

Solutions for
Analysis I&II (Forth Edition)
by Terence Tao

Ilia Koloiarov

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Chapter 1

Introduction

No exercises in this chapter.

Chapter 2

Starting at the beginning: the natural numbers

2.1 The Peano axioms

Axiom 2.1. *0 is a natural number.*

Axiom 2.2. *If n is a natural number, then $n++$ is also a natural number.*

Axiom 2.3. *0 is not the successor of any natural number; i.e., we have $n++ \neq 0$ for every natural number n .*

Axiom 2.4. *Different natural numbers must have different successors; i.e., if n, m are natural numbers and $n \neq m$, then $n++ \neq m++$. Equivalently, if $n++ = m++$, then we must have $n = m$.*

Axiom 2.5. (Principle of mathematical induction). *Let $P(n)$ be any property pertaining to a natural number n . Suppose that $P(0)$ is true, and suppose that whenever $P(n)$ is true, $P(n++)$ is also true. Then $P(n)$ is true for every natural number n .*

Definition 2.1.3. *We define 1 to be the number $0++$, 2 to be the number $(0++)++$, etc.*

Proposition 2.1.4. *3 is a natural number.*

Proof. Given the Axiom 2.1, 0 is a natural number. $1 := 0++$ is a natural number by Axiom 2.2. Same as $2 := 1++$ and $3 := 2++$. \square

Proposition 2.1.6. *4 is not equal to 0.*

Proof. By Definition 2.1.3, $4 := 3++$, thus $3++ \stackrel{\neq}{=} 0$ what contradicts Axiom 2.3 \square

Proposition 2.1.8. *6 is not equal to 2*

Proof. Let's assume that $6 = 2$. By Definition 2.1.3, $6 = 5++$ and $2 = 1++$. That means, $5 = 1$ by Axiom 2.4. Repeating the procedure, we end up with $4 \stackrel{\neq}{=} 0$ what contradicts previously proven Proposition 2.1.6 \square

Lemma 2.1.8.a. *For any natural number n , $n \neq n++$.*

Proof. For the base case, $0 \neq 0++$ by Axiom 2.3. For the step case, we need to prove if $n \neq n++$, then $n++ \neq (n++)++$. Let's assume that $n++ = (n++)++$. Then by Axiom 2.4, $n \stackrel{\neq}{=} n++$, what contradicts the inductive hypothesis. Now we have closed the induction. \square

Proposition 2.1.16. *(Recursive definitions). Suppose for each natural number n , we have some function $f_n : \mathbb{N} \rightarrow \mathbb{N}$ from the natural numbers to the natural numbers. Let c be a natural number. Then we can assign a unique natural number to each natural number n , such that $a_0 = c$ and $a_{n++} = f_n(a_n)$ for each natural number n .*

Proof. First, none of a_n redefines a_0 by Axiom 2.3. Second, let's assume that the procedure gives the unique value for a_n . Then it also provides the unique value for a_{n++} by Axiom 2.4 what closes the induction. \square

2.2 Addition

Definition 2.2.1. (*Addition of natural numbers*). Let m be a natural number. To add zero to m , we define $0 + m := m$. Now suppose inductively that we have defined how to add n to m . Then we can add $n++$ to m by defining $(n++) + m := (n + m)++$.

Proposition 2.2.1.a. *The sum of two natural numbers is again a natural number.*

Proof. We induct on n . Using Definition 2.2.1, $0 + m := m$ is a natural number by the proposition's assumption. Let's assume that $n + m$ is a natural number. Then $(n++) + m := (n + m)++$ by Definition 2.2.1 and $(n + m)++$ is a natural number by Axiom 2.2. That closes the induction. \square

Lemma 2.2.2. *For any natural number n , $n + 0 = n$.*

Proof. Guess what, we use induction. Given that 0 is a natural number and Definition 2.2.1, $0 + 0 := 0$ what proves the base case. Let's assume that $n + 0 := n$, then $(n++) + 0 := (n + 0)++$ using Definition 2.2.1, and $(n + 0)++ = n++$ by the induction assumption what proves the step case. That closes the induction. \square

