

Understanding Analysis Solutions

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Notation

I will sometimes use notation and terminology that differ from Abbott's choices. I will try to collect these differences here; please refer back to this section if you are unfamiliar with a term I have used.

Functions

Suppose $f : A \rightarrow B$ is a function. If $a_1 \neq a_2$ in A implies that $f(a_1) \neq f(a_2)$ in B , then I will refer to f as injective or as an injection. Abbott uses the term one-to-one (1-1); both injective and one-to-one are common terms for this property of a function.

If given any $b \in B$ there exists an $a \in A$ such that $f(a) = b$, then I will refer to f as surjective or as a surjection. Abbott uses the term onto; both surjective and onto are common terms for this property of a function.

If f is both injective and surjective, then I will refer to f as bijective, or a bijection. Abbott simply calls such a function 1-1 and onto.

Chapter 1

The Real Numbers

1.2 Some Preliminaries

Exercise 1.2.1. (a) Prove that $\sqrt{3}$ is irrational. Does the same argument work to show that $\sqrt{6}$ is irrational?

(b) Where does the proof of Theorem 1.1.1 break down if we try to use it to prove $\sqrt{4}$ is irrational?

Solution. (a) Suppose there was a rational number $p = \frac{m}{n}$, which we may assume is in lowest terms, such that $p^2 = 3$. Then $m^2 = 3n^2$, so that m^2 is divisible by 3. This implies that m is divisible by 3. To see this, observe that for any $k \in \mathbf{Z}$ we have

$$(3k + 1)^2 = 3(3k^2 + 2k) + 1 \quad \text{and} \quad (3k + 2)^2 = 3(3k^2 + 4k + 1) + 1.$$

Since m is of the form $3k + 1$ or $3k + 2$ for some integer k if m is not divisible by 3, it follows that

if m is not divisible by 3, then m^2 is not divisible by 3;

the contrapositive of this statement is what we wanted to see.

Thus we may write $m = 3k$ for some $k \in \mathbf{Z}$ and substitute this into the equation $m^2 = 3n^2$ to obtain the equation $n^2 = 3k^2$, which implies that n is also divisible by 3. So m and n share the factor 3; this is a contradiction since we assumed that m and n had no common factors. We may conclude that there is no rational number whose square is 3.

The same argument works to show that there is no rational number whose square is 6; the crux of this argument is the implication

if m^2 is divisible by 6, then m is divisible by 6.

This can be seen using what we have already proved. If m^2 is divisible by $6 = 2 \cdot 3$, then m^2 is divisible by 2 and 3. It follows that m is divisible by 2 and 3 and hence that m is divisible by 6.

(b) The argument breaks down when we try to assert that

if m^2 is divisible by 4, then m is divisible by 4.

This implication is false. For example, $2^2 = 4$ is divisible by 4 but 2 is not divisible by 4.

Exercise 1.2.2. Show that there is no rational number r satisfying $2^r = 3$.

Solution. Suppose there was a rational number $r = \frac{m}{n}$, which we may assume is in lowest terms with $n > 0$, such that $2^r = 3$. This implies that $2^m = 3^n$. Since $n > 0$ gives $3^n \geq 3$ and $2^m < 2$ for $m \leq 0$, it must be the case that $m > 0$. Then the left-hand side of the equation $2^m = 3^n$ is a positive even integer whereas the right-hand side is a positive odd integer, which is a contradiction. We may conclude that there is no rational number r such that $2^r = 3$.

Exercise 1.2.3. Decide which of the following represent true statements about the nature of sets. For any that are false, provide a specific example where the statement in question does not hold.

- (a) If $A_1 \supseteq A_2 \supseteq A_3 \supseteq A_4 \cdots$ are all sets containing an infinite number of elements, then the intersection $\bigcap_{n=1}^{\infty} A_n$ is infinite as well.
- (b) If $A_1 \supseteq A_2 \supseteq A_3 \supseteq A_4 \cdots$ are all finite, nonempty sets of real numbers, then the intersection $\bigcap_{n=1}^{\infty} A_n$ is finite and nonempty.
- (c) $A \cap (B \cup C) = (A \cap B) \cup C$.
- (d) $A \cap (B \cap C) = (A \cap B) \cap C$.
- (e) $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$.

Solution. (a) This is false, as Example 1.2.2 shows.

(b) This is true and we can use the following lemma to prove it.

Lemma L.1. If $(a_n)_{n=1}^{\infty}$ is a decreasing sequence of positive integers, i.e., $a_{n+1} \leq a_n$ and $a_n \geq 1$ for all $n \in \mathbf{N}$, then $(a_n)_{n=1}^{\infty}$ must be eventually constant. That is, there exists an $N \in \mathbf{N}$ such that $a_n = a_N$ for all $n > N$.

Proof. Let A be the set $\{a_n : n \in \mathbf{N}\}$, which is non-empty and bounded below by 1. It follows from the [well-ordering principle](#) that A has a least element, say $\min A = a_N$ for some $N \in \mathbf{N}$. Let $n > N$ be given. It cannot be the case that $a_n < a_N$, since this would contradict that a_N is the least element of A , so we must have $a_n \geq a_N$. By assumption $a_n \leq a_N$ and so we may conclude that $a_n = a_N$. \square

Consider the sequence $(|A_n|)_{n=1}^{\infty}$, where $|A_n|$ is the number of elements contained in A_n . This is a sequence of positive integers, because each A_n is finite and non-empty, and furthermore this sequence is decreasing because the sets $(A_n)_{n=1}^{\infty}$ are nested:

$$A_1 \supseteq A_2 \supseteq A_3 \supseteq A_4 \supseteq \cdots.$$

We may now invoke [Lemma L.1](#) to obtain an $N \in \mathbf{N}$ such that $|A_n| = |A_N|$ for all $n > N$. Combining this equality with the inclusion $A_n \subseteq A_N$ for each $n > N$, we see that $A_n = A_N$ for all $n > N$. It follows that $\bigcap_{n=1}^{\infty} A_n = A_N$, which by assumption is finite and non-empty.

(c) This is false. Consider $A = B = \emptyset$ and $C = \{0\}$. Then

$$A \cap (B \cup C) = \emptyset \neq \{0\} = (A \cap B) \cup C.$$

(d) This is true, since

$$\begin{aligned} x \in A \cap (B \cap C) &\iff x \in A \text{ and } x \in (B \cap C) \iff x \in A \text{ and } (x \in B \text{ and } x \in C) \\ &\iff (x \in A \text{ and } x \in B) \text{ and } x \in C \iff x \in (A \cap B) \text{ and } x \in C \iff x \in (A \cap B) \cap C, \end{aligned}$$

where we have used that [logical conjunction \(“and”\) is associative](#) for the third equivalence. It follows that x belongs to $A \cap (B \cap C)$ if and only if x belongs to $(A \cap B) \cap C$, which is to say that $A \cap (B \cap C) = (A \cap B) \cap C$.

(e) This is true, since

$$\begin{aligned}
 x \in A \cap (B \cup C) &\iff x \in A \text{ and } x \in (B \cup C) \iff x \in A \text{ and } (x \in B \text{ or } x \in C) \\
 &\iff (x \in A \text{ and } x \in B) \text{ or } (x \in A \text{ and } x \in C) \iff x \in (A \cap B) \text{ or } x \in (A \cap C) \\
 &\iff x \in (A \cap B) \cup (A \cap C),
 \end{aligned}$$

where we have used that **logical conjunction (“and”) distributes over logical disjunction (“or”)** for the third equivalence. It follows that x belongs to $A \cap (B \cup C)$ if and only if x belongs to $(A \cap B) \cup (A \cap C)$, which is to say that $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$.

Exercise 1.2.4. Produce an infinite collection of sets A_1, A_2, A_3, \dots with the property that every A_i has an infinite number of elements, $A_i \cap A_j = \emptyset$ for all $i \neq j$, and $\bigcup_{i=1}^{\infty} A_i = \mathbf{N}$.

Solution. Arrange \mathbf{N} in a grid like so:

| A_1 | A_2 | A_3 | A_4 | \dots |
|----------|----------|----------|----------|----------|
| 1 | 3 | 6 | 10 | \dots |
| 2 | 5 | 9 | 14 | \dots |
| 4 | 8 | 13 | 19 | \dots |
| 7 | 12 | 18 | 25 | \dots |
| \vdots | \vdots | \vdots | \vdots | \ddots |

Now take A_i to be the set of numbers appearing in the i^{th} column.

Exercise 1.2.5 (De Morgan’s Laws). Let A and B be subsets of \mathbf{R} .

- (a) If $x \in (A \cap B)^c$, explain why $x \in A^c \cup B^c$. This shows that $(A \cap B)^c \subseteq A^c \cup B^c$.
- (b) Prove the reverse inclusion $(A \cap B)^c \supseteq A^c \cup B^c$, and conclude that $(A \cap B)^c = A^c \cup B^c$.
- (c) Show $(A \cup B)^c = A^c \cap B^c$ by demonstrating inclusion both ways.

Solution. (a) Observe that

$$\begin{aligned}
 x \in (A \cap B)^c &\iff x \notin A \cap B \iff \text{not } (x \in A \text{ and } x \in B) \\
 &\iff x \notin A \text{ or } x \notin B \iff x \in A^c \cup B^c.
 \end{aligned}$$

(b) See part (a).

(c) The proof is similar to the one given in parts (a) and (b):

$$\begin{aligned} x \in (A \cup B)^c &\iff x \notin A \cup B \iff \text{not } (x \in A \text{ or } x \in B) \\ &\iff x \notin A \text{ and } x \notin B \iff x \in A^c \cap B^c. \end{aligned}$$

Exercise 1.2.6. (a) Verify the triangle inequality in the special case where a and b have the same sign.

(b) Find an efficient proof for all the cases at once by first demonstrating $(a+b)^2 \leq (|a|+|b|)^2$.

(c) Prove $|a-b| \leq |a-c| + |c-d| + |d-b|$ for all a, b, c , and d .

(d) Prove $||a| - |b|| \leq |a-b|$. (The unremarkable identity $a = a - b + b$ may be useful.)

Solution. (a) First suppose that a and b are both non-negative, so that $a+b$ is also non-negative; it follows that $|a+b| = a+b$ and $|a|+|b| = a+b$. Thus the triangle inequality in this case reduces to the evidently true statement $a+b \leq a+b$.

Now suppose that a and b are both negative, so that $a+b$ is also negative; it follows that $|a+b| = -a-b$ and $|a|+|b| = -a-b$. Thus the triangle inequality in this case reduces to the evidently true statement $-a-b \leq -a-b$.

(b) Starting from the true statement $ab \leq |ab|$ and using that $a^2 = |a|^2$ and $|ab| = |a||b|$ for any real numbers a and b , observe that

$$\begin{aligned} 2ab \leq 2|ab| &\iff a^2 + 2ab + b^2 \leq |a|^2 + 2|a||b| + |b|^2 \\ &\iff (a+b)^2 \leq (|a|+|b|)^2 \iff |a+b|^2 \leq (|a|+|b|)^2. \end{aligned}$$

Because both $|a+b|$ and $|a|+|b|$ are non-negative, the inequality $|a+b|^2 \leq (|a|+|b|)^2$ is equivalent to $|a+b| \leq |a|+|b|$, as desired.

