Understanding Analysis Solutions

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Contents

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 $f : A \to B$ 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

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

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 $a_n = a_N$. □

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

$$x \in A \cap (B \cap C) \iff x \in A \text{ and } x \in (B \cap C) \iff x \in A \text{ and } (x \in B \text{ and } x \in C)$$

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

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

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

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 $A_1, A_2, A_3, \ldots$ 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	$\cdots$
1	3	6	10	$\cdots$
2	5	9	14	$\cdots$
4	8	13	19	$\cdots$
7	12	18	25	$\cdots$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$

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 $x \in (A \cap B)^{\mathsf{c}}$, explain why $x \in A^{\mathsf{c}} \cup B^{\mathsf{c}}$. This shows that $(A \cap B)^{\mathsf{c}} \subseteq A^{\mathsf{c}} \cup B^{\mathsf{c}}$.

(b) Prove the reverse inclusion $(A \cap B)^{\mathsf{c}} \supseteq A^{\mathsf{c}} \cup B^{\mathsf{c}}$, and conclude that $(A \cap B)^{\mathsf{c}} = A^{\mathsf{c}} \cup B^{\mathsf{c}}$.

(c) Show $(A \cup B)^{\mathsf{c}} = A^{\mathsf{c}} \cap B^{\mathsf{c}}$ by demonstrating inclusion both ways.

Solution. (a) Observe that

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

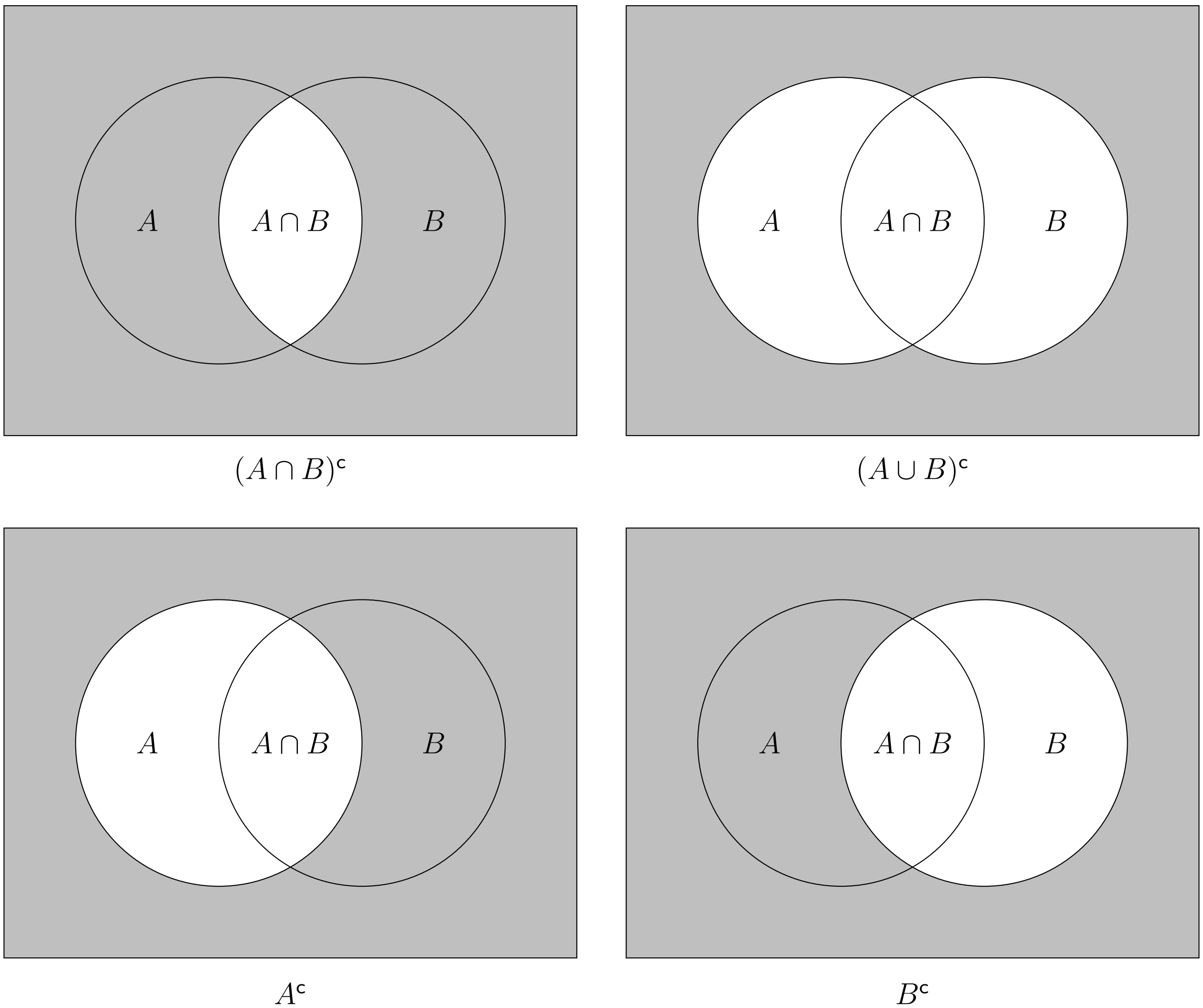


Figure F.1: Venn diagram for De Morgan's Laws; shaded regions are included, white regions are excluded

(b) See part (a). Figure F.1 shows some Venn diagrams which help to visualize De Morgan's Laws.

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

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

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

$$2ab \leq 2|ab| \iff a^2 + 2ab + b^2 \leq |a|^2 + 2|a||b| + |b|^2$$
$$\iff (a+b)^2 \leq (|a|+|b|)^2 \iff |a+b|^2 \leq (|a|+|b|)^2.$$

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 $g : \mathbf{R} \to \mathbf{R}$, 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

$$f(A) = [0, 4], \qquad f(A \cap B) = f([1, 2]) = [1, 4], \qquad f(A \cup B) = f([0, 4]) = [0, 16],$$

$$f(B) = [1, 16], \qquad f(A) \cap f(B) = [1, 4], \qquad f(A) \cup f(B) = [0, 16].$$

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

$$y \in g(A \cap B) \iff y = g(x) \text{ for some } x \in A \cap B$$

$$\implies (y = g(x_1) \text{ for some } x_1 \in A) \text{ and } (y = g(x_2) \text{ for some } x_2 \in B)$$

$$\iff y \in g(A) \text{ and } y \in g(B) \iff y \in g(A) \cap g(B).$$

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 $f : A \to B$. 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:

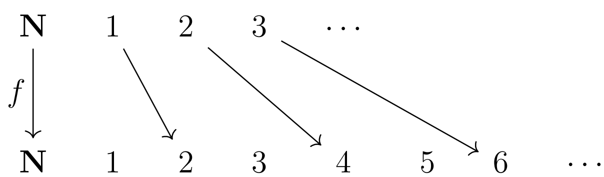
(a) $f : \mathbf{N} \to \mathbf{N}$ that is 1-1 but not onto.

(b) $f : \mathbf{N} \to \mathbf{N}$ that is onto but not 1-1.

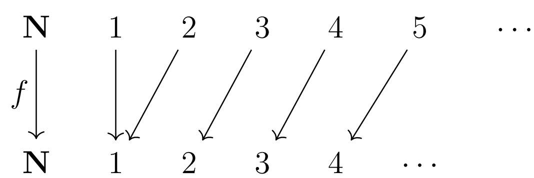
(c) $f : \mathbf{N} \to \mathbf{Z}$ that is 1-1 and onto.

Solution. (I 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 $f : \mathbf{N} \to \mathbf{N}$ 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 $f : \mathbf{N} \to \mathbf{N}$ 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 $f : \mathbf{N} \to \mathbf{Z}$ be given by

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

$$\begin{array}{ccccccc} \mathbf{N} & 1 & 2 & 3 & 4 & 5 & \cdots \\ f\big\downarrow & \big\downarrow & \big\downarrow & \big\downarrow & \big\downarrow & \big\downarrow & \\ \mathbf{Z} & 0 & 1 & -1 & 2 & -2 & \cdots \end{array}$$

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 $f : D \to \mathbf{R}$ 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.

(a) 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 $f^{-1}(A \cup B) = f^{-1}(A) \cup f^{-1}(B)$?

(b) The good behavior of preimages demonstrated in (a) is completely general. Show that for an arbitrary function $g : \mathbf{R} \to \mathbf{R}$, 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

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

Similarly,

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

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 $(y_1, y_2, y_3, \ldots)$ 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

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

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

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

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

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 $B_1, B_2, B_3, \ldots$ 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 $(A_1 \cup \cdots \cup A_n)^{\mathsf{c}} = A_1^{\mathsf{c}} \cap \cdots \cap A_n^{\mathsf{c}}$ for any sets $A_1, \ldots, A_n$. The truth of $P(1)$ is clear. Suppose that $P(n)$ holds for some $n \in \mathbf{N}$, let $A_1, \ldots, A_n, A_{n+1}$ be given, and observe that

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

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 $B_i = \{i, i+1, i+2, \ldots\}$, so that

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

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

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

It follows that

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

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

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

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:

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

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 $\inf B \ge \sup B$.

(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 $a \le b$. 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. □

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 $B = \{b \in \mathbf{R} : b$ 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 $A_1, A_2, A_3, \ldots$ 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 $k \in \{1, \ldots, n\}$, the Axiom of Completeness guarantees that $\sup A_k$ exists. By Lemma L.3, the finite set $\{\sup A_1, \ldots, \sup A_k\}$ 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 $k \in \{1, \ldots, n\}$; 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 $k \in \{1, \ldots, n\}$ 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 $\{\sup A_1, \sup A_2, \ldots\}$ 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 $\sup(A+B) = \sup A + \sup B$.

(a) Let $s = \sup A$ and $t = \sup B$. Show $s + t$ is an upper bound for $A + B$.

(b) Now let u be an arbitrary upper bound for $A + B$, and temporarily fix $a \in A$. Show $t \leq u - a$.

(c) Finally, show $\sup(A + B) = s + t$.

(d) 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 $A + B$.

(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 $t \leq u - a$.

(c) 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

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

(d) 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

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

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

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

$$q = p + \frac{2 - p^2}{p + 2} = \frac{2p + 2}{p + 2}. \tag{1}$$

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 $q \in B$. □

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

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

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 $\bigcap_{n=1}^{\infty}\left(0, \frac{1}{n}\right)$. 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 $x \notin \left(0, \frac{1}{N}\right)$ and hence that $x \notin \bigcap_{n=1}^{\infty}\left(0, \frac{1}{n}\right)$. We may conclude that $\bigcap_{n=1}^{\infty}\left(0, \frac{1}{n}\right) = \emptyset$.

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 $I_1, I_2, I_3, \ldots$ 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

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

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

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., $J_1 \supseteq J_2 \supseteq J_3 \supseteq \cdots$;

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

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 $f : \mathbf{N} \to B$ 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 $g : \mathbf{N} \to A$, 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

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

for $k \geq 2$. Because A is infinite and f is surjective, the set $\{n \in \mathbf{N} : f(n) \in A\} \setminus \{n_1, \ldots, n_{k-1}\}$ 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.2 for an example construction of the sequence $(n_k)_{k=1}^{\infty}$, for some bijection $f : \mathbf{N} \to B$.

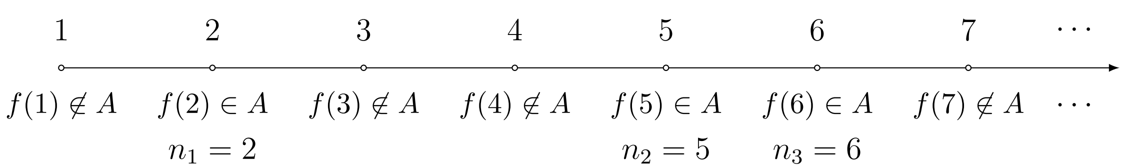


Figure F.2: Example construction of $(n_k)_{k=1}^{\infty}$

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

Define $g : \mathbf{N} \to A$ 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 $\{n \in \mathbf{N} : f(n) \in A\} \setminus \{n_1, \ldots, n_k\}$. 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 $\mathbf{Q} = \{r_1, r_2, r_3, \ldots\}$ 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

$$\begin{array}{cccccc}
1 & 3 & 6 & 10 & 15 & \cdots \\
2 & 5 & 9 & 14 & \cdots & \\
4 & 8 & 13 & \cdots & & \\
7 & 12 & \cdots & & & \\
11 & \cdots & & & & \\
\vdots & & & & &
\end{array}$$

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 $f : \mathbf{N} \to A_1$. 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 $g : \mathbf{N} \to A_1 \cup B_2$ by

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

$$\begin{array}{cccccccccc}
\mathbf{N} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & \cdots \\
{\scriptstyle g}\Big\downarrow & \Big\downarrow & \Big\downarrow & \Big\downarrow & \Big\downarrow & \Big\downarrow & \Big\downarrow & \Big\downarrow & \Big\downarrow & \\
A_1 \cup B_2 & x_1 & x_2 & x_3 & f(1) & f(2) & f(3) & f(4) & f(5) & \cdots \\
 & \multicolumn{3}{c}{\underbrace{\hspace{9em}}_{B_2}} & \multicolumn{5}{c}{\underbrace{\hspace{17em}}_{A_1}} &
\end{array}$$