Lemma 2.2.3. *For any natural numbers n and m , $n + (m++) = (n + m)++$.*

Proof. Let's induct on n . To prove the base case, $0 + (m++) := m++ := (0 + m)++$ using Definition 2.2.1. For the step case, we need to prove $(n++) + (m++) = ((n++) + m)++$. Let's assume $n + (m++) = (n + m)++$, then

$$\begin{aligned} (n++) + (m++) &:= (n + (m++))++ && \text{Definition 2.2.1} \\ &= ((n + m)++)++ && \text{Inductive Hypothesis} \\ &= ((n++) + m)++ && \text{Definition 2.2.1} \end{aligned}$$

What closes the induction. \square

Corollary 2.2.3.a. *For any natural number n , $n++ = n + 1$.*

Proof. The base case:

$$\begin{aligned} 0++ &= (0 + 0)++ && \text{Definition 2.2.1} \\ &= 0 + (0++) && \text{Lemma 2.2.3} \\ &= 0 + 1 && \text{Definition 2.1.3} \end{aligned}$$

For the step case, we need to prove $(n++)++ = (n++) + 1$, assuming $n++ = n + 1$:

$$\begin{aligned}
(n++)++ &= ((n+0)++)++ && \text{Definition 2.2.1} \\
&= (n+0++)++ && \text{Lemma 2.2.3} \\
&= (n+1)++ && \text{Definition 2.1.3} \\
&= (n++) + 1 && \text{Definition 2.2.1}
\end{aligned}$$

□

Proposition 2.2.4. (Addition is commutative). *For any natural numbers n and m , $n + m = m + n$.*

Proof. Let's (again) induct on n . For the base case we need to prove $0 + m = m + 0$. The left term equals to m by Definition 2.2.1. The right term equals also to m by Lemma 2.2.2. Thus, both terms are equal. For the step case, we need to prove $(n++) + m = m + (n++)$, assuming $n + m = m + n$:

$$\begin{aligned}
(n++) + m &= (n + m)++ && \text{Definition 2.2.1} \\
&= (m + n)++ && \text{Inductive Hypothesis} \\
&= (m + (n++)) && \text{Lemma 2.2.3}
\end{aligned}$$

What closes the induction.

□

Proposition 2.2.5. (Addition is associative). *For any natural numbers a, b, c , we have $(a + b) + c = a + (b + c)$.*

Proof. Let's induct on a . For the base case, we need to prove

$$\begin{aligned}
(0 + b) + c &= 0 + (b + c) \\
\text{Definition 2.2.1} \quad b + c &= b + c \quad \text{Lemma 2.2.2}
\end{aligned}$$

For the step case, we need to prove $((a++) + b) + c = (a++) + (b + c)$, assuming $(a + b) + c = a + (b + c)$:

$$\begin{aligned}
((a++) + b) + c &= ((a + b)++) + c && \text{Definition 2.2.1} \\
&= ((a + b) + c)++ && \text{Definition 2.2.1} \\
&= (a + (b + c))++ && \text{Inductive Hypothesis} \\
&= (a++) + (b + c) && \text{Definition 2.2.1}
\end{aligned}$$

what closes the induction.

□

Proposition 2.2.6. (Cancellation Law). *Let a, b, c be natural numbers such $a + b = a + c$. Then we have $b = c$.*

Proof. Let's induct on a . The base case, we need to prove $0 + b = 0 + c$ what leads to $b = c$ by Definition 2.2.1. For the step case, we need to prove if $(a++) + b = (a++) + c$, assuming $a + b = a + c$, then $b = c$.

$$\begin{array}{ll}
 (a++) + b = (a++) + c & \\
 (a + b)++ = (a + c)++ & \text{Definition 2.2.1} \\
 (a + b) = (a + c) & \text{Axiom 2.4} \\
 b = c & \text{Inductive Hypothesis}
 \end{array}$$

□

Definition 2.2.7. (Positive natural numbers). *A natural number n is said to be positive iff it is not equal to 0.*

Proposition 2.2.8. *If a is positive and b is a natural number, then $a + b$ is positive.*