(c) We apply the triangle inequality twice:

$$|a-b| = |a-c+c-b| \leq |a-c| + |c-b| \leq |a-c| + |c-d| + |d-b|.$$

(d) Using the triangle inequality and the fact that $|-a| = |a|$ for any $a \in \mathbf{R}$, we find that

$$|a| = |a-b+b| \leq |a-b| + |b| \iff |a| - |b| \leq |a-b|,$$

$$|b| = |b - a + a| \leq |b - a| + |a| = |a - b| + |a| \iff |b| - |a| \leq |a - b|.$$

Since $||a| - |b||$ equals either $|a| - |b|$ or $|b| - |a|$, it follows that $||a| - |b|| \leq |a - b|$.

Exercise 1.2.7. Given a function f and a subset A of its domain, let $f(A)$ represent the range of f over the set A ; that is, $f(A) = \{f(x) : x \in A\}$.

- (a) Let $f(x) = x^2$. If $A = [0, 2]$ (the closed interval $\{x \in \mathbf{R} : 0 \leq x \leq 2\}$) and $B = [1, 4]$, find $f(A)$ and $f(B)$. Does $f(A \cap B) = f(A) \cap f(B)$ in this case? Does $f(A \cup B) = f(A) \cup f(B)$?
- (b) Find two sets A and B for which $f(A \cap B) \neq f(A) \cap f(B)$.
- (c) Show that, for an arbitrary function $g : \mathbf{R} \rightarrow \mathbf{R}$, it is always true that $g(A \cap B) \subseteq g(A) \cap g(B)$ for all sets $A, B \subseteq \mathbf{R}$.
- (d) Form and prove a conjecture about the relationship between $g(A \cup B)$ and $g(A) \cup g(B)$ for an arbitrary function g .

Solution. (a) Some straightforward calculations reveal that

$$\begin{aligned} f(A) &= [0, 4], & f(A \cap B) &= f([1, 2]) = [1, 4], & f(A \cup B) &= f([0, 4]) = [0, 16], \\ f(B) &= [1, 16], & f(A) \cap f(B) &= [1, 4], & f(A) \cup f(B) &= [0, 16]. \end{aligned}$$

From this we see that $f(A \cap B) = f(A) \cap f(B)$ and $f(A \cup B) = f(A) \cup f(B)$.

- (b) Let $A = \{-1\}$ and $B = \{1\}$. Then $f(A \cap B) = f(\emptyset) = \emptyset$ but

$$f(A) \cap f(B) = \{1\} \cap \{1\} = \{1\} \neq \emptyset.$$

- (c) Observe that

$$\begin{aligned} y \in g(A \cap B) &\iff y = g(x) \text{ for some } x \in A \cap B \\ \implies (y = g(x_1) \text{ for some } x_1 \in A) \text{ and } (y = g(x_2) \text{ for some } x_2 \in B) \\ \iff y \in g(A) \text{ and } y \in g(B) &\iff y \in g(A) \cap g(B). \end{aligned}$$

It follows that y belongs to $g(A) \cap g(B)$ whenever y belongs to $g(A \cap B)$, which is to say that $g(A \cap B) \subseteq g(A) \cap g(B)$.

(d) We always have $g(A \cup B) = g(A) \cup g(B)$; indeed,

$$\begin{aligned}
 y \in g(A \cup B) &\iff y = g(x) \text{ for some } x \in A \cup B \\
 &\iff y = g(x) \text{ for some } x \text{ such that } (x \in A \text{ or } x \in B) \\
 &\iff (y = g(x_1) \text{ for some } x_1 \in A) \text{ or } (y = g(x_2) \text{ for some } x_2 \in B) \\
 &\iff y \in g(A) \text{ or } y \in g(B) \iff y \in g(A) \cup g(B).
 \end{aligned}$$

It follows that $g(A \cup B) = g(A) \cup g(B)$.

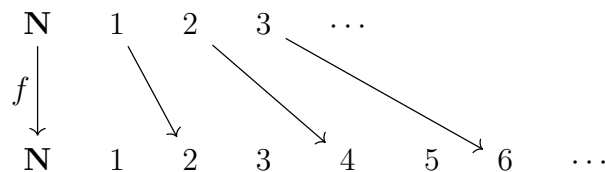
Exercise 1.2.8. Here are two important definitions related to a function $f : A \rightarrow B$. The function f is *one-to-one* (1-1) if $a_1 \neq a_2$ in A implies that $f(a_1) \neq f(a_2)$ in B . The function f is *onto* if, given any $b \in B$, it is possible to find an element $a \in A$ for which $f(a) = b$.

Give an example of each or state that the request is impossible:

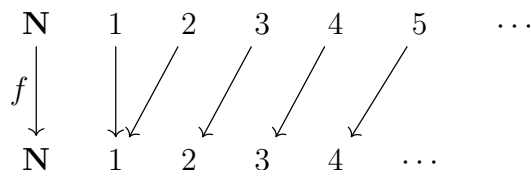
- (a) $f : \mathbf{N} \rightarrow \mathbf{N}$ that is 1-1 but not onto.
- (b) $f : \mathbf{N} \rightarrow \mathbf{N}$ that is onto but not 1-1.
- (c) $f : \mathbf{N} \rightarrow \mathbf{Z}$ that is 1-1 and onto.

Solution. (I much prefer the terms injective/surjective/bijective rather than one-to-one and onto; see [notation](#). I will use these terms throughout this document.)

- (a) Let $f : \mathbf{N} \rightarrow \mathbf{N}$ be given by $f(n) = 2n$. Then f is injective since $n = m$ if and only if $2n = 2m$, but f is not surjective since the range of f contains only even numbers.



- (b) Let $f : \mathbf{N} \rightarrow \mathbf{N}$ be given by $f(1) = 1$ and $f(n) = n - 1$ for $n \geq 2$. Then $f(n + 1) = n$ for any $n \in \mathbf{N}$, so that f is surjective, but f is not injective since $f(1) = f(2) = 1$.



(c) Let $f : \mathbf{N} \rightarrow \mathbf{Z}$ be given by

$$f(n) = \begin{cases} \frac{n}{2} & \text{if } n \text{ is even,} \\ -\frac{n-1}{2} & \text{if } n \text{ is odd.} \end{cases}$$

| | | | | | | |
|----------------|--------------|--------------|--------------|--------------|--------------|-----|
| \mathbf{N} | 1 | 2 | 3 | 4 | 5 | ... |
| $f \downarrow$ | \downarrow | \downarrow | \downarrow | \downarrow | \downarrow | |
| \mathbf{Z} | 0 | 1 | -1 | 2 | -2 | ... |

To see that f is injective, let $n \neq m$ be given and consider these cases.

Case 1. If n and m are both even, then $f(n) \neq f(m)$ since $n \neq m$ if and only if $\frac{n}{2} \neq \frac{m}{2}$.

Case 2. If n and m are both odd, then $f(n) \neq f(m)$ since $n \neq m$ if and only if $-\frac{n-1}{2} \neq -\frac{m-1}{2}$.

Case 3. If n and m have opposite signs, say n is even and m is odd, then $f(n) \neq f(m)$ since $f(n) > 0$ and $f(m) \leq 0$.

To see that f is surjective, let $n \in \mathbf{Z}$ be given. If $n > 0$, then $f(2n) = n$, and if $n \leq 0$ then $f(-2n + 1) = n$.

Exercise 1.2.9. Given a function $f : D \rightarrow \mathbf{R}$ and a subset $B \subseteq \mathbf{R}$, let $f^{-1}(B)$ be the set of all points from the domain D that get mapped into B ; that is, $f^{-1}(B) = \{x \in D : f(x) \in B\}$. This set is called the *preimage* of B .

- Let $f(x) = x^2$. If A is the closed interval $[0, 4]$ and B is the closed interval $[-1, 1]$, find $f^{-1}(A)$ and $f^{-1}(B)$. Does $f^{-1}(A \cap B) = f^{-1}(A) \cap f^{-1}(B)$ in this case? Does $f^{-1}(A \cup B) = f^{-1}(A) \cup f^{-1}(B)$?
- The good behavior of preimages demonstrated in (a) is completely general. Show that for an arbitrary function $g : \mathbf{R} \rightarrow \mathbf{R}$, it is always true that $g^{-1}(A \cap B) = g^{-1}(A) \cap g^{-1}(B)$ and $g^{-1}(A \cup B) = g^{-1}(A) \cup g^{-1}(B)$ for all sets $A, B \subseteq \mathbf{R}$.

Solution. (a) Some straightforward calculations reveal that

$$\begin{aligned} f^{-1}(A) &= [-2, 2], & f^{-1}(A \cap B) &= [-1, 1], & f^{-1}(A \cup B) &= [-2, 2], \\ f^{-1}(B) &= [-1, 1], & f^{-1}(A) \cap f^{-1}(B) &= [-1, 1], & f^{-1}(A) \cup f^{-1}(B) &= [-2, 2]. \end{aligned}$$

From this we see that $f^{-1}(A \cap B) = f^{-1}(A) \cap f^{-1}(B)$ and $f^{-1}(A \cup B) = f^{-1}(A) \cup f^{-1}(B)$.

(b) Observe that

$$\begin{aligned} x \in g^{-1}(A \cap B) &\iff g(x) \in A \cap B \iff (g(x) \in A) \text{ and } (g(x) \in B) \\ &\iff (x \in g^{-1}(A)) \text{ and } (x \in g^{-1}(B)) \iff x \in g^{-1}(A) \cap g^{-1}(B). \end{aligned}$$

Similarly,

$$\begin{aligned} x \in g^{-1}(A \cup B) &\iff g(x) \in A \cup B \iff (g(x) \in A) \text{ or } (g(x) \in B) \\ &\iff (x \in g^{-1}(A)) \text{ or } (x \in g^{-1}(B)) \iff x \in g^{-1}(A) \cup g^{-1}(B). \end{aligned}$$

Exercise 1.2.10. Decide which of the following are true statements. Provide a short justification for those that are valid and a counterexample for those that are not:

- (a) Two real numbers satisfy $a < b$ if and only if $a < b + \epsilon$ for every $\epsilon > 0$.
- (b) Two real numbers satisfy $a < b$ if $a < b + \epsilon$ for every $\epsilon > 0$.
- (c) Two real numbers satisfy $a \leq b$ if and only if $a < b + \epsilon$ for every $\epsilon > 0$.

Solution. (a) This is false; the implication

$$\text{if } a < b + \epsilon \text{ for every } \epsilon > 0, \text{ then } a < b$$

does not hold. The problem occurs when we consider the case where $a = b$. For example, we certainly have $1 < 1 + \epsilon$ for every $\epsilon > 0$ but of course $1 < 1$ is false.

(b) See part (a).

(c) This is true. The implication

$$\text{if } a \leq b, \text{ then } a < b + \epsilon \text{ for every } \epsilon > 0$$

follows since $a \leq b < b + \epsilon$ for every $\epsilon > 0$ and the implication

$$\text{if } a > b, \text{ then } a \geq b + \epsilon \text{ for some } \epsilon > 0$$

can be seen by taking $\epsilon = a - b > 0$, so that $b + \epsilon = a \leq a$.

Exercise 1.2.11. Form the logical negation of each claim. One trivial way to do this is to simply add “It is not the case that...” in front of each assertion. To make this interesting, fashion the negation into a positive statement that avoids using the word “not” altogether. In each case, make an intuitive guess as to whether the claim or its negation is the true statement.

- (a) For all real numbers satisfying $a < b$, there exists an $n \in \mathbf{N}$ such that $a + 1/n < b$.
- (b) There exists a real number $x > 0$ such that $x < 1/n$ for all $n \in \mathbf{N}$.
- (c) Between every two distinct real numbers there is a rational number.