Figure F.3: Example construction of g with $B_2 = \{x_1, x_2, x_3\}$

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 $h : \mathbf{N} \to B_2$. Define $g : \mathbf{N} \to A_1 \cup B_2$ by

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

$$\begin{array}{ccccccc}
\mathbf{N} & 1 & 2 & 3 & 4 & 5 & \cdots \\
{\scriptstyle g}\Big\downarrow & \Big\downarrow & \Big\downarrow & \Big\downarrow & \Big\downarrow & \Big\downarrow & \\
A_1 \cup B_2 & h(1) & f(1) & h(2) & f(2) & h(3) & \cdots
\end{array}$$

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 $A_1, \ldots, A_n$, the union $A_1 \cup \cdots \cup A_n$ 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 $A_1, \ldots, A_n, A_{n+1}$. Let $A' = A_1 \cup \cdots \cup A_n$; the induction hypothesis guarantees that A' is countable. Observe that

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

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 $f_n : \mathbf{N} \to A_n$. Let $a_{mn} = f_n(m)$ and arrange these into another two-dimensional array like so:

$$\begin{array}{cccccc} A_1 & A_2 & A_3 & A_4 & A_5 & \cdots \\ \hline a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & \cdots \\ a_{21} & a_{22} & a_{23} & a_{24} & \ddots & \\ a_{31} & a_{32} & a_{33} & \ddots & & \\ a_{41} & a_{42} & \ddots & & & \\ a_{51} & \ddots & & & & \\ \vdots & & & & & \end{array} \qquad \begin{array}{cccccc} 1 & 3 & 6 & 10 & 15 & \cdots \\ 2 & 5 & 9 & 14 & \ddots & \\ 4 & 8 & 13 & \ddots & & \\ 7 & 12 & \ddots & & & \\ 11 & \ddots & & & & \\ \vdots & & & & & \end{array}$$

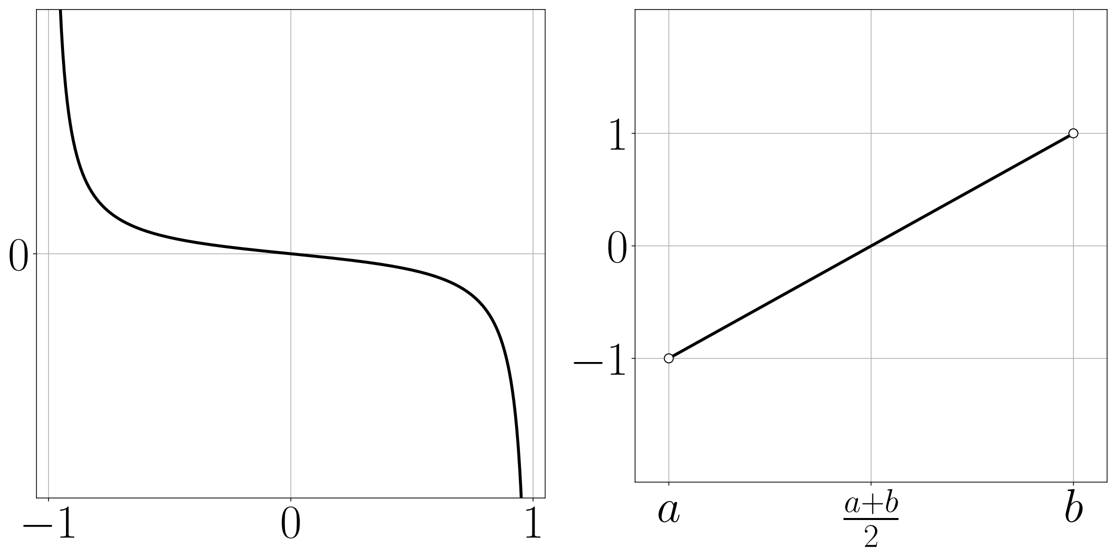
Since each f_n is surjective, each element of $\bigcup_{n=1}^{\infty} A_n$ appears somewhere in the left array. We define a function $g : \bigcup_{n=1}^{\infty} A_n \to \mathbf{N}$ by working through the grid along the diagonals (first a_{11}, then a_{21}, then a_{12}, then a_{31}, and so on), mapping 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 $g : \bigcup_{n=1}^{\infty} A_n \to B$ 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 $h : \mathbf{N} \to B$. It follows that the function $g^{-1} \circ h : \mathbf{N} \to \bigcup_{n=1}^{\infty} A_n$ 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 $f : (-1, 1) \to \mathbf{R}$ be the bijection given by $f(x) = \frac{x}{x^2-1}$ (see Example 1.5.4 and Figure F.4) and let $g : (a, b) \to (-1, 1)$ be given by $g(x) = \frac{2(x-a)}{b-a} - 1$ (see Figure F.4); 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).



(a) $f(x) = \frac{x}{x^2-1}$ on $(-1,1)$ (b) $g(x) = \frac{2(x-a)}{b-a} - 1$ on (a,b)

Figure F.4: Bijections $f : (-1,1) \to \mathbf{R}$ and $g : (a,b) \to (-1,1)$

(b) Let $f : (a,\infty) \to (0,1)$ be the bijection given by $f(x) = \frac{1}{x+1-a}$ (see Figure F.5). Thus $(a,\infty) \sim (0,1)$ and, by part (a), $(0,1) \sim \mathbf{R}$; it follows from Exercise 1.5.5 that $(a,\infty) \sim \mathbf{R}$.

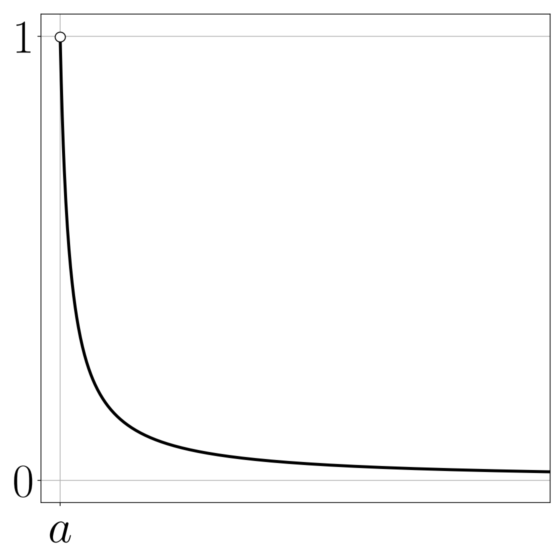


Figure F.5: Bijection $f : (a,\infty) \to (0,1)$ given by $f(x) = \frac{1}{x+1-a}$

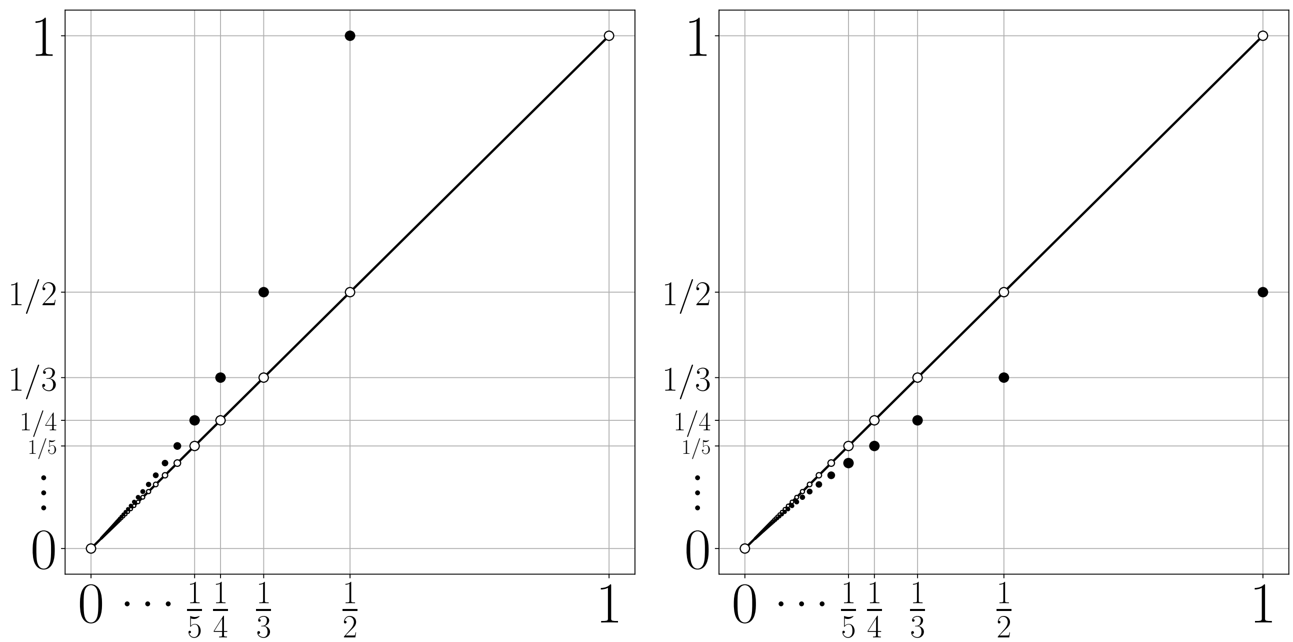
(c) It is clear that $[0,1) \sim (0,1]$ via the map $x \mapsto 1-x$ and so, by Exercise 1.5.5, it will suffice to show that $(0,1) \sim (0,1]$. Define a function $f : (0,1) \to (0,1]$ by

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

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

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

See Figure F.6 for a graph of f and f^{-1}.



(a) f on $(0,1)$ (b) f^{-1} on $(0,1]$

Figure F.6: Bijections $f : (0,1) \to (0,1]$ and $f^{-1} : (0,1] \to (0,1)$

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 $f : A \to A$ given by $f(x) = x$ is a bijection.

(b) Since $A \sim B$, there is a bijection $f : A \to B$. A function is bijective if and only if it has an inverse function $f^{-1} : B \to A$, which must also be bijective.

(c) There are bijections $f : A \to B$ and $g : B \to C$. It follows that the composition $g \circ f : A \to C$ 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 $f : (0, 1) \to S$ given by $f(x) = \left(x, \frac{1}{2}\right)$.

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

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 $0.x_1x_2x_3\ldots$ be the decimal representation of x and let $0.a_1a_2a_3\ldots$ 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 $0.s_1s_2s_3\ldots$ and $g(a, b)$ has decimal representation $0.t_1t_2t_3\ldots$, 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,

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

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 $\{b_1, \ldots, b_n\}$, then since each $b_i > a$ we have

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

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

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

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 $a_0, a_1, a_2, \ldots, a_n \in \mathbf{Z}$, not all zero, such that

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

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 $A_1, \ldots, A_n$ are countable sets, then $A_1 \times \cdots \times A_n$ is also countable.

Proof. Suppose that A and B are countable sets, so that $B = \{b_1, b_2, b_3, \ldots\}$. 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. $P_n = \{a_n x^n + a_{n-1}x^{n-1} + \cdots + a_1 x + a_0 : a_n, \dots, a_0 \in \mathbf{Z}, a_n \neq 0\}$. Notice that

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

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 $\mathbf{R} = A \cup A^{\mathsf{c}}$, 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 $C = \left\{\frac{1}{n} : n \in \mathbf{N}\right\}$ 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 $f : X \to Y$ and another 1-1 function $g : Y \to X$. Follow the steps to show that there exists a 1-1, onto function $h : X \to Y$ 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 $f : A \to B$ and $g : B' \to A'$, and their inverses $f^{-1} : B \to A$ and $g^{-1} : A' \to B'$. Since $A \cap A' = \emptyset$ and $B \cap B' = \emptyset$, the functions $h : X \to Y$ and $h' : Y \to X$ given by

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

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 $1 \le k \le n$. 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 $2 \le k \le n$ 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

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

$$\iff g(b) \notin A_n \text{ for all } n \geq 2.$$

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

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

Thus g maps B' into A'. To see that $g : B' \to A'$ 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

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

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...). 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 $n \in \mathbf{N}$. Here is an example construction of x given some function $f : \mathbf{N} \to (0,1)$:

$$\begin{array}{rcccccccccc} f(1) & = & 0 & . & 9 & 2 & 8 & 4 & 7 & 6 & \dots \\ f(2) & = & 0 & . & 2 & 2 & 8 & 4 & 9 & 1 & \dots \\ f(3) & = & 0 & . & 9 & 9 & 1 & 0 & 2 & 5 & \dots \\ f(4) & = & 0 & . & 2 & 1 & 1 & 9 & 2 & 1 & \dots \\ f(5) & = & 0 & . & 1 & 2 & 5 & 7 & 2 & 3 & \dots \\ f(6) & = & 0 & . & 9 & 7 & 7 & 5 & 1 & 8 & \dots \\ \vdots & & & & & & & & & & \\ x & = & 0 & . & 2 & 3 & 2 & 2 & 3 & 2 & \dots \end{array}$$

Notice how the first digit (after the decimal point) of x differs from the first digit of $f(1)$, the second digit of x differs from the second digit of $f(2)$, and so on.

(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.

Exercise 1.6.3. Supply rebuttals to the following complaints about the proof of Theorem 1.6.1.

