.3.9 once again)}
\end{aligned}$$

This closes the induction.

2. Show that  $(xy)^n = x^n y^n$ . Let's induct on  $n$ . The base case  $n = 0$  is obvious, since both sides are equal to 1. Now suppose inductively that  $(xy)^n = x^n y^n$ . Thus we have:

$$\begin{aligned}
(xy)^{n+1} &= (xy)^n (xy) && \text{(by Definition 4.3.9)} \\
&= x^n y^n xy && \text{(by inductive hypothesis)} \\
&= x^n xy^n y && \text{(by commutativity of multiplication)} \\
&= x^{n+1} y^{n+1} && \text{(by Definition 4.3.9 once again)}
\end{aligned}$$

3. Show that  $(x^n)^m = x^{nm}$ . We induct on  $n$  while keeping  $m$  fixed.

For the base case  $n = 0$ , we have  $(x^n)^m = 1^m = 1$ , since  $1^m = 1$  for all natural number  $m$ <sup>14</sup>. On the other hand,  $x^{nm} = x^{0m} = 1$ . Thus, both sides are equal, and the base case is done.

Now suppose inductively that  $(x^n)^m = x^{nm}$ . Then we have:

$$\begin{aligned}
(x^{n+1})^m &= (x^n x)^m && \text{(by Definition 4.3.9)} \\
&= (x^n)^m x^m && \text{(proved in 2. from this exercise)} \\
&= x^{nm} x^m && \text{(by inductive hypothesis)} \\
&= x^{nm+m} && \text{(proved in 1. from this exercise)} \\
&= x^{(n+1)m}
\end{aligned}$$

This closes the induction.

4. Show that if  $n > 0$ , then  $x^n = 0$  iff  $x = 0$ . For that, let's induct on  $n$ . Here the base case starts with  $n = 1$  since we suppose  $n > 0$ . For  $n = 1$ ,  $x^1 = x$ , thus we obviously have  $x^1 = 0 \Leftrightarrow x = 0$  since both objects are equal.

Now suppose inductively that  $x^n = 0$  iff  $x = 0$ . We must show that  $x^{n+1} = 0$  iff  $x = 0$ . Here we'll need the following lemma:

**Lemma.** *Let  $x, y$  be rational numbers. Then, if  $xy = 0$ , we have either  $x = 0$  or  $y = 0$ .*

*Proof.* Let's denote  $x = a // b$  and  $y = c // d$ . By Definition 4.2.2,  $xy = (ac) // (bd)$ . Thus, since  $xy = 0$ , we have  $ac = 0$  (see Tao's remark p. 83). And, by Proposition 4.1.8, we have either  $a = 0$  or  $c = 0$ . In the first case, this means that  $x = 0$ ; in the second case this means that  $y = 0$ .  $\square$

Now go back to the main proof. First, if  $x = 0$ , we have  $x^{n+1} = x^n x = 0^n \times 0 = 0$ . Conversely, if  $x^{n+1} = 0$ , then  $x^n x = 0$ . According to the previous lemma, this means that either  $x^n = 0$  or  $x = 0$ . In the second case, we are done. In the first case, the induction hypothesis also allows to conclude that  $x^n = 0$ . This closes the induction.

<sup>14</sup>This can easily be proved by induction, which we'll not write formally here.

5. Show that if  $x \geq y \geq 0$ , then  $x^n \geq y^n \geq 0$ . Let's induct on  $n$ .

For the base case  $n = 0$ ,  $x^0 = y^0 = 1$ . Thus in particular we have indeed  $x^0 \geq y^0 \geq 0$ .

Now suppose inductively that  $x^n \geq y^n \geq 0$ , and show that  $x^{n+1} \geq y^{n+1} \geq 0$ . We start from  $x^n \geq y^n \geq 0$  and multiply all terms by  $x$  (which preserves inequality since  $x$  is supposed to be positive): we get  $x^{n+1} \geq xy^n \geq 0$ . If we start from  $x \geq y \geq 0$  and multiply all terms by  $y^n$  (which is also positive by induction hypothesis), we get  $y^n x \geq y^{n+1} \geq 0$ . Now combine all those inequalities:

$$x^{n+1} \geq xy^n \geq y^{n+1} \geq 0$$

This closes the induction.

6. Show that  $|x^n| = |x|^n$ . Let's induct on  $n$ .

For the base case  $n = 0$ , we have  $|x^n| = |x^0| = |1| = 1$ ; and  $|x|^n = |x|^0 = 1$ . Thus both sides are equal, and the base case is done.