Solution. (a) The negated statement is:

there exist real numbers $a < b$ such that $a + \frac{1}{n} \geq b$ for all $n \in \mathbf{N}$.

The original statement is true and follows from the Archimedean Property (Theorem 1.4.2).

- (b) The negated statement is:

for all $x > 0$, there exists an $n \in \mathbf{N}$ such that $\frac{1}{n} \leq x$.

The negated statement is true and again follows from the Archimedean Property (Theorem 1.4.2).

- (c) The negated statement is:

there are two distinct real numbers with no rational number between them.

The original statement is true; this is the density of \mathbf{Q} in \mathbf{R} (Theorem 1.4.3).

Exercise 1.2.12. Let $y_1 = 6$, and for each $n \in \mathbf{N}$ define $y_{n+1} = (2y_n - 6)/3$.

- (a) Use induction to prove that the sequence satisfies $y_n > -6$ for all $n \in \mathbf{N}$.
- (b) Use another induction argument to show the sequence (y_1, y_2, y_3, \dots) is decreasing.

Solution. (a) For $n \in \mathbf{N}$, let $P(n)$ be the statement that $y_n > -6$. Since $y_1 = 6$, the truth of $P(1)$ is clear. Suppose that $P(n)$ holds for some $n \in \mathbf{N}$ and observe that

$$y_{n+1} = \frac{2}{3}y_n - 2 > \frac{2}{3}(-6) - 2 = -6,$$

i.e., $P(n+1)$ holds. This completes the induction step and we may conclude that $P(n)$ holds for all $n \in \mathbf{N}$.

- (b) For $n \in \mathbf{N}$, let $P(n)$ be the statement that $y_{n+1} \leq y_n$. Since $y_1 = 6$ and $y_2 = 2$, the truth of $P(1)$ is clear. Suppose that $P(n)$ holds for some $n \in \mathbf{N}$ and observe that

$$y_{n+2} = \frac{2}{3}y_{n+1} - 2 \leq \frac{2}{3}y_n - 2 = y_{n+1},$$

i.e., $P(n+1)$ holds. This completes the induction step and we may conclude that $P(n)$ holds for all $n \in \mathbf{N}$.

Exercise 1.2.13. For this exercise, assume [Exercise 1.2.5](#) has been successfully completed.

- (a) Show how induction can be used to conclude that

$$(A_1 \cup A_2 \cup \cdots \cup A_n)^c = A_1^c \cap A_2^c \cap \cdots \cap A_n^c$$

for any finite $n \in \mathbf{N}$.

- (b) It is tempting to appeal to induction to conclude that

$$\left(\bigcup_{i=1}^{\infty} A_i \right)^c = \bigcap_{i=1}^{\infty} A_i^c,$$

but induction does not apply here. Induction is used to prove that a particular statement holds for every value of $n \in \mathbf{N}$, but this does not imply the validity of the infinite case. To illustrate this point, find an example of a collection of sets B_1, B_2, B_3, \dots where $\bigcap_{i=1}^n B_i \neq \emptyset$ is true for every $n \in \mathbf{N}$, but $\bigcap_{i=1}^{\infty} B_i \neq \emptyset$ fails.

- (c) Nevertheless, the infinite version of De Morgan's Law stated in (b) is a valid statement. Provide a proof that does not use induction.

Solution. (a) For $n \in \mathbf{N}$, let $P(n)$ be the statement that $(A_1 \cup \cdots \cup A_n)^c = A_1^c \cap \cdots \cap A_n^c$ for any sets A_1, \dots, A_n . The truth of $P(1)$ is clear. Suppose that $P(n)$ holds for some $n \in \mathbf{N}$, let A_1, \dots, A_n, A_{n+1} be given, and observe that

$$\begin{aligned} (A_1 \cup \cdots \cup A_n \cup A_{n+1})^c &= ((A_1 \cup \cdots \cup A_n) \cup (A_{n+1}))^c \\ &= (A_1 \cup \cdots \cup A_n)^c \cap A_{n+1}^c && \text{(Exercise 1.2.5)} \\ &= A_1^c \cap \cdots \cap A_n^c \cap A_{n+1}^c, && \text{(induction hypothesis)} \end{aligned}$$

i.e., $P(n+1)$ holds. This completes the induction step and we may conclude that $P(n)$ holds for all $n \in \mathbf{N}$.

(b) Let $B_i = \{i, i+1, i+2, \dots\}$, so that

$$B_1 = \{1, 2, 3, \dots\}, \quad B_2 = \{2, 3, 4, \dots\}, \quad B_3 = \{3, 4, 5, \dots\}, \quad \text{etc.}$$

It is straightforward to verify that $\bigcap_{i=1}^n B_i = B_n \neq \emptyset$ for any $n \in \mathbf{N}$; however, as Example 1.2.2 shows, the intersection $\bigcap_{i=1}^{\infty} B_i$ is empty.

(c) Observe that

$$x \in \left(\bigcup_{i=1}^{\infty} A_i \right)^c \iff x \notin \bigcup_{i=1}^{\infty} A_i \iff x \notin A_i \text{ for every } i \in \mathbf{N} \iff x \in \bigcap_{i=1}^{\infty} A_i^c.$$

It follows that

$$\left(\bigcup_{i=1}^{\infty} A_i \right)^c = \bigcap_{i=1}^{\infty} A_i^c.$$

1.3 The Axiom of Completeness

Exercise 1.3.1. (a) Write a formal definition in the style of Definition 1.3.2 for the *infimum* or *greatest lower bound* of a set.

(b) Now, state and prove a version of Lemma 1.3.8 for greatest lower bounds.

Solution. (a) A real number t is the *greatest lower bound* for a set $A \subseteq \mathbf{R}$ if it meets the following two criteria:

- (i) t is a lower bound for A ;
- (ii) if b is any lower bound for A , then $b \leq t$.

(b) Here is a version of Lemma 1.3.8 for greatest lower bounds.

Lemma L.2. Assume $t \in \mathbf{R}$ is a lower bound for a set $A \subseteq \mathbf{R}$. Then $t = \inf A$ if and only if, for every choice of $\epsilon > 0$, there exists an element $a \in A$ satisfying $a < t + \epsilon$.

Proof. First, let us prove the implication

$$\text{if } t = \inf A, \text{ then for every } \epsilon > 0 \text{ there exists an } a \in A \text{ such that } a < t + \epsilon$$

by proving the contrapositive statement

if there exists an $\epsilon > 0$ such that $t + \epsilon \leq a$ for every $a \in A$ then $t \neq \inf A$.

If such an $\epsilon > 0$ exists, then $t + \epsilon$ is a lower bound for A strictly greater than t ; it follows that t is not the greatest lower bound for A , i.e., $t \neq \inf A$.

Now let us prove the converse:

if for every $\epsilon > 0$ there exists an $a \in A$ such that $a < t + \epsilon$, then $t = \inf A$.

Suppose $b \in \mathbf{R}$ is such that $b > t$. Taking $\epsilon = b - t > 0$, by assumption we are guaranteed the existence of an $a \in A$ such that $a < t + \epsilon = b$. Thus b is not a lower bound for A ; this proves the contrapositive of criterion (ii) in part (a) and we may conclude that $t = \inf A$. \square

Exercise 1.3.2. Give an example of each of the following, or state that the request is impossible.

- (a) A set B with $\inf B \geq \sup B$.
- (b) A finite set that contains its infimum but not its supremum.
- (c) A bounded subset of \mathbf{Q} that contains its supremum but not its infimum.

Solution. (a) Take $B = \{0\}$, so that $\inf B = \sup B = 0$.

- (b) This is impossible. To see this, let us first use induction to show that any non-empty finite subset of \mathbf{R} contains a minimum and a maximum element.

Lemma L.3. If $E \subseteq \mathbf{R}$ is non-empty and finite, then E contains a minimum and a maximum element.

Proof. For $n \in \mathbf{N}$, let $P(n)$ be the statement that any subset of \mathbf{R} containing n elements has a minimum and a maximum element. For the base case $P(1)$, simply observe that $\min\{x\} = \max\{x\} = x$ for any $x \in \mathbf{R}$.

Suppose that $P(n)$ holds for some $n \in \mathbf{N}$ and let $E \subseteq \mathbf{R}$ be a set containing $n + 1$ elements. Fix some $x \in E$ and consider the set $F = E \setminus \{x\}$, which contains n elements. Our induction hypothesis guarantees the existence of a minimum element $a := \min F$ and a maximum element $b := \max F$, which must satisfy $a \leq b$. There are then three cases; the conclusion in each case is straightforward to verify.

Case 1. If $x < a$, then $\min E = x$ and $\max E = b$.

Case 2. If $x > b$, then $\min E = a$ and $\max E = x$.

Case 3. If $a \leq x \leq b$, then $\min E = a$ and $\max E = b$.

In any case, the set E has a minimum and a maximum element, i.e., $P(n+1)$ holds. This completes the induction step and the proof. \square

It is immediate from the definition of the supremum and the maximum of a set $E \subseteq \mathbf{R}$ that if $\max E$ exists then $\sup E = \max E$ (see [Exercise 1.3.7](#)); similarly, if $\min E$ exists then $\inf E = \min E$. It follows that the given request is impossible: if $E \subseteq \mathbf{R}$ is finite, then [Lemma L.3](#) implies that $\min E = \inf E$ and $\max E = \sup E$ both exist and hence E contains both its infimum and its supremum.

- (c) Consider the bounded set $E = \{p \in \mathbf{Q} : 0 < p \leq 1\}$, which satisfies $\sup E = 1 \in E$ and $\inf E = 0 \notin E$.

Exercise 1.3.3. (a) Let A be nonempty and bounded below, and define $B = \{b \in \mathbf{R} : b \text{ is a lower bound for } A\}$. Show that $\sup B = \inf A$.

- (b) Use (a) to explain why there is no need to assert that greatest lower bounds exist as part of the Axiom of Completeness.

Solution. (a) B is non-empty since A is bounded below, and B is bounded above by any $x \in A$; there exists at least one such x since A is non-empty. It follows from the Axiom of Completeness that $\sup B$ exists. To see that $\sup B = \inf A$, we need to show that $\sup B$ satisfies criteria (i) and (ii) from [Exercise 1.3.1](#) (a).

- (i) First we need to prove that $\sup B$ is a lower bound for A , i.e., if $x \in A$, then $\sup B \leq x$.

We will prove the contrapositive statement: if $x < \sup B$, then $x \notin A$. If x is strictly less than $\sup B$, then x cannot be an upper bound for B . Thus there exists some $b \in B$ such that $x < b$. Since b is a lower bound for A , it follows that $x \notin A$.

- (ii) Suppose $y \in \mathbf{R}$ is a lower bound of A , so that y belongs to B ; it follows that $y \leq \sup B$.

We may conclude that $\sup B = \inf A$.

- (b) Part (a) shows that the existence of the greatest lower bound for non-empty bounded below subsets of \mathbf{R} is implied by the Axiom of Completeness; adding this existence as part of the Axiom of Completeness would be redundant.

Exercise 1.3.4. Let A_1, A_2, A_3, \dots be a collection of nonempty sets, each of which is bounded above.

- (a) Find a formula for $\sup(A_1 \cup A_2)$. Extend this to $\sup(\bigcup_{k=1}^n A_k)$.
- (b) Consider $\sup(\bigcup_{k=1}^\infty A_k)$. Does the formula in (a) extend to the infinite case?