(a) Every rational number has a decimal expansion, so we could apply this same argument to show that the set of rational numbers between 0 and 1 is uncountable. However, because we know that any subset of $\mathbf{Q}$ must be countable, the proof of Theorem 1.6.1 must be flawed.

(b) Some numbers have *two* different decimal representations. Specifically, any decimal expansion that terminates can also be written with repeating 9's. For instance, $1/2$ can also be written as $.5$ or as $.4999\dots$. Doesn't this cause some problems?

Solution. (a) The problem with this reasoning is that the real number

$$x = .b_1 b_2 b_3 b_4 \dots$$

that we construct may not be rational. For example, consider the function $f : \mathbf{N} \to (0,1) \cap \mathbf{Q}$

given by

$$\begin{array}{lll} f(1) = .3, & f(6) = .000003, & \\ f(2) = .02, & f(7) = .0000003, & \\ f(3) = .003, & f(8) = .00000003, & \cdots \\ f(4) = .0003, & f(9) = .000000002, & \\ f(5) = .00002, & f(10) = .0000000003, & \end{array}$$

This results in $x = .2322322232\ldots$, which is not rational since its decimal expansion does not repeat. So while x does not belong to the image of f, this is not a problem because x does not belong to $(0,1) \cap \mathbf{Q}$ either.

(b) We addressed this issue in Exercise 1.6.2 (a).

Exercise 1.6.4. Let S be the set consisting of all sequences of 0's and 1's. Observe that S is not a particular sequence, but rather a large set whose elements are sequences; namely

$$S = \{(a_1, a_2, a_3, \ldots) : a_n = 0 \text{ or } 1\}.$$

As an example, the sequence $(1, 0, 1, 0, 1, 0, 1, 0, \ldots)$ is an element of S, as is the sequence $(1, 1, 1, 1, 1, 1, \ldots)$.

Give a rigorous argument showing that S is uncountable.

Solution. Suppose we have a function $f : \mathbf{N} \to S$. For each $m \in \mathbf{N}$, let a_{mn} be the element in the n^{th} position of $f(m)$, so that

$$f(m) = (a_{m1}, a_{m2}, a_{m3}, a_{m4}, \ldots) \in S.$$

Let $b = (b_1, b_2, b_3, b_4, \ldots)$ be the sequence given by

$$b_n = \begin{cases} 0 & \text{if } a_{nn} = 1, \\ 1 & \text{if } a_{nn} = 0. \end{cases}$$

Notice that $b \in S$ but $b \neq f(n)$ for any $n \in \mathbf{N}$, since b differs from $f(n)$ in the n^{th} position. Here is an example construction of the sequence b, given some $f : \mathbf{N} \to S$:

$$\begin{array}{rcl}
f(1) & = & (1,\ \ 0,\ \ 0,\ \ 1,\ \ 0,\ \ 1,\ \ \ldots \\
f(2) & = & (0,\ \ 0,\ \ 1,\ \ 1,\ \ 1,\ \ 0,\ \ \ldots \\
f(3) & = & (0,\ \ 1,\ \ 1,\ \ 0,\ \ 0,\ \ 0,\ \ \ldots \\
f(4) & = & (1,\ \ 1,\ \ 1,\ \ 1,\ \ 0,\ \ 0,\ \ \ldots \\
f(5) & = & (0,\ \ 0,\ \ 1,\ \ 0,\ \ 0,\ \ 1,\ \ \ldots \\
f(6) & = & (1,\ \ 0,\ \ 0,\ \ 1,\ \ 0,\ \ 1,\ \ \ldots \\
\vdots & & \\
b & = & (0,\ \ 1,\ \ 0,\ \ 0,\ \ 1,\ \ 0,\ \ \ldots
\end{array}$$

Notice that b differs from $f(1)$ in the first position, from $f(2)$ in the second position, and so on.

Thus $b \notin f(\mathbf{N})$, so that f is not a surjection. Since f was arbitrary, it follows that there can be no bijection between $\mathbf{N}$ and S. It is clear that S is infinite, so we may conclude that S is uncountable.

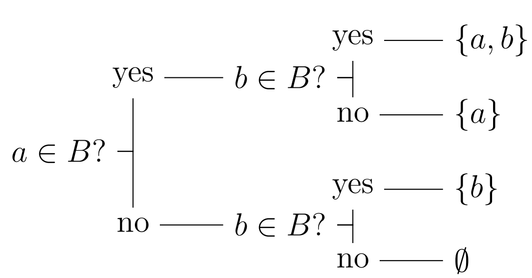
Exercise 1.6.5. (a) Let $A = \{a, b, c\}$. List the eight elements of $P(A)$. (Do not forget that $\emptyset$ is considered to be a subset of every set.)

(b) If A is finite with n elements, show that $P(A)$ has 2^n elements.

Solution. (a) We have

$$P(A) = \{\emptyset, \{a\}, \{b\}, \{c\}, \{a, b\}, \{a, c\}, \{b, c\}, \{a, b, c\}\}.$$

(b) To form a subset B of A, for each element $a \in A$, we must decide whether to include a in B or not. This is a binary choice to be made for each of the n elements of A; it follows that there are 2^n subsets of A. For example, here is a tree listing all $2^2 = 4$ subsets of $\{a, b\}$:



Exercise 1.6.6. (a) Using the particular set $A = \{a, b, c\}$, exhibit two different 1-1 mappings from A into $P(A)$.

(b) Letting $C = \{1, 2, 3, 4\}$, produce an example of a 1-1 map $g : C \to P(C)$.

(c) Explain why, in parts (a) and (b), it is impossible to construct mappings that are *onto*.

Solution. (a) Here are two injections $f : A \to P(A)$ and $g : A \to P(A)$:

$$\begin{aligned} f(a) &= \{a\}, & g(a) &= \{a, b\}, \\ f(b) &= \{b\}, & g(b) &= \{b, c\}, \\ f(c) &= \{c\}, & g(c) &= \{a, c\}. \end{aligned}$$

(b) Let g be given by

$$\begin{aligned} g(1) &= \{1\}, & g(3) &= \{3\}, \\ g(2) &= \{2\}, & g(4) &= \{4\}. \end{aligned}$$

(c) The power set of a finite set A always contains strictly more elements than A (Exercise 1.6.5 (b)). For finite sets, it is impossible to construct a surjective function from a set A to a set B if B contains strictly more elements than A.

Exercise 1.6.7. Return to the particular functions constructed in Exercise 1.6.6 and construct the subset B that results using the preceding rule. In each case, note that B is not in the range of the function used.

Solution. For all three functions from Exercise 1.6.6 we have $B = \emptyset$, which does not belong to the range of any of the functions.

Exercise 1.6.8. (a) First, show that the case $a' \in B$ leads to a contradiction.

(b) Now, finish the argument by showing that the case $a' \notin B$ is equally unacceptable.

Solution. (a) and (b). We have $a' \in B$ if and only if $a' \notin f(a') = B$, which is clearly a contradiction since a' either does or does not belong to B.

Exercise 1.6.9. Using the various tools and techniques developed in the last two sections (including the exercises from Section 1.5), give a compelling argument showing that $P(\mathbf{N}) \sim \mathbf{R}$.

Solution. First, let us show that $P(\mathbf{N}) \sim S$, where S is the set of all binary sequences defined in Exercise 1.6.4. Consider the function $f : P(\mathbf{N}) \to S$ given by $f(E) = (a_1, a_2, a_3, \ldots)$ where

$$a_n = \begin{cases} 1 & \text{if } n \in E, \\ 0 & \text{if } n \notin E. \end{cases}$$

For example,

$$f(\{1, 3, 4, 6, 7, 10, \ldots\}) = (1, 0, 1, 1, 0, 1, 1, 0, 0, 1, \ldots).$$

This function is a bijection since it has an inverse $f^{-1} : S \to P(\mathbf{N})$ given by

$$f^{-1}(a_1, a_2, a_3, \ldots) = \{n \in \mathbf{N} : a_n = 1\}.$$

Now let us show that $S \sim (0, 1)$. Consider the function $g : S \to (0, 1)$ given by

$$g(a_1, a_2, a_3, \ldots) = 0.5a_1a_2a_3\ldots,$$

where $0.5a_1a_2a_3\ldots$ is a decimal expansion (for example, $g(1, 0, 1, 0, 0, 0, \ldots) = 0.5101$). This function is injective since if $a = (a_1, a_2, a_3, \ldots) \neq b = (b_1, b_2, b_3, \ldots)$, there must exist some $n \in \mathbf{N}$ such that $a_n \neq b_n$. It follows that $g(a) \neq g(b)$, provided $g(a) = 0.5a_1a_2a_3\ldots$ and $g(b) = 0.5b_1b_2b_3\ldots$ are not two different decimal expansions of the same real number. This cannot be the case since each a_i and b_i is either 0 or 1, and never 9.

Now consider the function $h : (0, 1) \to S$ given by

$$h(x) = h(0.a_1a_2a_3\ldots) = (a_1, a_2, a_3, \ldots),$$

where $0.a_1a_2a_3\ldots$ is the **binary** expansion of $x \in (0, 1)$, choosing that expansion which terminates in 0's if x has two different binary expansions. This function is injective since if $x = 0.a_1a_2a_3\ldots \neq y = 0.b_1b_2b_3\ldots$, then there must be some $n \in \mathbf{N}$ such that $a_n \neq b_n$. It follows that $h(x) \neq h(y)$.

The Schröder-Bernstein Theorem (Exercise 1.5.11) now implies that $S \sim (0, 1)$. We showed in Exercise 1.5.4 that $(0, 1) \sim \mathbf{R}$ and thus

$$P(\mathbf{N}) \sim S \sim (0, 1) \sim \mathbf{R}.$$

In Exercise 1.5.5 we showed that $\sim$ is an equivalence relation, so the chain of equivalences above allows us to conclude that $P(\mathbf{N}) \sim \mathbf{R}$.

Exercise 1.6.10. As a final exercise, answer each of the following by establishing a 1-1 correspondence with a set of known cardinality.

(a) Is the set of all functions from $\{0,1\}$ to $\mathbf{N}$ countable or uncountable?

(b) Is the set of all functions from $\mathbf{N}$ to $\{0,1\}$ countable of uncountable?

(c) Given a set B, a subset $\mathcal{A}$ of $P(B)$ is called an *antichain* if no element of $\mathcal{A}$ is a subset of any other element of $\mathcal{A}$. Does $P(\mathbf{N})$ contain an uncountable antichain?

Solution. (a) Let $\mathbf{N}^{\{0,1\}}$ be the set of all functions from $\{0,1\}$ to $\mathbf{N}$. Consider the function $F : \mathbf{N}^{\{0,1\}} \to \mathbf{N} \times \mathbf{N}$ given by $F(f) = (f(0), f(1))$. This function is a bijection since it has an inverse $F^{-1} : \mathbf{N} \times \mathbf{N} \to \mathbf{N}^{\{0,1\}}$ given by $F^{-1}(a,b) = f$, where $f : \{0,1\} \to \mathbf{N}$ is the function satisfying $f(0) = a, f(1) = b$. Thus

$$\mathbf{N}^{\{0,1\}} \sim \mathbf{N} \times \mathbf{N} \sim \mathbf{N},$$

where we have used Lemma L.5 for the second equivalence. We may conclude that $\mathbf{N}^{\{0,1\}}$ is countable.

(b) The set of all functions from $\mathbf{N}$ to $\{0,1\}$ is nothing but the set of all binary sequences S defined in Exercise 1.6.4, since a function $f : \mathbf{N} \to \{0,1\}$ can be identified with the sequence $(f(0), f(1), f(2), \ldots)$. Thus the set of all functions from $\mathbf{N}$ to $\{0,1\}$ is uncountable, since we showed that S is uncountable in Exercise 1.6.4.

(c) Consider the following collection of subsets of $P(\mathbf{Q})$:

$$\mathcal{A} := \{(a, a+1) \cap \mathbf{Q} : a \in \mathbf{R}\}.$$

For real numbers $a < b$, it follows from the density of $\mathbf{Q}$ in $\mathbf{R}$ (Theorem 1.4.3) that there exist rational numbers p and q such that $a < p < b$ and $a < q < a+1$. Let $r = \min\{p, q\}$ and notice that $a < r < b$ and $a < r < a+1$. It follows that $r \in (a, a+1)$ and $r \notin (b, b+1)$, whence

$$(a, a+1) \cap \mathbf{Q} \not\subseteq (b, b+1) \cap \mathbf{Q}.$$

A similar argument shows that this non-inclusion still holds if $b < a$ and so it follows that for any real numbers $a \neq b$ we have

$$(a, a+1) \cap \mathbf{Q} \not\subseteq (b, b+1) \cap \mathbf{Q},$$

i.e., $\mathcal{A}$ is an antichain.

Another consequence of the previous paragraph is that if a and b are distinct real numbers, then

$$(a, a+1) \cap \mathbf{Q} \neq (b, b+1) \cap \mathbf{Q}.$$

It follows that the map $g : \mathbf{R} \to \mathcal{A}$ defined by $g(a) = (a, a+1) \cap \mathbf{Q}$ is injective. Since g is evidently surjective, we have that $\mathbf{R} \sim \mathcal{A}$.

To finish the exercise, we will need the following two lemmas.