Proof. Let's induct on b . For the base case, $a + 0 = a$ by Definition 2.2.1. The result is positive by the propositional assumption. For the step case, we need to prove $a + (b++)$ is positive, assuming $a + b$ is positive. $a + (b++) = (a + b)++$ by Lemma 2.2.3. Given Axiom 2.3, $(a + b)++$ is positive as well, what closes the induction. □

Corollary 2.2.9. *If a and b are natural numbers such that $a + b = 0$, then $a = 0$ and $b = 0$.*

Proof. Let's assume that $a \neq 0$ and induct on b . For the base case, we'll need to prove $a + 0 = 0$. The left term equals to a by Lemma 2.2.2, what contradicts our assumption $a \neq 0$. Doing the same for b , we'll end up with the same outcome. What leads to the conclusion that a and b must be both 0. □

Lemma 2.2.10. *Let a be a positive number. Then there exists exactly one natural number b such that $b++ = a$.*

Proof. Suppose for sake of contradiction, there is another natural number c such that $c++ = a$. Then $b++ = c++$, what makes $b = c$ by Axiom 2.4. □

Definition 2.2.11. (Ordering of the natural numbers). Let n and m be natural numbers. We say that n is greater than or equal to m , and write $n \geq m$ or $m \leq n$, iff we have $n = m + a$ for some natural number a . We say that n is strictly greater than m , and write $n > m$ or $m < n$, iff $n \geq m$ and $n \neq m$.

Lemma 2.2.11.a. *For any natural number n , $n++ > n$.*

Proof. For any natural number, we know that $n++ = n + 1$ from Corollary 2.2.3.a. Then using the fact that $n \neq n++$ from Lemma 2.1.8.a, we can conclude $n++ > n$ by Definition 2.2.11. \square

Proposition 2.2.12. (Basic properties of order for natural numbers). Let a, b, c be natural numbers. Then

Proposition 2.2.12.a. (Order is reflexive) $a \geq a$.

Proof. Any natural number a can be represented $a = a + 0$ using Lemma 2.2.2 what proves by Definition 2.2.11 that $a \geq a$. \square

Proposition 2.2.12.b. (Order is transitive) *If $a \geq b$ and $b \geq c$, then $a \geq c$.*

Proof. Given Definition 2.2.11 and the propositional assumption, b can be represented as $c + \tilde{c}$ and a can be represented as $b + \tilde{b}$ where \tilde{b} and \tilde{c} are natural numbers. Then combining both representations, $a = b + \tilde{b} = (c + \tilde{c}) + \tilde{b} = c + (\tilde{c} + \tilde{b})$ using Proposition 2.2.5. $\tilde{c} + \tilde{b}$ is a natural number by Proposition 2.2.1.a what leads us to $a \geq c$ by Definition 2.2.11. \square

Proposition 2.2.12.c. (Order is antisymmetric) $a \geq b$ and $b \geq a$ iff $a = b$.
(Original) *if $a \geq b$ and $b \geq a$, then $a = b$.*

Proof. The forward pass: by the propositional assumption and Definition 2.2.11, $a = b + \tilde{b}$ and $b = a + \tilde{a}$. Combining both terms, $a = b + \tilde{a} = (a + \tilde{a}) + \tilde{a}$ what equals to $a + (\tilde{a} + \tilde{a})$ using Proposition 2.2.5. Recalling Cancellation Law from Proposition 2.2.6, $(\tilde{a} + \tilde{a})$ must be equal to 0 since $a = a + 0$ by Definition 2.2.1. By Corollary 2.2.9, $\tilde{a} = 0$. Plugging it back to $b = a + \tilde{a} = a + 0 = a$.

The reverse pass: if $a = b$, then $a \geq b$ and $b \geq a$. If $a = b$, we can use the reflexivity of order from Proposition 2.2.12.a to transform $a \geq a$ and $b \geq b$ to $a \geq b$ and $b \geq a$ respectively. That closes the proof in both directions. \square

Proposition 2.2.12.d. (Addition preserves order) $a \geq b$ if and only if $a + c \geq b + c$.