Solution. (a) Let $n \in \mathbf{N}$ be given. For each $k \in \{1, \dots, n\}$, the Axiom of Completeness guarantees that $\sup A_k$ exists. By Lemma L.3, the finite set $\{\sup A_1, \dots, \sup A_n\}$ has a maximum element, say M ; we claim that $\sup(\bigcup_{k=1}^n A_k) = M$. To prove this, we must verify criteria (i) and (ii) from Definition 1.3.2.

- (i) If $x \in \bigcup_{k=1}^n A_k$, then $x \in A_k$ for some $k \in \{1, \dots, n\}$; it follows that $x \leq \sup A_k \leq M$. Since x was arbitrary, we see that M is an upper bound for $\bigcup_{k=1}^n A_k$.
- (ii) If $b \in \mathbf{R}$ is an upper bound for $\bigcup_{k=1}^n A_k$, then b must be an upper bound for each A_k . It follows that $\sup A_k \leq b$ for each $k \in \{1, \dots, n\}$ and hence that $M \leq b$.

We may conclude that $\sup(\bigcup_{k=1}^n A_k) = M$.

- (b) The proof given above does not extend to the infinite case, since in general the set $\{\sup A_1, \sup A_2, \dots\}$ need not have a maximum. Indeed, it may be the case that $\sup(\bigcup_{k=1}^\infty A_k)$ does not exist. For example, take $A_k = [0, k]$. Then each A_k is non-empty and bounded above with $\sup A_k = k$, but $\bigcup_{k=1}^\infty A_k = [0, \infty)$, which does not have a supremum in \mathbf{R} .

Exercise 1.3.5. As in Example 1.3.7, let $A \subseteq \mathbf{R}$ be nonempty and bounded above, and let $c \in \mathbf{R}$. This time define the set $cA = \{ca : a \in A\}$.

- (a) If $c \geq 0$, show that $\sup(cA) = c \sup A$.
- (b) Postulate a similar type of statement for $\sup(cA)$ for the case $c < 0$.

Solution. (a) If $c = 0$ then the result is clear, so suppose that $c > 0$. For any $x \in A$, notice that

$$x \leq \sup A \iff cx \leq c \sup A.$$

This demonstrates that $c \sup A$ is an upper bound for cA .

Suppose $b \in \mathbf{R}$ is an upper bound for cA , i.e., $cx \leq b$ for all $x \in A$. Then $x \leq c^{-1}b$ for all $x \in A$, i.e., $c^{-1}b$ is an upper bound for A . It follows that $\sup A \leq c^{-1}b$ and hence that $c \sup A \leq b$. We may conclude that $\sup(cA) = c \sup A$.

- (b) If $c < 0$ and $\inf A$ exists then $\sup(cA) = c \inf A$. The proof is similar to part (a). For any $x \in A$, we have

$$\inf A \leq x \iff cx \leq c \inf A,$$

so that $c \inf A$ is an upper bound for cA .

Suppose $b \in \mathbf{R}$ is an upper bound for cA , i.e., $cx \leq b$ for all $x \in A$. Then $c^{-1}b \leq x$ for all $x \in A$, so that $c^{-1}b$ is a lower bound for A . It follows that $c^{-1}b \leq \inf A$ and hence that $c \inf A \leq b$. We may conclude that $\sup(cA) = c \inf A$.

If $\inf A$ doesn't exist then $\sup(cA)$ doesn't exist either, since for $c < 0$ the set A is bounded below if and only if cA is bounded above. For example, $A = (-\infty, 0)$ and $c = -1$ gives $cA = (0, \infty)$.

Exercise 1.3.6. Given sets A and B , define $A + B = \{a + b : a \in A \text{ and } b \in B\}$. Follow these steps to prove that if A and B are nonempty and bounded above then $\sup(A+B) = \sup A + \sup B$.

- Let $s = \sup A$ and $t = \sup B$. Show $s + t$ is an upper bound for $A + B$.
- Now let u be an arbitrary upper bound for $A + B$, and temporarily fix $a \in A$. Show $t \leq u - a$.
- Finally, show $\sup(A + B) = s + t$.
- Construct another proof of this same fact using Lemma 1.3.8.

Solution. (a) For any $a \in A$ and $b \in B$ we have $a \leq s$ and $b \leq t$. It follows that $a + b \leq s + t$ and thus $s + t$ is an upper bound for $A + B$.

- For any $b \in B$ we have $a + b \leq u$, which gives $b \leq u - a$. This demonstrates that $u - a$ is an upper bound for B and so it follows that $t \leq u - a$.
- Part (b) implies that for any $a \in A$ we have $t \leq u - a$, which gives $a \leq u - t$. This shows that $u - t$ is an upper bound for A and it follows that $s \leq u - t$, i.e., $s + t \leq u$. Since u was an arbitrary upper bound for $A + B$, we may conclude that

$$\sup(A + B) = s + t = \sup A + \sup B.$$

- Let $\epsilon > 0$ be given. By Lemma 1.3.8, there exist elements $a \in A$ and $b \in B$ such that $s - \frac{\epsilon}{2} < a$ and $t - \frac{\epsilon}{2} < b$, which implies that $s + t - \epsilon < a + b$. We showed in part (a) that $s + t$ is an upper bound for $A + B$, so we may invoke Lemma 1.3.8 to conclude that $\sup(A + B) = \sup A + \sup B$.

Exercise 1.3.7. Prove that if a is an upper bound for A , and if a is also an element of A , then it must be that $a = \sup A$.

Solution. Let $b \in \mathbf{R}$ be an upper bound of A . Since $a \in A$, we must have $a \leq b$; it follows that $a = \sup A$.

Exercise 1.3.8. Compute, without proofs, the suprema and infima (if they exist) of the following sets:

- (a) $\{m/n : m, n \in \mathbf{N} \text{ with } m < n\}$.
- (b) $\{(-1)^m/n : m, n \in \mathbf{N}\}$.
- (c) $\{n/(3n+1) : n \in \mathbf{N}\}$.
- (d) $\{m/(m+n) : m, n \in \mathbf{N}\}$.

Solution. (a) The supremum is 1 and the infimum is 0.

- (b) The supremum is 1 and the infimum is -1 .
- (c) The supremum is $\frac{1}{3}$ and the infimum is $\frac{1}{4}$.
- (d) The supremum is 1 and the infimum is 0.

Exercise 1.3.9. (a) If $\sup A < \sup B$, show that there exists an element $b \in B$ that is an upper bound for A .

- (b) Give an example to show that this is not always the case if we only assume $\sup A \leq \sup B$.

Solution. (a) Let $\epsilon = \sup B - \sup A > 0$. By Lemma 1.3.8, there exists a $b \in B$ such that $\sup B - \epsilon = \sup A < b$. It follows that b is an upper bound for A .

- (b) Take $A = B = (0, 1)$. Then $\sup A = \sup B = 1$, but no element of B is an upper bound for A (the interval $(0, 1)$ has no maximum element).

Exercise 1.3.10 (Cut Property). The *Cut Property* of the real numbers is the following:

If A and B are nonempty, disjoint sets with $A \cup B = \mathbf{R}$ and $a < b$ for all $a \in A$ and $b \in B$, then there exists $c \in \mathbf{R}$ such that $x \leq c$ whenever $x \in A$ and $x \geq c$ whenever $x \in B$.

- (a) Use the Axiom of Completeness to prove the Cut Property.

- (b) Show that the implication goes the other way; that is, assume \mathbf{R} possesses the Cut Property and let E be a nonempty set that is bounded above. Prove $\sup E$ exists.
- (c) The punchline of parts (a) and (b) is that the Cut Property could be used in place of the Axiom of Completeness as the fundamental axiom that distinguishes the real numbers from the rational numbers. To drive this point home, give a concrete example showing that the Cut Property is not a valid statement when \mathbf{R} is replaced by \mathbf{Q} .

Solution. (a) Suppose that A and B are non-empty disjoint subsets of \mathbf{R} such that $A \cup B = \mathbf{R}$ and $a < b$ for all $a \in A$ and $b \in B$. Notice that A is non-empty (by assumption) and bounded above (because B is non-empty); the Axiom of Completeness then implies that $c := \sup A$ exists. It follows that $x \leq c$ for all $x \in A$ and, since each element of B is an upper bound for A , we also have $x \geq c$ for all $x \in B$.

- (b) Suppose that $E \subseteq \mathbf{R}$ is non-empty and bounded above. Define

$$A = \{a \in \mathbf{R} : a \text{ is not an upper bound of } E\},$$

$$B = A^c = \{b \in \mathbf{R} : b \text{ is an upper bound of } E\}.$$

Notice that B is non-empty as E is bounded above and A is non-empty because $x - 1 \in A$ for any $x \in E$; we are guaranteed the existence of at least one $x \in E$ as E is non-empty. Furthermore, A and B are evidently disjoint and satisfy $A \cup B = \mathbf{R}$.

Let $a \in A$ and $b \in B$ be given. Since a is not an upper bound for E there exists some $x \in E$ such that $a < x$ and since b is an upper bound for E , we must then have $x \leq b$; it follows that $a < b$. We may now invoke the Cut Property to obtain a $c \in \mathbf{R}$ such that $x \leq c$ for all $x \in A$ and $x \geq c$ for all $x \in B$.

We claim that $c = \sup E$. Since $A \cup B = \mathbf{R}$ and $A \cap B = \emptyset$, exactly one of $c \in A$ or $c \in B$ holds. Suppose that $c \in A$, i.e., c is not an upper bound of E , which is the case if and only if there is some $z \in E$ such that $c < z$. Observe that $y := \frac{c+z}{2}$ satisfies $c < y < z$, so that $y \in A$; but this contradicts the fact that $x \leq c$ for all $x \in A$.

So it must be the case that $c \in B$, i.e., c is an upper bound for E . The Cut Property says that $c \leq x$ for all $x \in B$; in other words, c is less than all other upper bounds of E . We may conclude that $c = \sup E$.

- (c) A concrete example is given in the following lemma, which will also be useful for later exercises.

Lemma L.4. Let

$$A = \{p \in \mathbf{Q} : p < 0 \text{ or } p^2 < 2\} \quad \text{and} \quad B = \{p \in \mathbf{Q} : p > 0 \text{ and } p^2 > 2\}.$$

Then:

- (i) A and B are non-empty, $A \cup B = \mathbf{Q}$, and $A \cap B = \emptyset$.
- (ii) $p < q$ for all $p \in A$ and $q \in B$.
- (iii) A has no maximum element and B has no minimum element.

Proof. (i) It is clear that A and B are non-empty. The negation of the statement “ $p < 0$ or $p^2 < 2$ ” is “ $p > 0$ and $p^2 \geq 2$ ”; by Theorem 1.1.1, this negated statement is equivalent to “ $p > 0$ and $p^2 > 2$ ” for $p \in \mathbf{Q}$. Thus $B = \mathbf{Q} \setminus A$, from which it follows that $A \cup B = \mathbf{Q}$ and $A \cap B = \emptyset$.

(ii) Let $p \in A$ and $q \in B$ be given. If $p \leq 0$ then evidently $p < q$, so suppose that $p > 0$. It must then be the case that $p^2 < 2$, whence $p^2 < q^2$. Since p and q are positive, this implies that $p < q$.