Lemma L.6. Suppose A and B are sets and $f : A \to B$ is a bijection. Define $F : P(A) \to P(B)$

$$F(X) = f(X) = \{f(x) : x \in X\}.$$

Then F is a bijection.

Proof. Suppose $X, Y \in P(A)$ are such that $X \neq Y$. Without loss of generality suppose that $X \not\subseteq Y$, so that there is some $x \in X$ such that $x \notin Y$. The injectivity of f then implies that $f(x) \notin f(Y)$, whence $F(X) \neq F(Y)$. Thus F is injective.

Now let $Y \in P(B)$ be given. For each $y \in Y$, the surjectivity of f implies that there is some $x \in A$ such that $f(x) = y$; let X be the collection of these x. It follows that $F(X) = Y$ and hence that F is surjective. □

Lemma L.7. Suppose A and B are sets and $f : A \to B$ is injective. Then if $\mathcal{A} \subseteq P(A)$ is an antichain, so is $\mathcal{A}' := \{f(X) : X \in \mathcal{A}\} \subseteq P(B)$.

Proof. Suppose we have two elements $f(X)$ and $f(Y)$ in $\mathcal{A}'$, where X and Y belong to $\mathcal{A}$. Since $\mathcal{A}$ is an antichain, we have $X \not\subseteq Y$, which can be the case if and only if there is some $x \in X$ such that $x \notin Y$. The injectivity of f then implies that $f(x) \in f(X)$ but $f(x) \notin f(Y)$. It follows that $f(X)$ is not a subset of $f(Y)$ and we may conclude that $\mathcal{A}'$ is an antichain. □

Returning to the exercise, let $f : \mathbf{Q} \to \mathbf{N}$ be a bijection (such a function exists by Theorem 1.5.6 (i)). By Lemma L.6, the function $F : P(\mathbf{Q}) \to P(\mathbf{N})$ defined by $F(X) = f(X)$ is also a bijection, which restricts to a bijection $F : \mathcal{A} \to F(\mathcal{A})$. Thus $F(\mathcal{A}) \sim \mathcal{A} \sim \mathbf{R}$, so that $F(\mathcal{A})$ is uncountable. We may now use Lemma L.7 to conclude that $F(\mathcal{A}) \subseteq P(\mathbf{N})$ is an uncountable antichain.

Chapter 2

Sequences and Series

2.2 The Limit of a Sequence

Exercise 2.2.1. What happens if we reverse the order of the quantifiers in Definition 2.2.3?

Definition: A sequence (x_n) *verconges* to x if *there exists* an $\epsilon > 0$ such that *for all* $N \in \mathbf{N}$ it is true that $n \geq N$ implies $|x_n - x| < \epsilon$.

Give an example of a vercongent sequence. Is there an example of a vercongent sequence that is divergent? Can a sequence verconge to two different values? What exactly is being described in this strange definition?

Solution. First observe that the statement

$$\text{for all } N \in \mathbf{N},\, n \geq N \implies |x_n - x| < \epsilon$$

is equivalent to

$$\text{for all } n \in \mathbf{N},\, |x_n - x| < \epsilon.$$

So a sequence verconges to x if there exists an $\epsilon > 0$ such that $|x_n - x| < \epsilon$, or equivalently such that $x_n \in (x - \epsilon, x + \epsilon)$, for all $n \in \mathbf{N}$.

For an example of a vercongent sequence that diverges, consider $(x_n) = (1, 0, 1, 0, \ldots)$. This sequence verconges to $\frac{1}{2}$ since $\left|x_n - \frac{1}{2}\right| = \frac{1}{2} < 1$ for all $n \in \mathbf{N}$. To see that this sequence diverges, suppose there was some $x \in \mathbf{R}$ such that $\lim x_n = x$. Then there must exist some $N \in \mathbf{N}$ such that $n \geq N$ implies that $|x_n - x| < \frac{1}{2}$. Observe that

$$1 = |x_N - x_{N+1}| \leq |x_N - x| + |x_{N+1} - x| < \frac{1}{2} + \frac{1}{2} = 1,$$

i.e., $1 < 1$, which is a contradiction.

A sequence can verconge to two different values. The sequence $(x_n) = (1, 1, 1, 1, \ldots)$ verconges to 1:

$$|x_n - 1| = 0 < 1 \text{ for all } n \in \mathbf{N},$$

and also to 0:

$$|x_n| = 1 < 2 \text{ for all } n \in \mathbf{N}.$$

This definition describes the bounded sequences (see Definition 2.3.1); a sequence which verconges to some $x \in \mathbf{R}$ must be bounded, and conversely any bounded sequence verconges to some $x \in \mathbf{R}$.

Exercise 2.2.2. Verify, using the definition of convergence of a sequence, that the following sequences converge to the proposed limit.

(a) $\lim \frac{2n+1}{5n+4} = \frac{2}{5}$.

(b) $\lim \frac{2n^2}{n^3+3} = 0$.

(c) $\lim \frac{\sin(n^2)}{\sqrt[3]{n}} = 0$.

Solution. See Figure F.7 for graphs of the first thirty terms of each sequence. The graphs of the sequences in parts (a) and (b) give us a good idea of the limiting value of each sequence; the graph for part (c) is not so clear.

(a) Let $\epsilon > 0$ be given. Choose $N \in \mathbf{N}$ such that $N > \frac{3}{25\epsilon}$ and observe that for $n \geq N$ we have

$$\left|\frac{2n+1}{5n+4} - \frac{2}{5}\right| = \frac{3}{25n+20} < \frac{3}{25n} \leq \frac{3}{25N} < \epsilon.$$

It follows that $\lim \frac{2n+1}{5n+4} = \frac{2}{5}$.

(b) Let $\epsilon > 0$ be given. Choose $N \in \mathbf{N}$ such that $N > \frac{2}{\epsilon}$ and observe that for $n \geq N$ we have

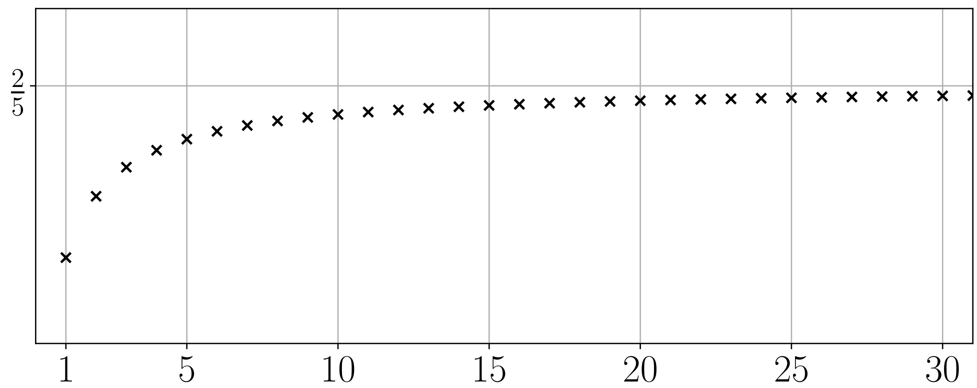
$$\left|\frac{2n^2}{n^3+3}\right| = \frac{2n^2}{n^3+3} < \frac{2n^2}{n^3} = \frac{2}{n} \leq \frac{2}{N} < \epsilon.$$

It follows that $\lim \frac{2n^2}{n^3+3} = 0$.

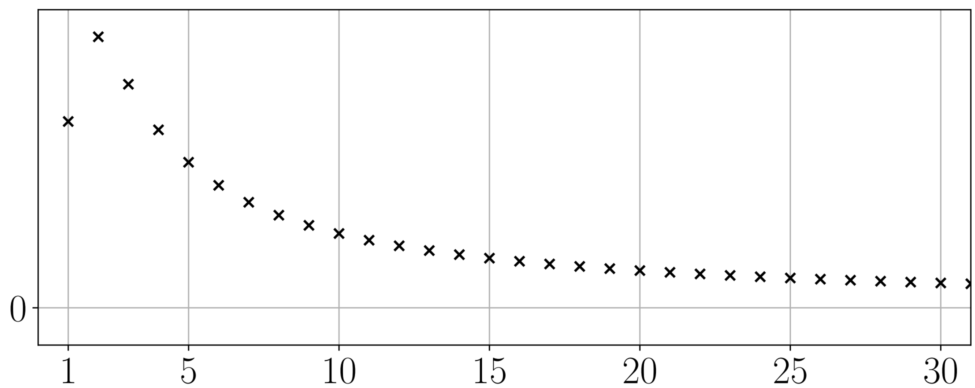
(c) Let $\epsilon > 0$ be given. Choose $N \in \mathbf{N}$ such that $N > \frac{1}{\epsilon^3}$ and observe that for $n \geq N$ we have

$$\left|\frac{\sin(n^2)}{\sqrt[3]{n}}\right| = \frac{|\sin(n^2)|}{\sqrt[3]{n}} \leq \frac{1}{\sqrt[3]{n}} \leq \frac{1}{\sqrt[3]{N}} < \epsilon.$$

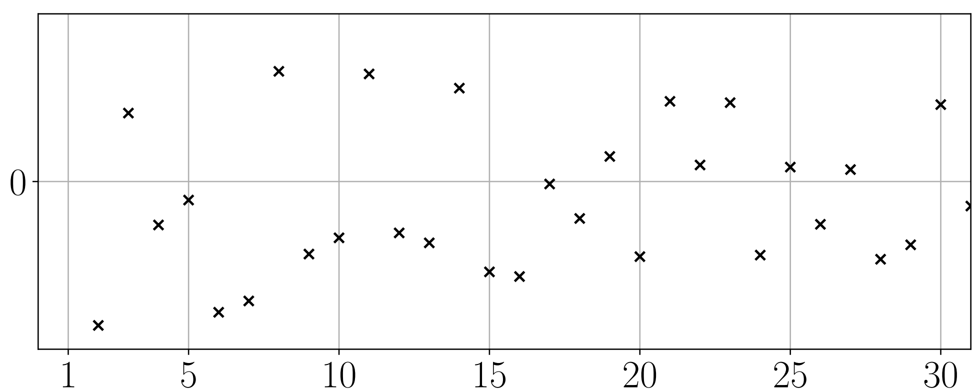
It follows that $\lim \frac{\sin(n^2)}{\sqrt[3]{n}} = 0$.



(a) $\frac{2n+1}{5n+4}$ for $1 \leq n \leq 30$



(b) $\frac{2n^2}{n^3+3}$ for $1 \leq n \leq 30$



(c) $\frac{\sin(n^2)}{\sqrt[3]{n}}$ for $1 \leq n \leq 30$

Figure F.7: Exercise 2.2.2 sequences for $1 \leq n \leq 30$

Exercise 2.2.3. Describe what we would have to demonstrate in order to disprove each of the following statements.

(a) At every college in the United States, there is a student who is at least seven feet tall.

(b) For all colleges in the United States, there exists a professor who gives every student a grade of either A or B.

(c) There exists a college in the United States where every student is at least six feet tall.

Solution. (a) We would have to find a college in the United States where every student is less than seven feet tall.

(b) We would have to find a college in the United States where each professor gives at least one student a grade of C or worse.

(c) We would have to show that every college in the United States has a student who is less than six feet tall.

Exercise 2.2.4. Give an example of each or state that the request is impossible. For any that are impossible, give a compelling argument for why that is the case.

(a) A sequence with an infinite number of ones that does not converge to one.

(b) A sequence with an infinite number of ones that converges to a limit not equal to one.

(c) A divergent sequence such that for every $n \in \mathbf{N}$ it is possible to find n consecutive ones somewhere in the sequence.

Solution. (a) Consider $(x_n) = (1, 0, 1, 0, \ldots)$. This sequence has an infinite number of ones but, as shown in Exercise 2.2.1, diverges.

(b) This is impossible. Suppose (x_n) is such a sequence with $\lim x_n = x \neq 1$. Then there must exist some $N \in \mathbf{N}$ such that for all $n \geq N$ we have $|x_n - x| < |1 - x|$. Since this sequence contains infinitely many ones, it must be the case that there is some $m \geq N$ such that $x_m = 1$. This implies that $|x_m - x| = |1 - x| < |1 - x|$, which is a contradiction.

(c) Consider the sequence

$$(x_n) = (1, 0, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, \ldots).$$

For each $n \in \mathbf{N}$ we can find n consecutive ones starting at the m^{th} position and, for $n \geq 2$, we can find a zero at the $(m-1)^{\text{th}}$ position, where $m = \frac{n(n+1)}{2}$. Furthermore, the sequence is divergent. To see this, suppose there was some $x \in \mathbf{R}$ such that $\lim x_n = x$. It follows that there is an $N \in \mathbf{N}$ such that $n \geq N$ implies that $|x_n - x| < \frac{1}{2}$. Since the sequence contains infinitely many ones and zeros, we can find indices $k, \ell \geq N$ such that $x_k = 1$ and $x_\ell = 0$. Then

$$1 = |x_k - x_\ell| \leq |x_k - x| + |x_\ell - x| < \frac{1}{2} + \frac{1}{2} = 1,$$

i.e., $1 < 1$, which is a contradiction.

Exercise 2.2.5. Let $[[x]]$ be the greatest integer less than or equal to x. For example, $[[\pi]] = 3$ and $[[3]] = 3$. For each sequence, find $\lim a_n$ and verify it with the definition of convergence.