Now suppose that  $|x^n| = |x|^n$  and show that  $|x^{n+1}| = |x|^{n+1}$ . We have:

$$\begin{aligned} |x^{n+1}| &= |x^n x| && \text{(by Definition 4.3.9)} \\ &= |x^n| \cdot |x| && \text{(by Proposition 4.3.3d)} \\ &= |x|^n \cdot |x| && \text{(by inductive hypothesis)} \\ &= |x|^{n+1} \end{aligned}$$

This closes the induction.

EXERCISE 4.3.4. — *Prove Proposition 4.3.12.*

This is essentially the same exercise as 4.3.3, but dealing with integer exponents (instead of natural exponents). The claims to prove are the following (and once again, they are re-labeled):

1. Prove that  $x^n x^m = x^{n+m}$ . Let's distinguish three cases:

- If  $n, m \geq 0$ , then this is simply Proposition 4.3.10(a).
- If  $n, m < 0$ , then  $n = -p$  and  $m = -q$  with  $p, q$  positive natural numbers. Thus,  $x^n x^m = (1/x^p) \cdot (1/x^q) = 1/(x^p x^q)$  by Definition 4.2.2. But since  $p, q$  are positive, this is also equal to  $1/(x^{p+q})$  according to Proposition 4.3.10(a). This can also be written  $x^{-(p+q)}$  by Definition 4.3.11, which is finally equal to  $x^{n+m}$ .
- If  $n \geq 0$  and  $m < 0$  (or inversely, since they are exchangeable), then  $m = -q$  with  $q$  a positive natural number. Thus,  $x^n x^m = x^n \times (1/x^q) = x^n/x^q$ . We will (once again) split into two cases:
  - if  $n \geq -m$ , i.e. if  $n - q \geq 0$ , then we can note that  $x^{n-q} \cdot x^q = x^n$  according to Proposition 4.3.10(a). Thus, let's multiply both sides of this equality by  $x^{-q}$  to get  $x^{n-q} = x^n x^{-q}$ ; which can be rewritten  $x^{n+m} = x^n x^m$  as required.
  - if  $n < -m$ , i.e.  $q - n > 0$ , then we can note that  $x^{q-n} x^n = x^q$  according to Proposition 4.3.10(a). Also, since  $n - q < 0$ , according to Definition 4.3.11, we have  $x^{n-q} = 1/x^{q-n}$ . Let's multiply both sides by  $1/x^n$ , to get  $x^{n-q}/x^n = 1/(x^{q-n} x^n) = 1/x^q = x^{-q}$ . Finally, multiply both sides by  $x^n$  to get  $x^{n+m} = x^n x^m$ .



2. Prove that  $(x^n)^m = x^{nm}$ .
3. Show that  $(xy)^n = x^n y^n$ . If  $n \geq 0$ , this is simply Proposition 4.3.10(a). So let's consider the case  $n < 0$ . In this case,  $n = -p$ , with  $p$  a positive natural number. Thus we have successively:

$$\begin{aligned}
 (xy)^n &= (xy)^{-p} \\
 &= 1/(xy)^p && \text{(by Definition 4.3.11)} \\
 &= 1/(x^p y^p) && \text{(Proposition 4.3.10(a))} \\
 &= 1/(x^p) \times 1/(y^p) && \text{(Definition 4.2.2)} \\
 &= x^{-p} \times y^{-p} && \text{(by Definition 4.3.11)} \\
 &= x^n \times y^n
 \end{aligned}$$

4. Show that if  $x \geq y > 0$ , then  $x^n \geq y^n > 0$  if  $n$  is positive, and  $0 < x^n \leq y^n$  if  $n$  is negative.