(iii) Let $p \in A$ be given. We need to show that there exists some $q \in A$ such that $p < q$. If $p \leq 0$, we can take $q = 1$; if $p > 0$, so that $p^2 < 2$, then define

$$q = p + \frac{2 - p^2}{p + 2} = \frac{2p + 2}{p + 2}. \quad (1)$$

Notice that $0 < \frac{2 - p^2}{p + 2}$, since $p^2 < 2$, from which it follows that $p < q$. A straightforward calculation yields

$$2 - q^2 = \frac{2(2 - p^2)}{(p + 2)^2};$$

using again that $p^2 < 2$, we see that $2 - q^2 > 0$ and thus $q \in A$.

Now let $p \in B$ be given. We need to show that there exists some $q \in B$ such that $q < p$. In fact, we can define q by equation (1) again; an argument similar to the one just given shows that $q < p$ and $q \in B$. \square

Parts (i) and (ii) of [Lemma L.4](#) show that the sets A and B satisfy the hypotheses of the Cut Property. If the Cut Property held for \mathbf{Q} , then we would be able to obtain a $c \in \mathbf{Q}$

such that $p \leq c$ for all $p \in A$ and $c \leq q$ for all $q \in B$. Since $A \cup B = \mathbf{Q}$ and $A \cap B = \emptyset$, this implies that c is either the maximum of A or the minimum of B —but this contradicts part (iii) of [Lemma L.4](#). We may conclude that the Cut Property does not hold for \mathbf{Q} .

Exercise 1.3.11. Decide if the following statements about suprema and infima are true or false. Give a short proof for those that are true. For any that are false, supply an example where the claim in question does not appear to hold.

- (a) If A and B are nonempty, bounded, and satisfy $A \subseteq B$, then $\sup A \leq \sup B$.
- (b) If $\sup A < \inf B$ for sets A and B , then there exists a $c \in \mathbf{R}$ satisfying $a < c < b$ for all $a \in A$ and $b \in B$.
- (c) If there exists a $c \in \mathbf{R}$ satisfying $a < c < b$ for all $a \in A$ and $b \in B$, then $\sup A < \inf B$.

Solution. (a) This is true. The Axiom of Completeness guarantees that $\sup A$ and $\sup B$ both exist. Furthermore, since each element of A is an element of B , any upper bound of B must be an upper bound of A also. In particular, $\sup B$ must be an upper bound of A ; it follows that $\sup A \leq \sup B$.

- (b) This is true. Let $c = \frac{\sup A + \inf B}{2}$, so that $\sup A < c < \inf B$, and notice that for any $a \in A$ and $b \in B$ we have

$$a \leq \sup A < c < \inf B \leq b.$$

- (c) This is false. Consider $A = (-1, 0)$ and $B = (0, 1)$, and notice that $c = 0$ satisfies $a < c < b$ for all $a \in A$ and $b \in B$, but $\sup A = \inf B = 0$.

1.4 Consequences of Completeness

Exercise 1.4.1. Recall that \mathbf{I} stands for the set of irrational numbers.

- (a) Show that if $a, b \in \mathbf{Q}$, then ab and $a + b$ are elements of \mathbf{Q} as well.
- (b) Show that if $a \in \mathbf{Q}$ and $t \in \mathbf{I}$, then $a + t \in \mathbf{I}$ and $at \in \mathbf{I}$ as long as $a \neq 0$.
- (c) Part (a) can be summarized by saying that \mathbf{Q} is closed under addition and multiplication. Is \mathbf{I} closed under addition and multiplication? Given two irrational numbers s and t , what can we say about $s + t$ and st ?

Solution. (a) Suppose $a = \frac{m}{n}$ and $b = \frac{p}{q}$. Then

$$ab = \frac{mp}{nq} \quad \text{and} \quad a + b = \frac{mq + np}{nq},$$

which are rational numbers.

(b) Let $a \in \mathbf{Q}$ be fixed. We want to prove that

$$\text{if } t \in \mathbf{I}, \text{ then } a + t \in \mathbf{I}.$$

To do this, we will prove the contrapositive statement

$$\text{if } a + t \in \mathbf{Q}, \text{ then } t \in \mathbf{Q}.$$

Simply observe that $t = (a + t) - a$; it follows from part (a) that $t \in \mathbf{Q}$.

Similarly, let $a \in \mathbf{Q}$ be non-zero. We can show that

$$\text{if } at \in \mathbf{Q}, \text{ then } t \in \mathbf{Q}$$

by observing that $t = a^{-1}(at)$ and appealing to part (a) to conclude that $t \in \mathbf{Q}$.

(c) \mathbf{I} is not closed under addition or multiplication. For example, $-\sqrt{2}$ and $\sqrt{2}$ are irrational numbers, but their sum is the rational number 0 and their product is the rational number -2 . The sum or product of two irrational numbers may be irrational; for example, it can be shown that $\sqrt{2} + \sqrt{3}$ and $\sqrt{2}\sqrt{3} = \sqrt{6}$ are irrational:

- For the irrationality of $\sqrt{6}$, see [Exercise 1.2.1](#) (a).
- For the irrationality of $\sqrt{2} + \sqrt{3}$, observe that $\sqrt{2} + \sqrt{3}$ is a root of the polynomial $x^4 - 10x^2 + 1$; the [rational root theorem](#) says that the only possible rational roots of this polynomial are ± 1 —but neither of these solve the equation $x^4 - 10x^2 + 1 = 0$.

So in general, we cannot say anything about the sum or product of two irrational numbers without more information.

Exercise 1.4.2. Let $A \subseteq \mathbf{R}$ be nonempty and bounded above, and let $s \in \mathbf{R}$ have the property that for all $n \in \mathbf{N}$, $s + \frac{1}{n}$ is an upper bound for A and $s - \frac{1}{n}$ is not an upper bound for A . Show $s = \sup A$.

Solution. If s is not an upper bound for A then there must exist some $x \in A$ such that $s < x$. By the Archimedean Property (Theorem 1.4.2), there exists a natural number n such that $s + \frac{1}{n} < x$, which implies that $s + \frac{1}{n}$ is not an upper bound for A . Given our hypothesis that $s + \frac{1}{n}$ is an upper bound for A for all $n \in \mathbf{N}$, we see that s must be an upper bound for A .

Now let $\epsilon > 0$ be given and using the Archimedean Property (Theorem 1.4.2), pick a natural number n such that $\frac{1}{n} < \epsilon$. By assumption $s - \frac{1}{n}$ is not an upper bound for A , so there must exist some $x \in A$ such that $s - \frac{1}{n} < x$; this implies that $s - \epsilon < x$ since $\frac{1}{n} < \epsilon$. Because $\epsilon > 0$ was arbitrary, we may invoke Lemma 1.3.8 to conclude that $s = \sup A$.

Exercise 1.4.3. Prove that $\bigcap_{n=1}^{\infty} (0, 1/n) = \emptyset$. Notice that this demonstrates that the intervals in the Nested Interval Property must be closed for the conclusion of the theorem to hold.

Solution. It is clear that any $x \leq 0$ does not belong to $\bigcap_{n=1}^{\infty} (0, \frac{1}{n})$. Let $x > 0$ be given and use the Archimedean Property (Theorem 1.4.2) to choose an $N \in \mathbf{N}$ such that $\frac{1}{N} < x$. It follows that $x \notin (0, \frac{1}{N})$ and hence that $x \notin \bigcap_{n=1}^{\infty} (0, \frac{1}{n})$. We may conclude that $\bigcap_{n=1}^{\infty} (0, \frac{1}{n}) = \emptyset$.

Exercise 1.4.4. Let $a < b$ be real numbers and consider the set $T = \mathbf{Q} \cap [a, b]$. Show $\sup T = b$.

Solution. It is clear that b is an upper bound for T . Let $\epsilon > 0$ be given. By the density of \mathbf{Q} in \mathbf{R} (Theorem 1.4.3), there exists a rational number p satisfying

$$\max\{a, b - \epsilon\} < p < b.$$

It follows that $p \in T$ and $b - \epsilon < p$ and hence, by Lemma 1.3.8, we may conclude that $\sup T = b$.

Exercise 1.4.5. Using [Exercise 1.4.1](#), supply a proof for Corollary 1.4.4 by considering the real numbers $a - \sqrt{2}$ and $b - \sqrt{2}$.

Solution. By the density of \mathbf{Q} in \mathbf{R} (Theorem 1.4.3), there exists a rational number p satisfying $a - \sqrt{2} < p < b - \sqrt{2}$, which gives $a < p + \sqrt{2} < b$. Since $p + \sqrt{2}$ is irrational ([Exercise 1.4.1](#) (b)), the corollary is proved.

Exercise 1.4.6. Recall that a set B is *dense* in \mathbf{R} if an element of B can be found between any two real numbers $a < b$. Which of the following sets are dense in \mathbf{R} ? Take $p \in \mathbf{Z}$ and $q \in \mathbf{N}$ in every case.

- (a) The set of all rational numbers p/q with $q \leq 10$.

- (b) The set of all rational numbers p/q with q a power of 2.
 (c) The set of all rational numbers p/q with $10|p| \geq q$.

Solution. (a) This set is not dense in \mathbf{R} . For $1 \leq q \leq 10$, observe that if $p \geq 1$ then $\frac{p}{q} \geq \frac{1}{10}$, if $p \leq -1$ then $\frac{p}{q} \leq -\frac{1}{10}$, and if $p = 0$ then $\frac{p}{q} = 0$. So there is no element of this set between the real numbers $\frac{1}{1000}$ and $\frac{1}{100}$, for example.

- (b) This set is dense in \mathbf{R} . Let $a < b$ be given real numbers. Using the Archimedean Property (Theorem 1.4.2), let $n \in \mathbf{N}$ be such that $\frac{1}{n} < b - a$, which implies that $\frac{1}{2^n} < b - a$. Now let p be the smallest integer greater than $2^n a$, so that $p - 1 \leq 2^n a < p$, and observe that

$$2^n a < p \leq 1 + 2^n a < 2^n b;$$

it follows that $\frac{p}{2^n}$ lies between a and b .

- (c) This set is not dense in \mathbf{R} . If $p > 0$ then

$$10|p| \geq q \iff 10p \geq q \iff \frac{p}{q} \geq \frac{1}{10},$$

and if $p < 0$ then

$$10|p| \geq q \iff -10p \geq q \iff \frac{p}{q} \leq -\frac{1}{10}.$$

We cannot have $p = 0$ since q is a positive integer. Thus there is no element of this set between the real numbers 0 and $\frac{1}{100}$, for example.

Exercise 1.4.7. Finish the proof of Theorem 1.4.5 by showing that the assumption $\alpha^2 > 2$ leads to a contradiction of the fact that $\alpha = \sup T$.

Solution. Assuming that $\alpha^2 - 2 > 0$, the Archimedean Property (Theorem 1.4.2) implies that there is an $n \in \mathbf{N}$ such that

$$\frac{2\alpha}{n} < \alpha^2 - 2 \iff 2 < \alpha^2 - \frac{2\alpha}{n}.$$

Let $\beta = \alpha - \frac{1}{n}$ and note that since $1 \in T$ we have $\alpha \geq 1$ and hence $\beta \geq 0$; it follows that $t \leq \beta$ for all $t \in T$ such that $t < 0$. Now observe that

$$\beta^2 = \left(\alpha - \frac{1}{n}\right)^2 = \alpha^2 - \frac{2\alpha}{n} + \frac{1}{n^2} > \alpha^2 - \frac{2\alpha}{n} > 2,$$

so that for any $t \in T$ we have $t^2 < 2 < \beta^2$. If $t \in T$ is such that $t \geq 0$ then the inequality $t^2 < \beta^2$ implies that $t < \beta$, as β is also non-negative.