(a) $a_n = [[5/n]]$,

(b) $a_n = [[(12 + 4n)/3n]]$.

Reflecting on these examples, comment on the statement following Definition 2.2.3 that "the smaller the ϵ-neighborhood, the larger N may have to be."

Solution. (a) We claim that $\lim a_n = 0$. Let $\epsilon > 0$ be given and observe that if $n \geq 6$, then

$$0 < \frac{5}{n} < 1 \implies \left[\left[\frac{5}{n}\right]\right] = 0.$$

So if we take $N = 6$, then $n \geq N$ implies that $\left|\left[\left[\frac{5}{n}\right]\right]\right| = 0 < \epsilon$.

(b) We claim that $\lim a_n = 1$. Let $\epsilon > 0$ be given and observe that if $n \geq 7$, then

$$\frac{1}{n} < \frac{1}{6} \iff \frac{4}{n} < \frac{2}{3} \iff \frac{4}{n} + \frac{1}{3} < 1.$$

Hence for $n \geq 7$ we have

$$0 < \frac{4}{n} + \frac{1}{3} < 1 \implies \left[\left[\frac{4}{n} + \frac{1}{3}\right]\right] = 0.$$

So if we take $N = 7$, then $n \geq N$ implies that

$$\left[\left[\frac{12 + 4n}{3n} - 1\right]\right] = \left[\left[\frac{4}{n} + \frac{1}{3}\right]\right] = 0 < \epsilon.$$

These examples demonstrate that taking smaller ϵ-neighbourhoods may not require us to take larger values of N; the same value of N in each example works for every ϵ-neighbourhood that we choose.

Exercise 2.2.6. Prove Theorem 2.2.7. To get started, assume $(a_n) \to a$ and $(a_n) \to b$. Now argue $a = b$.

Solution. Let $\epsilon > 0$ be given. There are positive integers N_1 and N_2 such that

$$n \geq N_1 \implies |a_n - a| < \frac{\epsilon}{2} \qquad \text{and} \qquad n \geq N_2 \implies |a_n - b| < \frac{\epsilon}{2}.$$

Let $N = \max\{N_1, N_2\}$ and observe that for $n \geq N$ we have

$$|a - b| = |a - a_n + a_n - b| \leq |a_n - a| + |a_n - b| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon.$$

So we have shown that $|a - b| < \epsilon$ for any $\epsilon > 0$; it follows from Theorem 1.2.6 that $a = b$.

Exercise 2.2.7. Here are two useful definitions:

(i) A sequence (a_n) is *eventually* in a set $A \subseteq \mathbf{R}$ if there exists an $N \in \mathbf{N}$ such that $a_n \in A$ for all $n \geq N$.

(ii) A sequence (a_n) is *frequently* in a set $A \subseteq \mathbf{R}$ if, for every $N \in \mathbf{N}$, there exists an $n \geq N$ such that $a_n \in A$.

(a) Is the sequence $(-1)^n$ eventually or frequently in the set $\{1\}$?

(b) Which definition is stronger? Does frequently imply eventually or does eventually imply frequently?

(c) Give an alternate rephrasing of Definition 2.2.3B using either frequently or eventually. Which is the term we want?

(d) Suppose an infinite number of terms of a sequence (x_n) are equal to 2. Is (x_n) necessarily eventually in the interval $(1.9, 2.1)$? Is it frequently in $(1.9, 2.1)$?

Solution. (a) The sequence $(-1)^n$ is frequently but not eventually in the set $\{1\}$. To see this, let $N \in \mathbf{N}$ be given. If N is even, then $(-1)^N \in \{1\}$ and $(-1)^{N+1} \notin \{1\}$, and if N is odd then $(-1)^N \notin \{1\}$ and $(-1)^{N+1} \in \{1\}$. In any case, we can always find indices $m, n \geq N$ such that $(-1)^m \notin \{1\}$ (this shows that the sequence is not eventually in $\{1\}$) and such that $(-1)^n \in \{1\}$ (this shows that the sequence is frequently in $\{1\}$).

(b) Eventually is the stronger definition. Frequently does not imply eventually, as part (a) shows, but eventually does imply frequently. To see this, suppose that (a_n) is eventually in a set A, i.e., there is an $N \in \mathbf{N}$ such that $a_n \in A$ for all $n \geq N$. Let $M \in \mathbf{N}$ be given. Set $n = \max\{M, N\}$ and observe that $n \geq M$ and $a_n \in A$. Hence (a_n) is frequently in A.

(c) The term we want is eventually. Here is a rephrasing of Definition 2.2.3B: a sequence (a_n) converges to a if, given any $\epsilon > 0$, the sequence (a_n) is eventually in the ϵ-neighbourhood $V_\epsilon(a)$ of a.

(d) Such a sequence is not necessarily eventually in $(1.9, 2.1)$; consider the sequence $(x_n) = (2, 0, 2, 0, 2, \ldots)$ for example. For any $N \in \mathbf{N}$, we can always find an index $n \geq N$ (either $n = N$ or $n = N + 1$) such that $x_n = 0 \notin (1.9, 2.1)$. However, such a sequence must be frequently in $(1.9, 2.1)$. To see this, let $N \in \mathbf{N}$ be given. Then there must exist an index $n \geq N$ such that $x_n = 2 \in (1.9, 2.1)$ (otherwise there would be only finitely many twos in the sequence).

Exercise 2.2.8. For some additional practice with nested quantifiers, consider the following invented defintion:

Let's call a sequence (x_n) *zero-heavy* if there exists $M \in \mathbf{N}$ such that for all $N \in \mathbf{N}$ there exists n satisfying $N \leq n \leq N + M$ where $x_n = 0$.

(a) Is the sequence $(0, 1, 0, 1, 0, 1, \ldots)$ zero-heavy?

(b) If a sequence is zero-heavy does it necessarily contain an infinite number of zeros? If not, provide a counterexample.

(c) If a sequence contains an infinite number of zeros, is it necessarily zero-heavy? If not, provide a counterexample.

(d) Form the logical negation of the above definition. That is, complete the sentence: A sequence is *not* zero-heavy if ....

Solution. (a) This sequence is zero-heavy; $M = 1$ works. Indeed, let $N \in \mathbf{N}$ be given. If N is odd then let $n = N$ and if N is even then let $n = N + 1$. In either case, we have $N \leq n \leq N + 1$ and $x_n = 0$.

(b) A zero-heavy sequence must contain an infinite number of zeros. To see this, suppose (x_n) is a sequence with a finite number of zeros, i.e. there is an $N \in \mathbf{N}$ such that $x_n \neq 0$ for all $n \geq N$. Then no matter which M we choose, we will never be able to find $n \in \mathbf{N}$ with $N \leq n \leq N+M$ and $x_n = 0$. Thus the sequence (x_n) is not zero-heavy.

(c) A sequence with an infinite number of zeros is not necessarily zero-heavy. For a counterexample, consider the sequence

$$(x_n) = (1, 0, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, \ldots).$$

This sequence contains infinitely many zeros, but is not zero-heavy. To see this, let $M \in \mathbf{N}$ be given. It is always possible to find M consecutive ones in the sequence (x_n) (see Exercise 2.2.4 (c)); suppose this string of ones starts at $x_N = 1$. Then for each $n \in \mathbf{N}$ satisfying $N \leq n \leq N+M$, we have $x_n = 1 \neq 0$.

(d) A sequence is not zero-heavy if for every $M \in \mathbf{N}$ there exists an $N \in \mathbf{N}$ such that $x_n \neq 0$ for each $n \in \mathbf{N}$ satisfying $N \leq n \leq N+M$.

2.3 The Algebraic and Order Limit Theorems

Exercise 2.3.1. Let $x_n \geq 0$ for all $n \in \mathbf{N}$.

(a) If $(x_n) \to 0$, show that $(\sqrt{x_n}) \to 0$.

(b) If $(x_n) \to x$, show that $(\sqrt{x_n}) \to \sqrt{x}$.

Solution. (a) Let $\epsilon > 0$ be given. Since $x_n \to 0$, there exists an $N \in \mathbf{N}$ such that

$$n \geq N \implies |x_n| = x_n < \epsilon^2 \iff \sqrt{x_n} < \epsilon.$$

It follows that $\lim\bigl(\sqrt{x_n}\bigr) = 0$.

(b) By Theorem 2.3.4, we must have $x \geq 0$. The case $x = 0$ was handled in part (a), so suppose that $x > 0$, which gives $\sqrt{x} > 0$. For each $n \in \mathbf{N}$, observe that

$$\bigl|\sqrt{x_n} - \sqrt{x}\bigr| = \frac{\bigl|\sqrt{x_n} - \sqrt{x}\bigr|\bigl(\sqrt{x_n} + \sqrt{x}\bigr)}{\sqrt{x_n} + \sqrt{x}} = \frac{|x_n - x|}{\sqrt{x_n} + \sqrt{x}} \leq \frac{|x_n - x|}{\sqrt{x}}.$$

Let $\epsilon > 0$ be given. Since $x_n \to x$, there exists an $N \in \mathbf{N}$ such that $|x_n - x| < \epsilon\sqrt{x}$ whenever $n \geq N$. For $n \geq N$, it follows that

$$\bigl|\sqrt{x_n} - \sqrt{x}\bigr| \leq \frac{|x_n - x|}{\sqrt{x}} < \epsilon.$$

Thus $\lim(\sqrt{x_n}) = \sqrt{x}$.

Exercise 2.3.2. Using only Definition 2.2.3, prove that if $(x_n) \to 2$ then

(a) $\left(\frac{2x_n-1}{3}\right) \to 1$;

(b) $(1/x_n) \to 1/2$.

Solution. (a) Let $\epsilon > 0$ be given. Since $x_n \to 2$, there exists an $N \in \mathbf{N}$ such that $n \geq N$ implies that $|x_n - 2| < \frac{3\epsilon}{2}$. For $n \geq N$ we then have

$$\left|\frac{2x_n - 1}{3} - 1\right| = \left|\frac{2x_n - 4}{3}\right| = \frac{2}{3}|x_n - 2| < \epsilon.$$

It follows that $\left(\frac{2x_n-1}{3}\right) \to 1$.

(b) Since $x_n \to 2$, there is an $N_1 \in \mathbf{N}$ such that $n \geq N_1 \implies |x_n - 2| < 1$. For $n \geq N_1$ we then have

$$2 \leq |x_n - 2| + |x_n| < 1 + |x_n| \implies 1 < |x_n| \implies \frac{1}{|x_n|} < 1.$$

Let $\epsilon > 0$ be given. Since $x_n \to 2$, there is an $N_2 \in \mathbf{N}$ such that $|x_n - 2| < 2\epsilon$ whenever $n \geq N_2$. Set $N = \max\{N_1, N_2\}$ and observe that for $n \geq N$ we have

$$\left|\frac{1}{x_n} - \frac{1}{2}\right| = \left|\frac{2 - x_n}{2x_n}\right| = \frac{|x_n - 2|}{2|x_n|} < \frac{|x_n - 2|}{2} < \epsilon.$$

It follows that $\frac{1}{x_n} \to \frac{1}{2}$.

Exercise 2.3.3 (Squeeze Theorem). Show that if $x_n \leq y_n \leq z_n$ for all $n \in \mathbf{N}$, and if $\lim x_n = \lim z_n = l$, then $\lim y_n = l$ as well.

Solution. Let $\epsilon > 0$ be given. There are positive integers N_1 and N_2 such that

$$n \geq N_1 \implies |x_n - l| < \epsilon \iff -\epsilon < x_n - l < \epsilon,$$

$$n \geq N_2 \implies |z_n - l| < \epsilon \iff -\epsilon < z_n - l < \epsilon.$$

Let $N = \max\{N_1, N_2\}$. Then since $x_n - l \leq y_n - l \leq z_n - l$ for all $n \in \mathbf{N}$, for $n \geq N$ we have

$$-\epsilon < y_n - l < \epsilon \iff |y_n - l| < \epsilon.$$

It follows that $\lim y_n = l$.

Exercise 2.3.4. Let $(a_n) \to 0$, and use the Algebraic Limit Theorem to compute each of the following limits (assuming the fractions are always defined):

(a) $\lim\left(\frac{1+2a_n}{1+3a_n-4a_n^2}\right)$

(b) $\lim\left(\frac{(a_n+2)^2-4}{a_n}\right)$

(c) $\lim\left(\frac{\frac{2}{a_n}+3}{\frac{1}{a_n}+5}\right)$.

Solution. The manipulations of limits in these solutions are justified by the Algebraic Limit Theorem (Theorem 2.3.3).

(a) We have
$$\lim\left(\frac{1+2a_n}{1+3a_n-4a_n^2}\right) = \frac{1+2\lim a_n}{1+3\lim a_n - 4(\lim a_n)^2} = \frac{1}{1} = 1.$$

(b) We have
$$\lim\left(\frac{(a_n+2)^2-4}{a_n}\right) = \lim\left(\frac{a_n^2+4a_n}{a_n}\right) = \lim(a_n+4) = \lim a_n + 4 = 4.$$

(c) We have
$$\lim\left(\frac{\frac{2}{a_n}+3}{\frac{1}{a_n}+5}\right) = \lim\left(\frac{2+3a_n}{1+5a_n}\right) = \frac{2+3\lim a_n}{1+5\lim a_n} = \frac{2}{1} = 2.$$

Exercise 2.3.5. Let (x_n) and (y_n) be given, and define (z_n) to be the "shuffled" sequence $(x_1, y_1, x_2, y_2, x_3, y_3, \ldots, x_n, y_n, \ldots)$. Prove that (z_n) is convergent if and only if (x_n) and (y_n) are both convergent with $\lim x_n = \lim y_n$.