Proof. Let's start with the true case: if $a \geq b$, then $a + c \geq b + c$. If $a \geq b$, then we can represent $a = b + \tilde{b}$ by Definition 2.2.11. Plugging the expression into $a + c$ results in $(b + \tilde{b}) + c$. Using Proposition 2.2.5 and Proposition 2.2.4, we can transform the expression into $(b + c) + \tilde{b}$ what proves $a + c \geq b + c$ by Definition 2.2.11.

Now the false case: if $a < b$, then $a + c < b + c$. If $a < b$, then $b = a + \tilde{a}$ and $b \neq a$ by Definition 2.2.11. Using the expression in $b + c$ results in $(a + \tilde{a}) + c$. Again using Propositions 2.2.5 and 2.2.4, we end up with $(a + c) + \tilde{a}$, what proves $b + c \geq a + c$ by Definition 2.2.11. Now we need to show that $(a + c) \neq (b + c)$. Let's assume they are equal. Then by Cancellation Law from Proposition 2.2.6, we can get rid of c , what results in $a \stackrel{!}{=} b$. That contradicts the antecedent $a < b$, from which we know that $a \neq b$. Thus, $a + c < b + c$, what closes the proof for all cases. \square

Proposition 2.2.12.e. *$a < b$ if and only if $b = a + (d++)$ for any natural number d .*

Proof. For the true case we need to prove that if $a < b$, then $b = a + d$ and $d \neq 0$. If $a < b$, then $b = a + d$ and $b \neq a$ by Definition 2.2.11. Let's assume that d is not a positive natural number (i.e. $d = 0$). Then $a + d = a + 0 = a \stackrel{!}{=} b$ by the antecedent $b \neq a$.

For the false case, we need to prove that if $a \geq b$, then $b \neq a + d$ or $d = 0$. If $a \geq b$, then $a = b + d$ and d is a natural number (including zero) by Definition 2.2.11, what contradicts $d = 0$. That closes both cases. \square

Proposition 2.2.12.f. *$a < b$ if and only if $a++ \leq b$.*

Proof. For true case, we need to prove if $a++ \leq b$, then $a < b$. Combining Definition 2.2.11 and associativity from Proposition 2.2.5, we can infer $b = (a++) + d = a + (d++)$ where $d++$ is a positive natural number by Axiom 2.3 and Definition 2.2.7. Thus, we can conclude that $b > a$ by Proposition 2.2.12.e.

For the false case, we need to prove if $a++ > b^1$, then $a \geq b$. If $a++ > b$, then $a++ = b + (d++) = (b + d)++$ using Proposition 2.2.12.e and Definition 2.2.1, where $d++$ is a positive number by Axiom 2.3. Then by Axiom 2.4, we can infer $a = b + d$ what proves $a \geq b$ by Definition 2.1.3. \square

Proposition 2.2.13. (Trichotomy of order for natural numbers). *Let a and b be natural numbers. Then exactly one of the following statements is true: $a < b, a = b, a > b$.*

¹Do we need to prove that this is the false case of $a++ \leq b$?

Proof. Let's start that **no more than one** statement holds at a time. If $a = b$, then neither $a < b$ nor $a > b$ holds by Definition 2.2.11. If $a > b$ and $a < b$, then by Definition 2.2.11, $a \geq b$, $a \leq b$ and $a \neq b$. If $a \geq b$ and $a \leq b$, then $a \stackrel{!}{=} b$ using Proposition 2.2.12.c, what contradicts the antecedent. Thus, no more than one statement holds at a time.