We have now shown that $t \leq \beta$ for all $t \in T$, i.e., β is an upper bound for T —but this contradicts the fact that α is the supremum of T since $\beta < \alpha$.

Exercise 1.4.8. Give an example of each or state that the request is impossible. When a request is impossible, provide a compelling argument for why this is the case.

- (a) Two sets A and B with $A \cap B = \emptyset$, $\sup A = \sup B$, $\sup A \notin A$ and $\sup B \notin B$.
- (b) A sequence of nested open intervals $J_1 \supseteq J_2 \supseteq J_3 \supseteq \cdots$ with $\bigcap_{n=1}^{\infty} J_n$ nonempty but containing only a finite number of elements.
- (c) A sequence of nested unbounded closed intervals $L_1 \supseteq L_2 \supseteq L_3 \supseteq \cdots$ with $\bigcap_{n=1}^{\infty} L_n = \emptyset$. (An unbounded closed interval has the form $[a, \infty) = \{x \in \mathbf{R} : x \geq a\}$.)
- (d) A sequence of closed bounded (not necessarily nested) intervals I_1, I_2, I_3, \dots with the property that $\bigcap_{n=1}^N I_n \neq \emptyset$ for all $N \in \mathbf{N}$, but $\bigcap_{n=1}^{\infty} I_n = \emptyset$.

Solution. (a) Let

$$A = \left\{ -\frac{1}{2n} : n \in \mathbf{N} \right\} = \left\{ -\frac{1}{2}, -\frac{1}{4}, -\frac{1}{6}, \dots \right\}$$

$$\text{and} \quad B = \left\{ -\frac{1}{2n-1} : n \in \mathbf{N} \right\} = \left\{ -1, -\frac{1}{3}, -\frac{1}{5}, \dots \right\}.$$

Then $A \cap B = \emptyset$ and $\sup A = \sup B = 0$, which belongs to neither A nor B .

- (b) If we let $J_n = \left(-\frac{1}{n}, \frac{1}{n}\right)$ for $n \in \mathbf{N}$, then $\bigcap_{n=1}^{\infty} J_n = \{0\}$.
- (c) For $n \in \mathbf{N}$, let $L_n = [n, \infty)$.
- (d) This is impossible. To see this, let $(I_n)_{n=1}^{\infty}$ be a sequence of closed bounded intervals satisfying $\bigcap_{n=1}^N I_n \neq \emptyset$ for every $N \in \mathbf{N}$. Define $J_N = \bigcap_{n=1}^N I_n$ for $N \in \mathbf{N}$ and note that any finite intersection of closed bounded intervals is a (possibly empty) closed bounded interval. Thus:

- each J_N is a closed bounded interval;
- these intervals are non-empty and nested, i.e., $J_1 \supseteq J_2 \supseteq J_3 \supseteq \cdots$;

$$\bullet \bigcap_{n=1}^{\infty} I_n = \bigcap_{N=1}^{\infty} J_N.$$

It then follows from the Nested Interval Property (Theorem 1.4.1) that $\bigcap_{n=1}^{\infty} I_n = \bigcap_{N=1}^{\infty} J_N$ is non-empty.

1.5 Cardinality

Exercise 1.5.1. Finish the following proof for Theorem 1.5.7.

Assume B is a countable set. Thus, there exists $f : \mathbf{N} \rightarrow B$ which is 1-1 and onto. Let $A \subseteq B$ be an infinite subset of B . We must show that A is countable.

Let $n_1 = \min\{n \in \mathbf{N} : f(n) \in A\}$. As a start to a definition of $g : \mathbf{N} \rightarrow A$, set $g(1) = f(n_1)$. Show how to inductively continue this process to produce a 1-1 function g from \mathbf{N} onto A .

Solution. Given $n_1 = \min f^{-1}(A) = \min\{n \in \mathbf{N} : f(n) \in A\}$, we can construct a sequence $(n_k)_{k=1}^{\infty}$ of natural numbers recursively by defining

$$n_k = \min(f^{-1}(A) \setminus \{n_1, \dots, n_{k-1}\}) = \min(\{n \in \mathbf{N} : f(n) \in A\} \setminus \{n_1, \dots, n_{k-1}\})$$

for $k \geq 2$. Because A is infinite and f is surjective, the set $\{n \in \mathbf{N} : f(n) \in A\} \setminus \{n_1, \dots, n_{k-1}\}$ is non-empty (indeed, it must be infinite) for each $k \geq 2$; it follows that each n_k is well-defined. See [Figure F.1](#) for an example construction of the sequence $(n_k)_{k=1}^{\infty}$, for some bijection $f : \mathbf{N} \rightarrow B$.

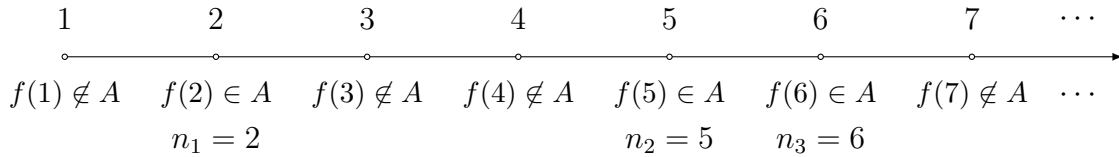


Figure F.1: Example construction of $(n_k)_{k=1}^{\infty}$

It is clear from this construction that $(n_k)_{k=1}^{\infty}$ is a strictly increasing sequence.

Define $g : \mathbf{N} \rightarrow A$ by $g(k) = f(n_k)$; we claim that g is a bijection. For injectivity, observe that

$$g(\ell) = g(k) \iff f(n_\ell) = f(n_k) \iff n_\ell = n_k \iff \ell = k,$$

where we have used the injectivity of f for the second equivalence and the strict monotonicity of the sequence $(n_k)_{k=1}^{\infty}$ for the third equivalence.

For the surjectivity of g , let $a \in A$ be given. Since f is surjective, there is a positive integer N such that $f(N) = a$; we need to find some $k \in \mathbf{N}$ such that $n_k = N$. It cannot be the case that $N < n_1$, otherwise n_1 would not be the minimum of $\{n \in \mathbf{N} : f(n) \in A\}$, so we must have $n_1 \leq N$. Given this, and the fact that $(n_k)_{k=1}^\infty$ is a strictly increasing sequence of natural numbers, there must exist a $k \in \mathbf{N}$ such that $n_k \leq N < n_{k+1}$. In fact, it must be the case that $n_k = N$, otherwise n_{k+1} would not be the minimum of $\{n \in \mathbf{N} : f(n) \in A\} \setminus \{n_1, \dots, n_k\}$. Thus $g(k) = f(n_k) = f(N) = a$.

Exercise 1.5.2. Review the proof of Theorem 1.5.6, part (ii) showing that \mathbf{R} is uncountable, and then find the flaw in the following erroneous proof that \mathbf{Q} is uncountable:

Assume, for contradiction, that \mathbf{Q} is countable. Thus we can write $\mathbf{Q} = \{r_1, r_2, r_3, \dots\}$ and, as before, construct a nested sequence of closed intervals with $r_n \notin I_n$. Our construction implies $\bigcap_{n=1}^\infty I_n = \emptyset$ while NIP implies $\bigcap_{n=1}^\infty I_n \neq \emptyset$. This contradiction implies \mathbf{Q} must therefore be uncountable.

Solution. The construction does not imply that $\bigcap_{n=1}^\infty I_n = \emptyset$; it only guarantees that this intersection does not contain any rational numbers.

Exercise 1.5.3. Use the following outline to supply proofs for the statements in Theorem 1.5.8.

- (a) First, prove statement (i) for two countable sets, A_1 and A_2 . Example 1.5.3 (ii) may be a useful reference. Some technicalities can be avoided by first replacing A_2 with the set $B_2 = A_2 \setminus A_1 = \{x \in A_2 : x \notin A_1\}$. The point of this is that the union $A_1 \cup B_2$ is equal to $A_1 \cup A_2$ and the sets A_1 and B_2 are disjoint. (What happens if B_2 is finite?)

Now, explain how the more general statement in (i) follows.

- (b) Explain why induction *cannot* be used to prove part (ii) of Theorem 1.5.8 from part (i).
 (c) Show how arranging \mathbf{N} into the two-dimensional array

| | | | | | |
|----|-----|-----|-----|-----|-----|
| 1 | 3 | 6 | 10 | 15 | ... |
| 2 | 5 | 9 | 14 | ... | |
| 4 | 8 | 13 | ... | | |
| 7 | 12 | ... | | | |
| 11 | ... | | | | |
| ⋮ | | | | | |

leads to a proof of Theorem 1.5.8 (ii).

Solution. (a) As noted, it will suffice to show that $A_1 \cup B_2$ is countable, where $B_2 = A_2 \setminus A_1$. Since A_1 is countable, there exists a bijection $f : \mathbf{N} \rightarrow A_1$. Consider the following cases.

Case 1. If B_2 is empty, then $A_1 \cup B_2 = A_1$, which is countable by assumption.

Case 2. Suppose that B_2 is non-empty and finite, say $B_2 = \{x_1, \dots, x_k\}$ for some $k \in \mathbf{N}$. Define $g : \mathbf{N} \rightarrow A_1 \cup B_2$ by

$$g(n) = \begin{cases} x_n & \text{if } 1 \leq n \leq k, \\ f(n - k) & \text{if } k < n. \end{cases}$$

The injectivity of g follows as A_1 and B_2 are disjoint and f is injective. For the surjectivity of g , it is clear that every element of B_2 belongs to the range of g ; the surjectivity of f implies that the elements of A_1 belong to the range of g also.

Case 3. Suppose that B_2 is infinite. Since B_2 is a subset of the countable set A_2 , [Exercise 1.5.1](#) implies that B_2 is countable, i.e., there exists a bijection $h : \mathbf{N} \rightarrow B_2$. Define $g : \mathbf{N} \rightarrow A_1 \cup B_2$ by

$$g(n) = \begin{cases} f\left(\frac{n}{2}\right) & \text{if } n \text{ is even,} \\ h\left(\frac{n+1}{2}\right) & \text{if } n \text{ is odd.} \end{cases}$$

To see that g is injective, suppose that m and n are distinct positive integers.

Case 3.1 If both of m and n are even then $g(m) \neq g(n)$ since f is injective.

Case 3.2 If both of m and n are odd then $g(m) \neq g(n)$ since h is injective.

Case 3.3 If one of m and n is even and the other is odd then $g(m) \neq g(n)$ since f maps into A_1 , h maps into B_2 , and $A_1 \cap B_2 = \emptyset$.

To see that g is surjective, let $x \in A_1 \cup B_2$ be given. Since $A_1 \cap B_2 = \emptyset$, exactly one of the statements $x \in A_1$ or $x \in B_2$ holds. Suppose $x \in A_1$. Because f is surjective, there is a positive integer n such that $f(n) = x$; it follows that $g(2n) = f(n) = x$. If $x \in B_2$, then the surjectivity of h implies that there is a positive integer n such that $h(n) = x$; it follows that $g(2n - 1) = h(n) = x$. We may conclude that g is a bijection and hence that $A_1 \cup B_2$ is countable.