Solution. (z_n) is the sequence given by
$$z_n = \begin{cases} x_{\frac{n+1}{2}} & \text{if } n \text{ is odd,} \\ y_{\frac{n}{2}} & \text{if } n \text{ is even.} \end{cases}$$

Suppose that (x_n) and (y_n) are both convergent with $\lim x_n = \lim y_n = L$ for some $L \in \mathbf{R}$ and let $\epsilon > 0$ be given. There are positive integers N_1 and N_2 such that
$$n \geq N_1 \implies |x_n - L| < \epsilon \qquad \text{and} \qquad n \geq N_2 \implies |y_n - L| < \epsilon.$$

Let $N = \max\{N_1, N_2\}$ and suppose $n \in \mathbf{N}$ is such that $n \geq 2N$. If n is odd then $\frac{n+1}{2} \in \mathbf{N}$ and

$$n \geq 2N > 2N - 1 \implies \frac{n+1}{2} > N \geq N_1 \implies \left|x_{\frac{n+1}{2}} - L\right| < \epsilon.$$

Hence

$$|z_n - L| = \left|x_{\frac{n+1}{2}} - L\right| < \epsilon.$$

If n is even then $\frac{n}{2} \in \mathbf{N}$ and

$$n \geq 2N \implies \frac{n}{2} \geq N \geq N_2 \implies \left|y_{\frac{n}{2}} - L\right| < \epsilon.$$

Hence

$$|z_n - L| = \left|y_{\frac{n}{2}} - L\right| < \epsilon.$$

In either case we have $|z_n - L| < \epsilon$, i.e.,

$$n \geq 2N \implies |z_n - L| < \epsilon.$$

It follows that $\lim z_n = L$.

Now suppose that (z_n) is convergent with $\lim z_n = L$ for some $L \in \mathbf{R}$. Let $\epsilon > 0$ be given. Since $z_n \to L$, there exists an $N \in \mathbf{N}$ such that $|z_n - L| < \epsilon$ whenever $n \geq N$. For such n, we have $2n > 2n - 1 \geq n \geq N$ and so

$$|x_n - L| = |z_{2n-1} - L| < \epsilon \qquad \text{and} \qquad |y_n - L| = |z_{2n} - L| < \epsilon.$$

It follows that $\lim x_n = \lim y_n = L$.

Exercise 2.3.6. Consider the sequence given by $b_n = n - \sqrt{n^2 + 2n}$. Taking $(1/n) \to 0$ as given, and using both the Algebraic Limit Theorem and the result in Exercise 2.3.1, show $\lim b_n$ exists and find the value of the limit.

Solution. Observe that

$$b_n = n - \sqrt{n^2 + 2n} = \frac{(n - \sqrt{n^2 + 2n})(n + \sqrt{n^2 + 2n})}{n + \sqrt{n^2 + 2n}} = \frac{-2n}{n + \sqrt{n^2 + 2n}} = \frac{-2}{1 + \sqrt{1 + \frac{2}{n}}}.$$

Hence, using Exercise 2.3.1,

$$\lim b_n = \lim \left(\frac{-2}{1 + \sqrt{1 + \frac{2}{n}}} \right) = \frac{-2}{1 + \sqrt{1 + 2 \lim \frac{1}{n}}} = \frac{-2}{1 + \sqrt{1}} = -1.$$

Figure F.8 shows a graph of the first thirty terms of this sequence.

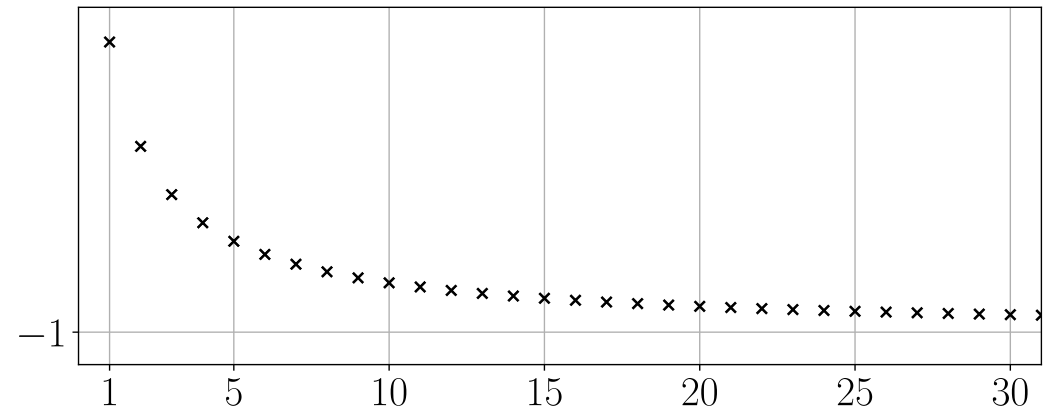


Figure F.8: $b_n = n - \sqrt{n^2 + 2n}$ for $1 \leq n \leq 30$

Exercise 2.3.7. Give an example of each of the following, or state that such a request is impossible by referencing the proper theorem(s):

(a) sequences (x_n) and (y_n), which both diverge, but whose sum $(x_n + y_n)$ converges;

(b) sequences (x_n) and (y_n), where (x_n) converges, (y_n) diverges, and $(x_n + y_n)$ converges;

(c) a convergent sequence (b_n) with $b_n \neq 0$ for all n such that $(1/b_n)$ diverges;

(d) an unbounded sequence (a_n) and a convergent sequence (b_n) with $(a_n - b_n)$ bounded;

(e) two sequences (a_n) and (b_n), where $(a_n b_n)$ and (a_n) converge but (b_n) does not.

Solution. (a) Take $x_n = n$ and $y_n = -n$.

(b) This is impossible. If (x_n) and (x_n+y_n) both converge, then by the Algebraic Limit Theorem (Theorem 2.3.3) (y_n) must be convergent with limit $\lim y_n = \lim(x_n + y_n) - \lim x_n$.

(c) Take $b_n = \frac{1}{n}$.

(d) This is impossible; $(a_n - b_n)$ must be unbounded. Since (b_n) is convergent, it must be bounded (Theorem 2.3.2), i.e., there exists some $B \geq 0$ such that $|b_n| \leq B$ for all $n \in \mathbf{N}$. Let $M \geq 0$ be given. Since (a_n) is unbounded, there exists some $N \in \mathbf{N}$ such that $|a_N| \geq M + B$. Then observe that

$$|a_N - b_N| \geq ||a_N| - |b_N|| \geq |a_N| - |b_N| \geq M + B - B = M,$$

where we have used Exercise 1.2.6 (d) for the first inequality. Since M was arbitrary, we see that the sequence $(a_n - b_n)$ is unbounded.

(e) Take $a_n = \frac{1}{n^2}$ and $b_n = n$.

Exercise 2.3.8. Let $(x_n) \to x$ and let $p(x)$ be a polynomial.

(a) Show $p(x_n) \to p(x)$.

(b) Find an example of a function $f(x)$ and a convergent sequence $(x_n) \to x$ where the sequence $f(x_n)$ converges, but not to $f(x)$.

Solution. (a) Suppose $p(x) = a_m x^m + a_{m-1}x^{m-1} + \cdots + a_1 x + a_0$. The Algebraic Limit Theorem (Theorem 2.3.3) and some simple induction arguments allow us to make the following manipulations:

$$\begin{aligned}\lim(p(x_n)) &= \lim(a_m x_n^m + a_{m-1}x_n^{m-1} + \cdots + a_1 x_n + a_0) \\ &= a_m(\lim x_n)^m + a_{m-1}(\lim x_n)^{m-1} + \cdots + a_1 \lim x_n + a_0 \\ &= a_m x^m + a_{m-1}x^{m-1} + \cdots + a_1 x + a_0 \\ &= p(x).\end{aligned}$$

(b) Consider the function $f : \mathbf{R} \to \mathbf{R}$ given by

$$f(x) = \begin{cases} 0 & \text{if } x = 0, \\ 1 & \text{otherwise,} \end{cases}$$

and the convergent sequence $x_n = \frac{1}{n} \to 0$. We then have $(f(x_n)) = (1, 1, 1, \ldots)$, which converges to $1 \neq 0 = f(0)$.

Exercise 2.3.9. (a) Let (a_n) be a bounded (not necessarily convergent) sequence, and assume $\lim b_n = 0$. Show that $\lim(a_n b_n) = 0$. Why are we not allowed to use the Algebraic Limit Theorem to prove this?

(b) Can we conclude anything about the convergence of $(a_n b_n)$ if we assume that (b_n) converges to some nonzero limit b?

(c) Use (a) to prove Theorem 2.3.3, part (iii), for the case when $a = 0$.

Solution. (a) There is an $M > 0$ such that $|a_n| \leq M$ for all $n \in \mathbf{N}$. Let $\epsilon > 0$ be given. Since $b_n \to 0$, there is an $N \in \mathbf{N}$ such that

$$n \geq N \implies |b_n| < \frac{\epsilon}{M}.$$

Observe that for $n \geq N$ we have

$$|a_n b_n| = |a_n||b_n| \leq M|b_n| < \frac{M\epsilon}{M} = \epsilon.$$

It follows that $\lim(a_n b_n) = 0$. We may not use the Algebraic Limit Theorem here since the sequence (a_n) is not necessarily convergent; the hypotheses of that theorem require both sequences (a_n) and (b_n) to be convergent.

(b) If the sequence (a_n) converges to some a then we may use the Algebraic Limit Theorem to conclude that $\lim(a_n b_n) = ab$. If the sequence (a_n) is divergent, then $(a_n b_n)$ must also be divergent. To see this, we will prove the contrapositive, i.e., if $(a_n b_n)$ converges to some $x \in \mathbf{R}$ then (a_n) is convergent. Indeed, since $b \neq 0$, the Algebraic Limit Theorem implies that

$$\lim a_n = \lim\left(\frac{a_n b_n}{b_n}\right) = \frac{x}{b}.$$

(c) Since (b_n) is convergent, it is bounded (Theorem 2.3.2). So we may apply part (a) (we have swapped the roles of (a_n) and (b_n)) to conclude that

$$\lim(a_n b_n) = 0 = 0b = ab.$$

Exercise 2.3.10. Consider the following list of conjectures. Provide a short proof for those that are true and a counterexample for any that are false.

(a) If $\lim(a_n - b_n) = 0$, then $\lim a_n = \lim b_n$.

(b) If $(b_n) \to b$, then $|b_n| \to |b|$.

(c) If $(a_n) \to a$ and $(b_n - a_n) \to 0$, then $(b_n) \to a$.

(d) If $(a_n) \to 0$ and $|b_n - b| \leq a_n$ for all $n \in \mathbf{N}$, then $(b_n) \to b$.

Solution. (a) This is false; consider $a_n = b_n = (-1)^n$.

(b) This is true. Let $\epsilon > 0$ be given. Since $b_n \to b$, there is an $N \in \mathbf{N}$ such that $|b_n - b| < \epsilon$ whenever $n \geq N$. For such n, the reverse triangle inequality (Exercise 1.2.6 (d)) gives

$$||b_n| - |b|| \leq |b_n - b| < \epsilon.$$

It follows that $\lim |b_n| = |b|$.

(c) This is true. Using the Algebraic Limit Theorem (Theorem 2.3.3), we have

$$\lim b_n = \lim(b_n - a_n + a_n) = \lim(b_n - a_n) + \lim a_n = 0 + a = a.$$

(d) This is true. Since $0 \leq |b_n - b| \leq a_n$ for every $n \in \mathbf{N}$, the Squeeze Theorem (Exercise 2.3.3) implies that $\lim |b_n - b| = 0$, i.e., for every $\epsilon > 0$ there is an $N \in \mathbf{N}$ such that

$$n \geq N \implies ||b_n - b| - 0| = |b_n - b| < \epsilon,$$

which is exactly the statement $\lim b_n = b$.

Exercise 2.3.11 (Cesaro Means). (a) Show that if (x_n) is a convergent sequence, then the sequence given by the averages

$$y_n = \frac{x_1 + x_2 + \cdots + x_n}{n}$$

also converges to the same limit.

(b) Give an example to show that it is possible for the sequence (y_n) of averages to converge even if (x_n) does not.

