

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

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## 1. Introduction

No exercises in this chapter.

## 2. 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 proven, 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.