A simple induction argument proves the more general statement in Theorem 1.5.8 (i). Let $P(n)$ be the statement that for countable sets A_1, \dots, A_n , the union $A_1 \cup \dots \cup A_n$ is countable. The truth of $P(1)$ is clear. Suppose that $P(n)$ holds for some $n \in \mathbf{N}$ and suppose we have countable sets A_1, \dots, A_n, A_{n+1} . Let $A' = A_1 \cup \dots \cup A_n$; the induction hypothesis guarantees that A' is countable. Observe that

$$A_1 \cup \dots \cup A_n \cup A_{n+1} = A' \cup A_{n+1}.$$

Since A' and A_{n+1} are countable, the union $A' \cup A_{n+1}$ is also countable by our previous proof, i.e., $P(n+1)$ holds. This completes the induction step and the proof.

- (b) Induction can only be used to show that a particular statement $P(n)$ holds for each value of $n \in \mathbf{N}$.
- (c) For each $n \in \mathbf{N}$ there exists a bijection $f_n : \mathbf{N} \rightarrow A_n$. Let $a_{mn} = f_n(m)$ and arrange these into another two-dimensional array like so:

| A_1 | A_2 | A_3 | A_4 | A_5 | \dots | | | | | | |
|----------|----------|----------|----------|----------|---------|----------|----------|----------|----------|----------|---------|
| a_{11} | a_{12} | a_{13} | a_{14} | a_{15} | \dots | 1 | 3 | 6 | 10 | 15 | \dots |
| a_{21} | a_{22} | a_{23} | a_{24} | \ddots | | 2 | 5 | 9 | 14 | \ddots | |
| a_{31} | a_{32} | a_{33} | \ddots | | | 4 | 8 | 13 | \ddots | | |
| a_{41} | a_{42} | \ddots | | | | 7 | 12 | \ddots | | | |
| a_{51} | \ddots | | | | | 11 | \ddots | | | | |
| \vdots | | | | | | \vdots | | | | | |

Since each f_n is surjective, each element of $\bigcup_{n=1}^{\infty} A_n$ appears somewhere in the left array. We define a function $g : \bigcup_{n=1}^{\infty} A_n \rightarrow \mathbf{N}$ by working through the grid along the diagonals (first a_{11} , then a_{21} , then a_{12} , then a_{31} , and so on), mapping an element a_{mn} to the natural number appearing in the corresponding position in the right array. The A_n 's may have elements in common; if we encounter an element a_{mn} that we have already seen before, we simply skip this element and move on to the next one. In this way, we obtain an injective function g . If we denote the range of g by $B \subseteq \mathbf{N}$, then $g : \bigcup_{n=1}^{\infty} A_n \rightarrow B$ is a bijection. Since the infinite set A_1 is contained in the union $\bigcup_{n=1}^{\infty} A_n$ and g is injective, it must be the case that B is infinite; [Exercise 1.5.1](#) then implies that B is countable, i.e., there is a

bijection $h : \mathbf{N} \rightarrow B$. It follows that the function $g^{-1} \circ h : \mathbf{N} \rightarrow \bigcup_{n=1}^{\infty} A_n$ is a bijection and we may conclude that $\bigcup_{n=1}^{\infty} A_n$ is countable.

Exercise 1.5.4. (a) Show $(a, b) \sim \mathbf{R}$ for any interval (a, b) .

(b) Show that an unbounded interval like $(a, \infty) = \{x : x > a\}$ has the same cardinality as \mathbf{R} as well.

(c) Using open intervals makes it more convenient to produce the required 1-1, onto functions, but it is not really necessary. Show that $[0, 1) \sim (0, 1)$ by exhibiting a 1-1 onto function between the two sets.

Solution. (a) Let $f : (-1, 1) \rightarrow \mathbf{R}$ be the bijection given by $f(x) = \frac{x}{x^2-1}$ (see Example 1.5.4) and let $g : (a, b) \rightarrow (-1, 1)$ be given by $g(x) = \frac{2(x-a)}{b-a} - 1$; it is straightforward to verify that g is a bijection. Thus $(a, b) \sim (-1, 1) \sim \mathbf{R}$ and it follows that $(a, b) \sim \mathbf{R}$ (Exercise 1.5.5).

(b) Let $f : (a, \infty) \rightarrow (0, 1)$ be the bijection given by $f(x) = \frac{1}{x+1-a}$. Thus $(a, \infty) \sim (0, 1)$ and, by part (a), $(0, 1) \sim \mathbf{R}$; it follows that $(a, \infty) \sim \mathbf{R}$.

(c) It is clear that $[0, 1) \sim (0, 1]$ via the map $x \mapsto 1 - x$. Define a function $f : (0, 1) \rightarrow (0, 1]$ by

$$f(x) = \begin{cases} \frac{1}{n} & \text{if } x = \frac{1}{n+1} \text{ for some } n \in \mathbf{N}, \\ x & \text{otherwise.} \end{cases}$$

This function is a bijection since it has an inverse $f^{-1} : (0, 1] \rightarrow (0, 1)$ given by

$$f^{-1}(x) = \begin{cases} \frac{1}{n+1} & \text{if } x = \frac{1}{n} \text{ for some } n \in \mathbf{N}, \\ x & \text{otherwise.} \end{cases}$$

It follows that $(0, 1) \sim (0, 1]$ and hence that $(0, 1) \sim [0, 1)$.

Exercise 1.5.5. (a) Why is $A \sim A$ for every set A ?

(b) Given sets A and B , explain why $A \sim B$ is equivalent to asserting $B \sim A$.

(c) For three sets A, B , and C , show that $A \sim B$ and $B \sim C$ implies $A \sim C$. These three properties are what is meant by saying that \sim is an *equivalence relation*.

Solution. (a) The identity function $f : A \rightarrow A$ given by $f(x) = x$ is a bijection.

- (b) Since $A \sim B$, there is a bijection $f : A \rightarrow B$. A function is bijective if and only if it has an inverse function $f^{-1} : B \rightarrow A$, which must also be bijective.
- (c) There are bijections $f : A \rightarrow B$ and $g : B \rightarrow C$. It follows that the composition $g \circ f : A \rightarrow C$ is also a bijection.

Exercise 1.5.6. (a) Give an example of a countable collection of disjoint open intervals.

- (b) Give an example of an uncountable collection of disjoint open intervals, or argue that no such collection exists.

Solution. (a) Take $A_n = (n, n + 1)$ for $n \in \mathbf{N}$.

- (b) No such collection exists. To see this, suppose there was such a collection $\{I_a : a \in A\}$ for some uncountable set A . By the density of \mathbf{Q} in \mathbf{R} , there exists a rational number $r_a \in I_a$ for each $a \in A$. Since the intervals are disjoint, each r_a must be distinct and hence the collection $\{r_a : a \in A\}$ must be an uncountable subset of \mathbf{Q} —but this contradicts [Exercise 1.5.1](#).

Exercise 1.5.7. Consider the open interval $(0, 1)$, and let S be the set of points in the open unit square; that is, $S = \{(x, y) : 0 < x, y < 1\}$.

- (a) Find a 1-1 function that maps $(0, 1)$ into, but not necessarily onto, S . (This is easy.)
- (b) Use the fact that every real number has a decimal expansion to produce a 1-1 function that maps S into $(0, 1)$. Discuss whether the formulated function is onto. (Keep in mind that any terminating decimal expansion such as .235 represents the same real number as .234999... .)

The Schröder-Bernstein Theorem discussed in [Exercise 1.5.11](#) can now be applied to conclude that $(0, 1) \sim S$.

Solution. (a) Take $f : (0, 1) \rightarrow S$ given by $f(x) = (x, \frac{1}{2})$.

- (b) For $(x, y) \in S$, suppose x has decimal representation $0.x_1x_2x_3\dots$ and y has decimal representation $0.y_1y_2y_3\dots$, where if necessary we choose the decimal representation terminating in 0's. To define $g : S \rightarrow (0, 1)$, let $g(x, y) = 0.x_1y_1x_2y_2x_3y_3\dots$.

For the injectivity of g , suppose we have $(x, y) \neq (a, b)$ in S , so that at least one of $x \neq a$ or $y \neq b$ holds. Assuming $x \neq a$ (the case where $y \neq b$ is handled similarly), let $0.x_1x_2x_3\dots$

be the decimal representation of x and let $0.a_1a_2a_3\dots$ be the decimal representation of a . Since $x \neq a$, there must be some index n such that $x_n \neq a_n$. If $g(x, y)$ has decimal representation $0.s_1s_2s_3\dots$ and $g(a, b)$ has decimal representation $0.t_1t_2t_3\dots$, then

$$s_{2n-1} = x_n \neq a_n = t_{2n-1}.$$

This implies that $g(x, y) \neq g(a, b)$, provided it is not the case that $g(x, y)$ terminates in 0's and $g(a, b)$ terminates in 9's, or vice versa. To rule this out, note that $g(a, b)$ terminates in 9's only if both a and b terminate in 9's—but our construction specifically chooses the decimal representations for a and b terminating in 0's if necessary. The case where $g(x, y)$ terminates in 9's is handled similarly.

This function g is not surjective since 0.1 does not belong to the range of g . Indeed,

$$g(x, y) = 0.x_1y_1x_2y_2\dots = 0.1000\dots$$

implies that $y = 0$, but $(x, 0) \notin S$ for any $x \in (0, 1)$.

Exercise 1.5.8. Let B be a set of positive real numbers with the property that adding together any finite subset of elements from B always gives a sum of 2 or less. Show B must be finite or countable.

Solution. Suppose $a \in (0, 1]$; we claim that $B \cap (a, 2]$ must be a (possibly empty) finite set. By the Archimedean Property (Theorem 1.4.2), there is an $n \in \mathbf{N}$ such that $na > 2$. If $B \cap (a, 2]$ contains at least n elements, say $\{b_1, \dots, b_n\}$, then since each $b_i > a$ we have

$$b_1 + \dots + b_n > na > 2.$$

This contradicts our hypotheses, so it must be the case that $B \cap (a, 2]$ contains less than n elements and our claim follows.

Any element of B must be less than or equal to 2, so $B \subseteq (0, 2]$ and it follows that

$$B = \bigcup_{n=1}^{\infty} (B \cap (\tfrac{1}{n}, 2]).$$

This expresses B as a countable union of finite sets and thus B is either finite or countable (Theorem 1.5.8).

Exercise 1.5.9. A real number $x \in \mathbf{R}$ is called *algebraic* if there exist integers $a_0, a_1, a_2, \dots, a_n \in \mathbf{Z}$, not all zero, such that

$$a_n x^n + a_{n-1} x^{n-1} + \dots + a_1 x + a_0 = 0.$$

Said another way, a real number is algebraic if it is the root of a polynomial with integer coefficients. Real numbers that are not algebraic are called *transcendental* numbers. Reread the last paragraph of Section 1.1. The final question posed here is closely related to the question of whether or not transcendental numbers exist.

- (a) Show that $\sqrt{2}$, $\sqrt[3]{2}$, and $\sqrt{3} + \sqrt{2}$ are algebraic.
- (b) Fix $n \in \mathbf{N}$, and let A_n be the algebraic numbers obtained as roots of polynomials with integer coefficients that have degree n . Using the fact that every polynomial has a finite number of roots, show that A_n is countable.
- (c) Now, argue that the set of all algebraic numbers is countable. What may we conclude about the set of transcendental numbers?