Solution. (a) Suppose $\lim x_n = x$ and let $\epsilon > 0$ be given. Since $x_n \to x$, there is a positive integer $N_1 \in \mathbf{N}$ such that

$$n \geq N_1 \implies |x_n - x| < \frac{\epsilon}{2}.$$

Given this N_1, notice that the sequence

$$\left(\frac{|x_1 - x| + \cdots + |x_{N_1} - x|}{n}\right)_{n=1}^{\infty}$$

has non-negative terms and converges to zero (the numerator is a constant); it follows that there is an $N_2 \in \mathbf{N}$ such that

$$n \geq N_2 \implies \frac{|x_1 - x| + \cdots + |x_{N_1} - x|}{n} < \frac{\epsilon}{2}.$$

Set $N = \max\{N_1, N_2\}$ and observe that for $n \geq N + 1$ we have

$$\begin{aligned}
|y_n - x| &= \left| \frac{x_1 + \cdots + x_n}{n} - \frac{nx}{n} \right| \\
&= \left| \frac{(x_1 - x) + \cdots + (x_n - x)}{n} \right| \\
&\leq \frac{|x_1 - x| + \cdots + |x_{N_1} - x|}{n} + \frac{|x_{N_1+1} - x| + \cdots + |x_n - x|}{n} \\
&< \frac{\epsilon}{2} + \frac{n - N_1}{n} \cdot \frac{\epsilon}{2} \\
&\leq \frac{\epsilon}{2} + \frac{\epsilon}{2} \\
&= \epsilon.
\end{aligned}$$

It follows that $\lim y_n = x$.

(b) Consider the divergent sequence $x_n = (-1)^{n+1}$. The sequence of averages (y_n) is then

$$y_n = \begin{cases} \frac{1}{n} & \text{if } n \text{ is odd,} \\ 0 & \text{if } n \text{ is even,} \end{cases}$$

which satisfies $\lim y_n = 0$.

Exercise 2.3.12. A typical task in analysis is to decipher whether a property possessed by every term in a convergent sequence is necessarily inherited by the limit. Assume $(a_n) \to a$, and determine the validity of each claim. Try to produce a counterexample for any that are false.

(a) If every a_n is an upper bound for a set B, then a is also an upper bound for B.

(b) If every a_n is in the complement of the interval $(0, 1)$, then a is also in the complement of $(0, 1)$.

(c) If every a_n is rational, then a is rational.

Solution. (a) This is true. For any $b \in B$ we have $b \leq a_n$ for all $n \in \mathbf{N}$; the Order Limit Theorem (Theorem 2.3.4) then implies that $b \leq a$ and it follows that a is an upper bound for B.

(b) This is true. Observe that for a real number x we have

$$x \notin (0,1) \iff x \leq 0 \text{ or } x \geq 1 \iff \left|x - \frac{1}{2}\right| \geq \frac{1}{2}.$$

So for each $n \in \mathbf{N}$ we have $\left|a_n - \frac{1}{2}\right| \geq \frac{1}{2}$. The Algebraic Limit Theorem (Theorem 2.3.3) and Exercise 2.3.10 (b) imply that $\lim\left|a_n - \frac{1}{2}\right| = \left|a - \frac{1}{2}\right|$, and hence the Order Limit Theorem (Theorem 2.3.4) implies that $\left|a - \frac{1}{2}\right| \geq \frac{1}{2}$. It follows that a belongs to the complement of $(0,1)$.

(c) This is false. By the density of $\mathbf{Q}$ in $\mathbf{R}$ (Theorem 1.4.3), for each $n \in \mathbf{N}$ we may pick a rational number a_n satisfying $\sqrt{2} < a_n < \sqrt{2} + \frac{1}{n}$. The Squeeze Theorem (Exercise 2.3.3) then implies that $\lim a_n = \sqrt{2}$, which is an irrational number.

Exercise 2.3.13 (Iterated Limits). Given a doubly indexed array a_{mn} where $m, n \in \mathbf{N}$, what should $\lim_{m,n\to\infty} a_{mn}$ represent?

(a) Let $a_{mn} = m/(m+n)$ and compute the *iterated* limits

$$\lim_{n\to\infty}\left(\lim_{m\to\infty} a_{mn}\right) \qquad \text{and} \qquad \lim_{m\to\infty}\left(\lim_{n\to\infty} a_{mn}\right).$$

Define $\lim_{m,n\to\infty} a_{mn} = a$ to mean that for all $\epsilon > 0$ there exists an $N \in \mathbf{N}$ such that if both $m, n \geq N$, then $|a_{mn} - a| < \epsilon$.

(b) Let $a_{mn} = 1/(m+n)$. Does $\lim_{m,n\to\infty} a_{mn}$ exist in this case? Do the two iterated limits exist? How do these three values compare? Answer these same questions for $a_{mn} = mn/(m^2+n^2)$.

(c) Produce an example where $\lim_{m,n\to\infty} a_{mn}$ exists but where neither iterated limit can be computed.

(d) Assume $\lim_{m,n\to\infty} a_{mn} = a$, and assume that for each fixed $m \in \mathbf{N}$, $\lim_{n\to\infty}(a_{mn}) = b_m$. Show $\lim_{m\to\infty} b_m = a$.

(e) Prove that if $\lim_{m,n\to\infty} a_{mn}$ exists and the iterated limits both exist, then all three limits must be equal.

Solution. (a) We apply the Algebraic Limit Theorem (Theorem 2.3.3):

$$\lim_{m\to\infty} a_{mn} = \lim_{m\to\infty}\left(\frac{m}{m+n}\right) = \lim_{m\to\infty}\left(\frac{1}{1+\frac{n}{m}}\right) = \frac{1}{1 + n\lim_{m\to\infty}\left(\frac{1}{m}\right)} = \frac{1}{1} = 1.$$

Hence $\lim_{n\to\infty}(\lim_{m\to\infty} a_{mn}) = \lim_{n\to\infty}(1) = 1$. Similarly,

$$\lim_{n\to\infty} a_{mn} = \lim_{n\to\infty}\left(\frac{m}{m+n}\right) = \lim_{n\to\infty}\left(\frac{\frac{m}{n}}{1+\frac{m}{n}}\right) = \frac{m\lim_{n\to\infty}\left(\frac{1}{n}\right)}{1+m\lim_{n\to\infty}\left(\frac{1}{n}\right)} = \frac{0}{1} = 0.$$

Thus $\lim_{m\to\infty}(\lim_{n\to\infty} a_{mn}) = \lim_{m\to\infty}(0) = 0$.

(b) For $a_{mn} = \frac{1}{m+n}$, we have $\lim_{m,n\to\infty} a_{mn} = 0$. To see this, let $\epsilon > 0$ be given. There is an $N \in \mathbf{N}$ such that $\frac{1}{n} < \epsilon$ whenever $n \geq N$, so that for $m, n \geq N$ we have

$$|a_{mn}| = \frac{1}{m+n} < \frac{1}{n} < \epsilon.$$

Thus $\lim_{m,n\to\infty} a_{mn} = 0$. The two iterated limits also exist and are equal to 0. Indeed, observe that for all $m, n \in \mathbf{N}$ we have $0 < \frac{1}{m+n} < \frac{1}{m}$. The Squeeze Theorem (Exercise 2.3.3) then implies that $\lim_{m\to\infty} a_{mn} = \lim_{m\to\infty}\frac{1}{m+n} = 0$ and it follows that $\lim_{n\to\infty}(\lim_{m\to\infty} a_{mn}) = \lim_{n\to\infty}(0) = 0$. A similar argument shows that $\lim_{m\to\infty}(\lim_{n\to\infty} a_{mn}) = 0$.

Now let $a_{mn} = \frac{mn}{m^2+n^2}$; we claim that $\lim_{m,n\to\infty} a_{mn}$ does not exist. To see this, let us seek a contradiction and suppose that $\lim_{m,n\to\infty} a_{mn} = x$ for some $x \in \mathbf{R}$. There then exists an $N \in \mathbf{N}$ such that $|a_{mn} - x| < \frac{1}{20}$ whenever $m, n \geq N$. In particular, taking $n = m$,

$$m \geq N \implies \left|\frac{m^2}{m^2+m^2} - x\right| = \left|\frac{1}{2} - x\right| < \frac{1}{20} \iff x \in \left(\frac{9}{20}, \frac{11}{20}\right).$$

Similarly, taking $n = 2m$,

$$m \geq N \implies \left|\frac{2m^2}{m^2+4m^2} - x\right| = \left|\frac{2}{5} - x\right| < \frac{1}{20} \iff x \in \left(\frac{7}{20}, \frac{9}{20}\right).$$

So assuming that $\lim_{m,n\to\infty} a_{mn} = x$ for some $x \in \mathbf{R}$ leads us to the contradiction that $x < \frac{9}{20}$ and $x > \frac{9}{20}$; it follows that $\lim_{m,n\to\infty} a_{mn}$ does not exist. However, the two iterated limits do exist and are equal to 0. Using the Algebraic Limit Theorem (Theorem 2.3.3), for any $n \in \mathbf{N}$ we have

$$\lim_{m\to\infty}\left(\frac{mn}{m^2+n^2}\right) = \lim_{m\to\infty}\left(\frac{\frac{n}{m}}{1+\frac{n^2}{m^2}}\right) = \frac{n\lim_{m\to\infty}\left(\frac{1}{m}\right)}{1+n^2\lim_{m\to\infty}\left(\frac{1}{m^2}\right)} = \frac{0}{1} = 0.$$

It follows that $\lim_{n\to\infty}(\lim_{m\to\infty} a_{mn}) = 0$ and we can use a similar argument to show that $\lim_{m\to\infty}(\lim_{n\to\infty} a_{mn}) = 0$.

(c) Let $a_{mn} = (-1)^{m+n}\left(\frac{1}{m} + \frac{1}{n}\right)$; we claim that $\lim_{m,n\to\infty} a_{mn} = 0$. To see this, let $\epsilon > 0$ be given. There is an $N \in \mathbf{N}$ such that $\frac{1}{n} < \frac{\epsilon}{2}$ whenever $n \geq N$. For $m, n \geq N$ we then have

$$|a_{mn}| = \left|(-1)^{m+n}\left(\frac{1}{m} + \frac{1}{n}\right)\right| = \frac{1}{m} + \frac{1}{n} < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon.$$

Thus $\lim_{m,n\to\infty} a_{mn} = 0$. However, neither iterated limit exists. Fix $n \in \mathbf{N}$ and observe that

$$\begin{aligned}
|a_{mn} - a_{m+1,n}| &= \left|(-1)^{m+n}\left(\frac{1}{m} + \frac{1}{n}\right) - (-1)^{m+n+1}\left(\frac{1}{m+1} + \frac{1}{n}\right)\right| \\
&= \left|(-1)^{m+n}\left(\frac{1}{m} + \frac{1}{n} + \frac{1}{m+1} + \frac{1}{n}\right)\right| \\
&= \left|\frac{1}{m} + \frac{1}{n} + \frac{1}{m+1} + \frac{1}{n}\right| \\
&= \frac{1}{m} + \frac{1}{m+1} + \frac{2}{n} \\
&\geq \frac{2}{n}.
\end{aligned}$$

Since $n \in \mathbf{N}$ is fixed, this implies that the sequence $(a_{mn} - a_{m+1,n})_{m=1}^{\infty}$ cannot converge to 0. Now observe that for any sequence (b_m), the Algebraic Limit Theorem (Theorem 2.3.3) implies that

$$\lim_{m\to\infty} b_m \text{ exists} \implies \lim_{m\to\infty}(b_m - b_{m+1}) = 0.$$

The contrapositive of this statement then implies that the limit $\lim_{m\to\infty} a_{mn}$ does not exist for any $n \in \mathbf{N}$ and it follows that the iterated limit $\lim_{n\to\infty}(\lim_{m\to\infty} a_{mn})$ does not exist. Using the symmetry of a_{mn} and swapping the roles of m and n in our argument shows that the iterated limit $\lim_{m\to\infty}(\lim_{n\to\infty} a_{mn})$ does not exist either.

(d) Seeking a contradiction, suppose that (b_m) does not converge to a, i.e., there is some $\epsilon > 0$ such that for all $N \in \mathbf{N}$ there is an $M \geq N$ such that $|b_M - a| \geq \epsilon$. Since $\lim_{m,n\to\infty} a_{mn} = a$, there exists some $N_1 \in \mathbf{N}$ such that

$$m, n \geq N_1 \implies |a_{mn} - a| < \frac{\epsilon}{2}. \tag{1}$$

By the previous discussion, there is an $M \geq N_1$ such that $|b_M - a| \geq \epsilon$. By assumption we have $\lim_{n\to\infty} a_{Mn} = b_M$, so there is an $N_2 \in \mathbf{N}$ such that $|a_{Mn} - b_M| < \frac{\epsilon}{2}$ whenever

$n \geq N_2$. Let $N = \max\{N_1, N_2\}$ and observe that $|a_{MN} - a| < \frac{\epsilon}{2}$ by (1). However, the reverse triangle inequality (Exercise 1.2.6 (d)) gives us

$$\begin{aligned}
|a_{MN} - a| &= |a_{MN} - b_M + b_M - a| \\
&\geq ||b_M - a| - |a_{MN} - b_M|| \\
&\geq |b_M - a| - |a_{MN} - b_M| \\
&> \epsilon - \frac{\epsilon}{2} \\
&= \frac{\epsilon}{2}.
\end{aligned}$$

So assuming that (b_m) does not converge to a leads us the contradiction that there exist positive integers M and N such that $|a_{MN} - a|$ is both less than and greater than $\frac{\epsilon}{2}$. We may conclude that $\lim_{m\to\infty} b_m = a$.