Now let's prove that there is **at least one** statement holds inducting on a . For the base case, b can be represented as $b = 0 + b$ by Definition 2.2.1, what makes it $0 \leq b$ by Definition 2.2.11. For the step case, suppose that one of the trichotomy statements holds for a . We need to prove whether any holds for $a++$. If $a < b$, then $a++ \leq b$ by Proposition 2.2.12.f. If $a = b$, then $a++ > b$ by Lemma 2.2.11.a. If $a > b$, then $a = b + (d++)$ by Proposition 2.2.12.e. Then we can take the successor $a++ = (b + (d++))++$ by Axiom 2.4, what equals to $b + (d++)++$ by Definition 2.2.1. $(d++)++$ is a positive number by Definition 2.2.7 and Axiom 2.3. Thus, $a++ > b$ still holds by Proposition 2.2.12.e. That covers all possible cases and closes the induction. \square

Proposition 2.2.14. (Strong principle of induction). *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 $n \geq m_0$, we have the following implication: if $P(m)$ is true for all natural numbers $m_0 \leq m < n$, then $P(n)$ 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 $P(n)$ is true for all natural numbers $m \geq m_0$.*

Proof. Let's define $Q(n) \iff (m_0 \leq m < n \implies P(m))$. We'll induct on n . Although it's not necessary, but I'd like to state the base case explicitly. For the base case $Q(m_0)$, $m_0 \leq m \leq m_0$ and $m \neq m_0$ by Definition 2.2.11. Since $m_0 \leq m$ and $m_0 \geq m$, we can conclude that $m_0 \stackrel{!}{=} m$ by Proposition 2.2.12.c, what contradicts our antecedent of $m \neq m_0$. Thus, the inductive hypothesis is vacuous, and the implication holds for all cases.

For the step case, suppose that $Q(n)$ and $Q(n) \implies P(n)$, then $P(n), \forall m_0 \leq m \leq n < n++$ and $m \neq n$. Which is equivalent to $m_0 \leq n < n++, P(n)$ what is by definition $Q(n++)$. Now we have closed the induction by Axiom 2.5. \square

Appendix A

The basics of mathematical logic

A.1 Mathematical statements

Exercise A.1.1. *What is the negation of the statement “either X is true or Y is true, but not both”?*

Solution. X and Y are false or X and Y are true. □

Exercise A.1.2. *What is the negation of the statement “ X is true if and only if Y is true”?*

Solution. “ X is false iff Y is false” □

Exercise A.1.3. *Suppose that you have shown that whenever X is true, then Y is true, and whenever X is false, then Y is false. Have you demonstrated that X and Y are logically equivalent? Explain.*

Solution. I assume, yes. A **well-defined** statement can be either true or false only (all possible values). Now, we consider the assumptions: (1) if X is false, then Y is false (Y is never true in that case), and (2) if X is true, then Y is false (Y is never true here). Thus, both statements coincide in all possible values what makes them “equivalent”. □

Exercise A.1.4. *Suppose that you have shown that X is true iff Y is true, and you know that Y is true iff Z is true. Is this enough to show that X, Y, Z are logically equivalent? Explain.*

Solution. Yes. We know that the pairs (X, Y) and (Y, Z) are logically equivalent, but we don’t know whether X and Z are equivalent. If X is true/false, then Y is true/false, and if Y is true/false, then Z is also true/false. We can also prove the same, but going from left to right ($X \rightarrow Y \rightarrow Z$) and from right-to-left ($Z \rightarrow Y \rightarrow X$). □

Exercise A.1.5. *Suppose that you have shown that whenever X is true, then Y is true; that if Y is true, then Z is true; and if Z is true, then X is true. Is this enough to show that X, Y, Z are logically equivalent? Explain.*

Solution. Yes, for all pairs of statements, we can construct the following. Let’s start at X . (Forward direction) If X is true, then Y is also true. (Reverse direction) If Y is true, then Z is also true, and if Z is true, then X is also true. That closes the cycle in both ways for all pairs, thus the statements logically equivalent. □

A.2 Implication

The main ideas in the chapter are the following:

- Vacuous hypothesis is a hypothesis where an antecedent is false. Since false implies false/true is always true, it does not provide any new information.
- We can also draw the following conclusions:

$X \implies Y \iff \neg Y \implies \neg X$	Contrapositive
$X \implies Y \not\iff Y \implies X$	Converse
$X \implies Y \not\iff \neg X \implies \neg Y$	Inverse

- Although, vacuous hypothesis can be viewed as “useless”, it can still be used for a proof by contradiction, for instance. For that case, we need to have a consequent that is known to be false.

A.3 The structure of proofs

Appendix B

The decimal system