Solution. (a) $\sqrt{2}$ is a root of the polynomial $x^2 - 2$, $\sqrt[3]{2}$ is a root of the polynomial $x^3 - 2$, and $\sqrt{3} + \sqrt{2}$ is a root of the polynomial $x^4 - 10x^2 + 1$.

- (b) We will use the following useful corollary of Theorem 1.5.8 (ii).

Lemma L.5. If A_1, \dots, A_n are countable sets, then $A_1 \times \dots \times A_n$ is also countable.

Proof. Suppose that A and B are countable sets, so that $B = \{b_1, b_2, b_3, \dots\}$. For each $n \in \mathbf{N}$, it is clear that the set $A \times \{b_n\}$ is countable. Now observe that

$$A \times B = \bigcup_{n=1}^{\infty} (A \times \{b_n\}).$$

It follows from Theorem 1.5.8 (ii) that $A \times B$ is countable. A straightforward induction argument proves the general case. \square

Let P_n be the collection of polynomials with integer coefficients that have degree n , i.e. $P_n = \{a_n x^n + a_{n-1} x^{n-1} + \dots + a_1 x + a_0 : a_n, \dots, a_0 \in \mathbf{Z}, a_n \neq 0\}$. Notice that

$$P_n \sim (\mathbf{Z} \setminus \{0\}) \times \underbrace{\mathbf{Z} \times \dots \times \mathbf{Z}}_{n \text{ times}}$$

via the map

$$a_n x^n + a_{n-1} x^{n-1} + \cdots + a_1 x + a_0 \mapsto (a_n, a_{n-1}, \dots, a_1, a_0).$$

It then follows from [Lemma L.5](#) that P_n is countable. For a polynomial $p \in P_n$, let R_p be the set of its roots, i.e., $R_p = \{x \in \mathbf{R} : p(x) = 0\}$, and note that R_p is always a finite set. Now observe that

$$A_n = \bigcup_{p \in P_n} R_p,$$

demonstrating that A_n is a countable union of finite sets; it follows from Theorem 1.5.8 that A_n is either finite or countable. Since $\sqrt[n]{k} \in A_n$ for each $k \in \mathbf{N}$ (it is a root of the polynomial $x^n - k$), we see that A_n must be infinite and hence countable.

- (c) If we let A be the set of all algebraic numbers then $A = \bigcup_{n=1}^{\infty} A_n$, i.e., A is a countable union of countable sets. It follows from Theorem 1.5.8 (ii) that A is countable.

A consequence of this is that the set of transcendental numbers A^c must be uncountable. To see this, note that $\mathbf{R} = A \cup A^c$, the union of two countable sets is countable, and \mathbf{R} is not countable.

- Exercise 1.5.10.** (a) Let $C \subseteq [0, 1]$ be uncountable. Show that there exists $a \in (0, 1)$ such that $C \cap [a, 1]$ is uncountable.
- (b) Now let A be the set of all $a \in (0, 1)$ such that $C \cap [a, 1]$ is uncountable, and let $\alpha = \sup A$. Is $C \cap [\alpha, 1]$ an uncountable set?
- (c) Does the statement in (a) remain true if “uncountable” is replaced by “infinite”?

Solution. (a) If we suppose that for each $a \in (0, 1)$ the set $C \cap [a, 1]$ is countable, then we can express C as a countable union of countable sets:

$$C = \bigcup_{n=2}^{\infty} \left(C \cap \left[\frac{1}{n}, 1 \right] \right).$$

This implies that C is countable (Theorem 1.5.8 (ii)). Thus, given that C is uncountable, there must exist some $a \in (0, 1)$ such that $C \cap [a, 1]$ is uncountable.

- (b) Not necessarily. Suppose $C = [0, 1]$. Then for all $a \in (0, 1)$, we have $C \cap [a, 1] = [a, 1]$, which is uncountable. Thus $A = (0, 1)$ and it follows that $\alpha = \sup A = 1$, but $C \cap [\alpha, 1] = \{1\}$ is not uncountable.

- (c) The statement is no longer true in general. If we let $C = \{\frac{1}{n} : n \in \mathbf{N}\}$ then no matter which $a \in (0, 1)$ we choose, the intersection $C \cap [a, 1]$ is a finite set (since there are only finitely many positive integers less than or equal to a^{-1} , there are only finitely many reciprocals of positive integers greater than or equal to a).

Exercise 1.5.11 (Schröder-Bernstein Theorem). Assume there exists a 1-1 function $f : X \rightarrow Y$ and another 1-1 function $g : Y \rightarrow X$. Follow the steps to show that there exists a 1-1, onto function $h : X \rightarrow Y$ and hence $X \sim Y$.

The strategy is to partition X and Y into components

$$X = A \cup A' \quad \text{and} \quad Y = B \cup B'$$

with $A \cap A' = \emptyset$ and $B \cap B' = \emptyset$, in such a way that f maps A onto B , and g maps B' onto A' .

- (a) Explain how achieving this would lead to a proof that $X \sim Y$.
- (b) Set $A_1 = X \setminus g(Y) = \{x \in X : x \notin g(Y)\}$ (what happens if $A_1 = \emptyset$?) and inductively define a sequence of sets by letting $A_{n+1} = g(f(A_n))$. Show that $\{A_n : n \in \mathbf{N}\}$ is a pairwise disjoint collection of subsets of X , while $\{f(A_n) : n \in \mathbf{N}\}$ is a similar collection in Y .
- (c) Let $A = \bigcup_{n=1}^{\infty} A_n$ and $B = \bigcup_{n=1}^{\infty} f(A_n)$. Show that f maps A onto B .
- (d) Let $A' = X \setminus A$ and $B' = Y \setminus B$. Show g maps B' onto A' .

Solution. (a) Abusing notation slightly, we have bijections $f : A \rightarrow B$ and $g : B' \rightarrow A'$, and their inverses $f^{-1} : B \rightarrow A$ and $g^{-1} : A' \rightarrow B'$. Since $A \cap A' = \emptyset$ and $B \cap B' = \emptyset$, the functions $h : X \rightarrow Y$ and $h' : Y \rightarrow X$ given by

$$h(x) = \begin{cases} f(x) & \text{if } x \in A, \\ g^{-1}(x) & \text{if } x \in A', \end{cases} \quad h'(y) = \begin{cases} f^{-1}(y) & \text{if } y \in B, \\ g(y) & \text{if } y \in B' \end{cases}$$

are well-defined. It is straightforward to verify that h and h' are mutual inverses and thus $X \sim Y$.

- (b) If A_1 is empty then $X = g(Y)$, i.e., g is surjective. Since g is injective by assumption, it immediately follows that $X \sim Y$ via g .

Let $P(n)$ be the statement that $\{A_1, \dots, A_n\}$ is a pairwise disjoint collection of sets; to prove that $\{A_n : n \in \mathbf{N}\}$ is a pairwise disjoint collection, we will first use induction to prove

that $P(n)$ holds for all $n \in \mathbf{N}$. The truth of $P(1)$ is clear, so suppose that $P(n)$ holds for some $n \in \mathbf{N}$. To demonstrate the truth of $P(n+1)$, we need to show that $A_k \cap A_{n+1} = \emptyset$ for all $1 \leq k \leq n$. Because $A_{n+1} = g(f(A_n)) \subseteq g(Y)$ and $A_1 = X \setminus g(Y)$, we see that $A_1 \cap A_{n+1} = \emptyset$. If $n \geq 2$, suppose that $2 \leq k \leq n$ and observe that

$$\begin{aligned} A_k \cap A_{n+1} &= g(f(A_{k-1})) \cap g(f(A_n)) \\ &= g(f(A_{k-1} \cap A_n)) && (f \text{ and } g \text{ are injective}) \\ &= g(f(\emptyset)) && (\text{induction hypothesis}) \\ &= \emptyset. \end{aligned}$$

Hence $P(n+1)$ holds; this completes the induction step and it follows that $P(n)$ holds for all $n \in \mathbf{N}$.

We can now show that $\{A_n : n \in \mathbf{N}\}$ is a pairwise disjoint collection of sets. Let A_m and A_n be given and suppose without loss of generality that $m < n$. By the previous paragraph the collection $\{A_1, \dots, A_m, \dots, A_n\}$ is pairwise disjoint and thus $A_m \cap A_n = \emptyset$.

That $\{f(A_n) : n \in \mathbf{N}\}$ is a pairwise disjoint collection now follows immediately from the injectivity of f .

(c) Observe that

$$f(A) = f\left(\bigcup_{n=1}^{\infty} A_n\right) = \bigcup_{n=1}^{\infty} f(A_n) = B,$$

where we have used that the image of a union is the union of the images; the proof of this is similar to the proof of the special case given in [Exercise 1.2.7](#) (d).

(d) Notice that

$$\begin{aligned} b \in B' &\iff b \notin f(A_n) \text{ for all } n \in \mathbf{N} \\ &\iff g(b) \notin g(f(A_n)) \text{ for all } n \in \mathbf{N} && (g \text{ is injective}) \\ &\iff g(b) \notin A_{n+1} \text{ for all } n \in \mathbf{N} \\ &\iff g(b) \notin A_n \text{ for all } n \geq 2. \end{aligned}$$

Notice further that $g(y) \notin X \setminus g(Y) = A_1$ for any $y \in Y$. It follows that

$$b \in B' \iff g(b) \notin A_n \text{ for all } n \in \mathbf{N} \iff g(b) \in A'. \quad (*)$$

Thus g maps B' into A' . To see that $g : B' \rightarrow A'$ is surjective, observe that for any $a \in A'$ we have, in particular, $a \notin A_1 = X \setminus g(Y)$, so that $a \in g(Y)$, i.e., $a = g(y)$ for some $y \in Y$. It then follows from $(*)$ that $y \in B'$.

1.6 Cantor's Theorem

Exercise 1.6.1. Show that $(0, 1)$ is uncountable if and only if \mathbf{R} is uncountable. This shows that Theorem 1.6.1 is equivalent to Theorem 1.5.6.

Solution. We have $(0, 1) \sim \mathbf{R}$ by [Exercise 1.5.4](#) (a).

Exercise 1.6.2. (a) Explain why the real number $x = .b_1b_2b_3b_4\ldots$ cannot be $f(1)$.

(b) Now, explain why $x \neq f(2)$, and in general why $x \neq f(n)$ for any $n \in \mathbf{N}$.

(c) Point out the contradiction that arises from these observations and conclude that $(0, 1)$ is uncountable.

Solution. (a) We have decimal expansions

$$f(1) = .a_{11}a_{12}a_{13}a_{14}\ldots \quad \text{and} \quad x = .b_1b_2b_3b_4\ldots$$

By construction, $b_1 \neq a_{11}$. This implies that $f(1) \neq x$, provided these decimal expansions are not two different representations of the same real number (for example, $.3$ and $.2999\ldots$). However, since the only way this can occur is when one decimal expansion terminates in repeating 0's and the other terminates in repeating 9's, and the digits b_n are always either 2 or 3, we see that $.b_1b_2b_3b_4\ldots$ must be the unique decimal representation of a real number.

(b) Since $.b_1b_2b_3b_4\ldots$ is the unique decimal expansion of the real number x (see part (a)) and $b_n \neq a_{nn}$, we have $x \neq f(n)$ for every $n \in \mathbf{N}$.

(c) The real number x belongs to $(0, 1)$ but not to the image of f , which contradicts our assumption that f was surjective. It follows that there cannot exist a bijection between \mathbf{N} and $(0, 1)$. Since $(0, 1)$ is clearly infinite, we may conclude that $(0, 1)$ is uncountable.