- If  $n > 0$ , according to Proposition 4.3.10(c), we already have  $x^n \geq y^n \geq 0$ , so that we just have to show that the rightmost inequality is strict, i.e. that  $y^n > 0$ . To show that, we only need to prove  $y^n \neq 0$ . For the sake of contradiction, let's suppose that  $y^n = 0$ . Our starting hypothesis was  $x \geq y > 0$ , thus we know that  $y \neq 0$ . According to Proposition 4.3.10(b), we can't have both  $y \neq 0$  and  $y^n = 0$ , this is a contradiction. Thus, we indeed have  $y^n \neq 0$ , which shows the inequality  $x^n \geq y^n > 0$  as required.
- If  $n < 0$ , this includes an important result, which is that taking the inverse reverses order. Indeed, let's begin by proving that if  $x \geq y > 0$ , then  $1/x \leq 1/y$ . Since both  $x$  and  $y$  are positive, their product  $xy$  is also positive, and  $1/(xy)$  is also positive. Following Proposition 4.2.9(e), we can multiply both sides of  $x \geq y$  by  $1/(xy)$  to get  $1/y \geq 1/x$ . Then, we immediately get  $(1/y)^p \geq (1/x)^p$  for any positive number  $p$  by Proposition 4.3.10(c), which can be rewritten  $y^n \geq x^n$  with  $n = -p$  negative. And since both numbers are positive (because  $x$  and  $y$  are positive), the claim follows.

5. Prove that if  $x, y > 0$  and  $n \neq 0$ , then  $x^n = y^n \implies x = y$ . Let's consider two cases:  $n > 0$  and  $n < 0$ .

First, if  $n > 0$ , suppose for the sake of contradiction that we have both  $x^n = y^n$  and  $x \neq y$ . According to the trichotomy of rationals (Lemma 4.2.7), this last claim means that we have either  $x > y$  or  $y > x$ . Since  $x$  and  $y$  are exchangeable, we only prove the first case here,  $x > y$ . In this case, Proposition 4.3.10(c) leads to  $x^n > y^n$ , which is obviously not compatible with our initial hypothesis  $x^n = y^n$ . A similar contradiction follows in the case  $y > x$ . Thus, both  $x > y$  and  $y > x$  are impossible, and the only possibility is  $x = y$ .

Now, if  $n < 0$ , then  $n = -p$ , with  $p$  a positive natural number. Suppose that  $x^n = y^n$ , i.e. that  $x^{-p} = y^{-p}$ , or finally  $1/x^p = 1/y^p$ . From this last equality, by multiplying both sides by  $x^p y^p$ , we get  $y^p = x^p$ . We are thus back in the previous case, and obtain  $x = y$ .

6. Prove that  $|x^n| = |x|^n$ . If  $n \geq 0$ , this is simply Proposition 4.3.10(d). So let's consider the case  $n < 0$ . We'll need a quick lemma:

**Lemma.** For all rationals  $x \neq 0$ , we have  $|1/x| = 1/|x|$ .

*Proof.* If  $x > 0$ , there is nothing to show. If  $x < 0$ , then  $1/x$  is also negative<sup>15</sup>. Thus,  $1/|x| = 1/(-x)$ ; and  $|1/x| = -(1/x)$ . And we have clearly  $1/(-x) = -(1/x)$  because  $1/(-x) + 1/x = 0$ .  $\square$

In this case,  $n = -p$ , with  $p$  a positive natural number. We have successively:

$$\begin{aligned}
 |x^n| &= |x^{-p}| \\
 &= |1/(x^p)| && \text{(by Definition 4.3.11)} \\
 &= |(1/x)^p| && \text{(Proposition 4.3.12(a))} \\
 &= |1/x|^p && \text{(Proposition 4.3.10(d))} \\
 &= (|1/|x||)^p && \text{(lemma introduced just above)} \\
 &= 1/|x|^p && \text{(Proposition 4.3.12(a))} \\
 &= |x|^{-p} && \text{(Definition 4.3.11)} \\
 &= |x|^n
 \end{aligned}$$

EXERCISE 4.3.5. — Prove that  $2^N \geq N$  for all positive integers  $N$ .

Let's use induction on  $N$ . Since we only consider positive integers, we have here  $N \geq 1$ , and in particular, the base case starts at  $N = 1$ .

For the base case  $N = 1$ , the assertion is true, since we have indeed  $2^1 \geq 1$ .

Now suppose inductively that  $2^N \geq N$ , and show that  $2^{N+1} \geq N + 1$ . We have  $2^{N+1} = 2^N \times 2 \geq N \times 2$  by induction hypothesis. But we know that  $2N = N + N$  (recall Definition 2.3.1 for instance), thus we can rewrite this as  $2^{N+1} \geq N + N$ . And since  $N \geq 1$ , we finally get  $2^{N+1} \geq N + 1$ .

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<sup>15</sup>Formally, see Definition 4.2.6, and note that  $a // (-b) = (-a) // b$  if  $a$  and  $b$  are positive integers.