(e) If the iterated limit $\lim_{m\to\infty}(\lim_{n\to\infty} a_{mn})$ exists, then it must be the case that for each fixed $m \in \mathbf{N}$, the limit $\lim_{n\to\infty} a_{mn}$ exists. Part (d) then implies that

$$\lim_{m\to\infty}\left(\lim_{n\to\infty} a_{mn}\right) = \lim_{m,n\to\infty} a_{mn}.$$

Swapping the roles of m and n and repeating the above argument shows that

$$\lim_{n\to\infty}\left(\lim_{m\to\infty} a_{mn}\right) = \lim_{m,n\to\infty} a_{mn}.$$

2.4 The Monotone Convergence Theorem and a First Look at Infinite Series

Exercise 2.4.1. (a) Prove that the sequence defined by $x_1 = 3$ and

$$x_{n+1} = \frac{1}{4 - x_n}$$

converges.

(b) Now that we know $\lim x_n$ exists, explain why $\lim x_{n+1}$ must also exist and equal the same value.

(c) Take the limit of each side of the recursive equation in part (a) to explicitly compute $\lim x_n$.

Solution. See Figure F.9 for a graph of the first thirty terms of (x_n).

(a) Let $P(n)$ be the statement that $x_{n+1} \leq x_n$ and $x_n \geq -1$; we will use strong induction to show that $P(n)$ holds for all $n \in \mathbf{N}$. Since $x_1 = 3$ and $x_2 = 1$, we see that $P(1)$ holds. Now suppose that $P(1), \ldots, P(n)$ all hold for some $n \in \mathbf{N}$ and observe that

$$x_{n+1} \leq x_n \leq 3 \implies 1 \leq 4 - x_n \leq 4 - x_{n+1} \implies \frac{1}{4 - x_{n+1}} \leq \frac{1}{4 - x_n},$$

i.e., $x_{n+2} \leq x_{n+1}$. Furthermore,

$$-1 \leq x_n \leq 3 \implies 1 \leq 4 - x_n \leq 5 \implies x_{n+1} = \frac{1}{4 - x_n} \geq \frac{1}{5} > -1.$$

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

We have now shown that the sequence (x_n) is bounded below and decreasing and hence by the Monotone Convergence Theorem (Theorem 2.4.2) we may conclude that the sequence converges.

(b) If (x_n) is any convergent sequence with $\lim x_n = x$, then the sequence (y_n) given by $y_n = x_{n+k}$ for any $k \in \mathbf{N}$ is also convergent with $\lim y_n = x$. To see this, let $\epsilon > 0$ be given. Since $x_n \to x$, there exists an $N \in \mathbf{N}$ such that $|x_n - x| < \epsilon$ whenever $n \geq N$. Suppose $n \geq \max\{N - k, 1\}$, so that $n + k \geq N$. It follows that

$$|y_n - x| = |x_{n+k} - x| < \epsilon.$$

Thus $\lim y_n = x$.

(c) By parts (a) and (b) we have $\lim x_n = \lim x_{n+1} = x$ for some $x \in \mathbf{R}$. It then follows from the Algebraic Limit Theorem (Theorem 2.3.3) that

$$x_{n+1} = \frac{1}{4 - x_n} \implies \lim x_{n+1} = \frac{1}{4 - \lim x_n} \iff x = \frac{1}{4 - x} \iff x^2 - 4x + 1 = 0.$$

This quadratic equation has solutions $x = 2 \pm \sqrt{3}$. Since (x_n) is decreasing and $x_2 = 1$, the Order Limit Theorem (Theorem 2.3.4) implies that $\lim x_n = x \leq 1 < 2 + \sqrt{3}$ and so we may discard the solution $x = 2 + \sqrt{3}$ to conclude that $\lim x_n = 2 - \sqrt{3}$.

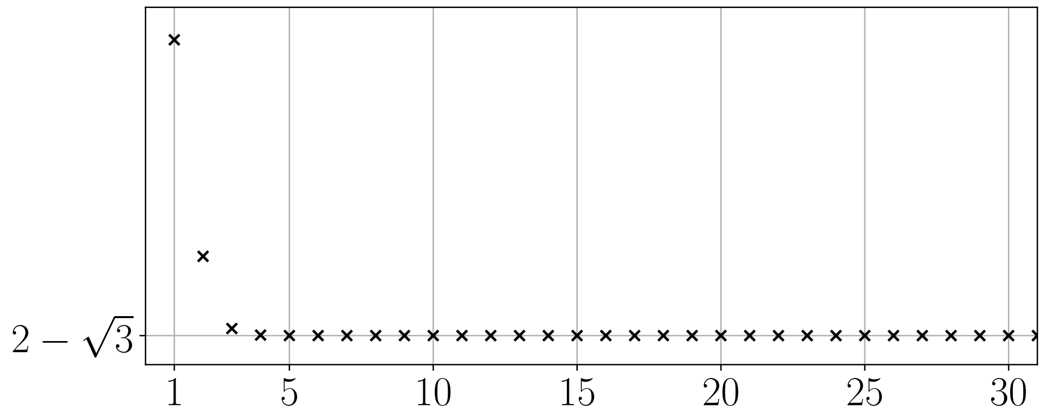


Figure F.9: x_n for $1 \le n \le 30$

Exercise 2.4.2. (a) Consider the recursively defined sequence $y_1 = 1$,

$$y_{n+1} = 3 - y_n,$$

and set $y = \lim y_n$. Because (y_n) and (y_{n+1}) have the same limit, taking the limit across the recursive equation gives $y = 3 - y$. Solving for y, we conclude $\lim y_n = 3/2$.

What is wrong with this argument?

(b) This time set $y_1 = 1$ and $y_{n+1} = 3 - \frac{1}{y_n}$. Can the strategy in (a) be applied to compute the limit of this sequence?

Solution. (a) The problem is we have assumed that $\lim y_n$ exists. Looking at the first few terms of the sequence $y_1 = 1, y_2 = 2, y_3 = 1, y_4 = 2, \ldots$, we see that in fact the sequence oscillates and does not converge.

(b) The strategy works this time. Let $P(n)$ be the statement that $y_{n+1} \ge y_n$ and $y_n \le 3$; we will use strong induction to show that $P(n)$ holds for all $n \in \mathbf{N}$. Since $y_1 = 1$ and $y_2 = 2$, we see that $P(1)$ holds. Suppose that $P(1), \ldots, P(n)$ all hold for some $n \in \mathbf{N}$ and observe that

$$y_{n+1} \ge y_n \ge 1 \implies \frac{1}{y_{n+1}} \le \frac{1}{y_n} \implies 3 - \frac{1}{y_{n+1}} \ge 3 - \frac{1}{y_n},$$

i.e., $y_{n+2} \ge y_{n+1}$. Furthermore,

$$1 \le y_n \le 3 \implies \frac{1}{3} \le \frac{1}{y_n} \implies y_{n+1} = 3 - \frac{1}{y_n} \le \frac{8}{3} < 3.$$

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

We have now shown that (y_n) is bounded above and increasing, so by the Monotone Convergence Theorem (Theorem 2.4.2) we have $\lim y_n = y$ for some $y \in \mathbf{R}$. Given this, the following manipulations are valid:

$$y_{n+1} = 3 - \frac{1}{y_n} \implies y = 3 - \frac{1}{y} \iff y^2 - 3y + 1 = 0.$$

This quadratic equation has solutions $\frac{3}{2} \pm \frac{1}{2}\sqrt{5}$. Since (y_n) is increasing and $y_2 = 2$, we must have $y \geq 2 > \frac{3}{2} - \frac{1}{2}\sqrt{5}$ and so we may discard the solution $y = \frac{3}{2} - \frac{1}{2}\sqrt{5}$ to conclude that $\lim y_n = \frac{3}{2} + \frac{1}{2}\sqrt{5}$. See Figure F.10 for a graph of the first thirty terms of (y_n).

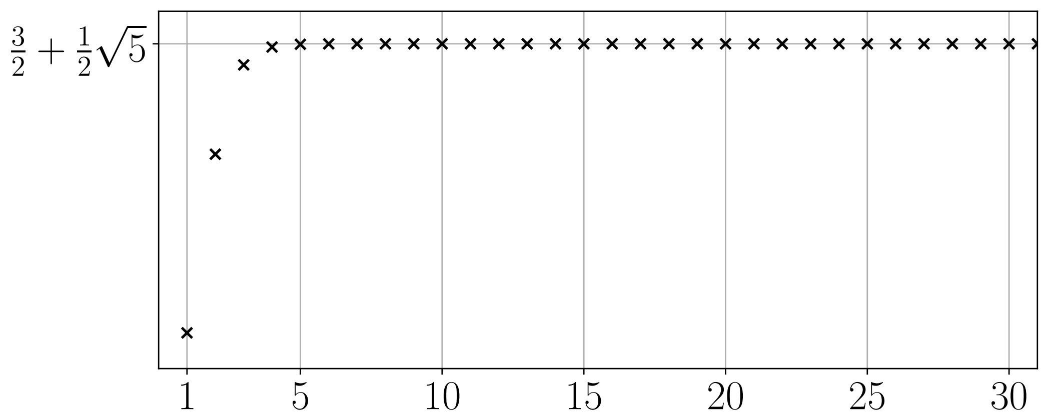


Figure F.10: y_n for $1 \leq n \leq 30$

Exercise 2.4.3. (a) Show that

$$\sqrt{2}, \sqrt{2+\sqrt{2}}, \sqrt{2+\sqrt{2+\sqrt{2}}}, \ldots$$

converges and find the limit.

(b) Does the sequence

$$\sqrt{2}, \sqrt{2\sqrt{2}}, \sqrt{2\sqrt{2\sqrt{2}}}, \ldots$$

converge? If so, find the limit.

Solution. (a) Let $x_1 = \sqrt{2}, x_{n+1} = \sqrt{2 + x_n}$, and let $P(n)$ be the statement that $x_{n+1} \geq x_n$ and $x_n \leq 2$; we will use strong induction to show that $P(n)$ holds for all $n \in \mathbf{N}$. Since $x_1 = \sqrt{2}$ and $x_2 = \sqrt{2 + \sqrt{2}}$, we see that $P(1)$ holds. Suppose that $P(1), \ldots, P(n)$ all hold for some $n \in \mathbf{N}$ and observe that

$$x_{n+1} \geq x_n \geq \sqrt{2} \implies \sqrt{2 + x_{n+1}} \geq \sqrt{2 + x_n},$$

i.e., $x_{n+2} \geq x_{n+1}$. Furthermore,

$$\sqrt{2} \leq x_n \leq 2 \implies \sqrt{2 + x_n} \leq \sqrt{4} = 2.$$

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

We have now shown that the sequence (x_n) is bounded above and increasing, so by the Monotone Convergence Theorem (Theorem 2.4.2) we have $\lim x_n = x$ for some $x \in \mathbf{R}$. We may now take the limit on both sides of the recursive equation:

$$x_{n+1} = \sqrt{2 + x_n} \implies x = \sqrt{2 + x} \implies x^2 - x - 2 = 0 \iff (x-2)(x+1) = 0.$$

So $x = 2$ or $x = -1$. Since the sequence is increasing and $x_1 = \sqrt{2}$, we must have $x \geq \sqrt{2} > -1$ and thus $\lim x_n = 2$. See Figure F.11 for a graph of the first thirty terms of the sequence (x_n).

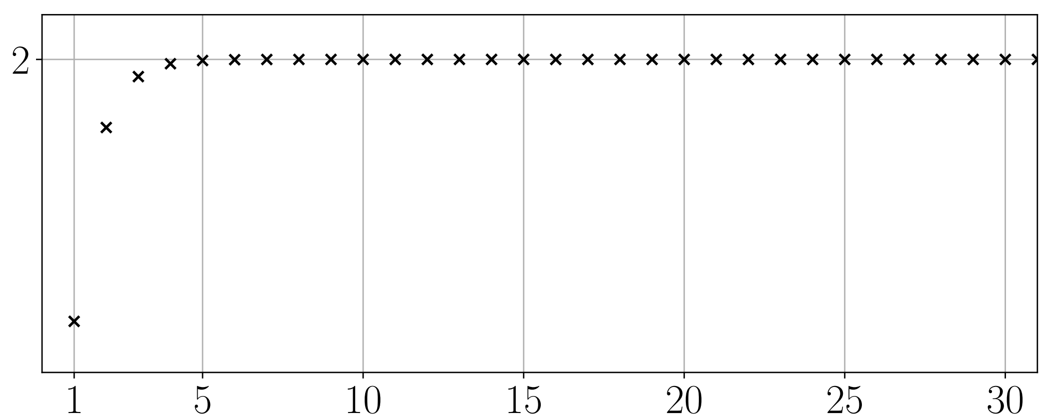


Figure F.11: x_n for $1 \leq n \leq 30$

(b) The sequence does converge. Let $x_1 = \sqrt{2}$, $x_{n+1} = \sqrt{2x_n}$, and let $P(n)$ be the statement that $x_{n+1} \geq x_n$ and $x_n \leq 2$. We will use strong induction to show that $P(n)$ holds for all $n \in \mathbf{N}$. Since $x_1 = \sqrt{2}$ and $x_2 = \sqrt{2\sqrt{2}}$, we see that $P(1)$ holds. Suppose that $P(1), \ldots, P(n)$ all hold for some $n \in \mathbf{N}$ and observe that

$$x_{n+1} \geq x_n \geq \sqrt{2} \implies \sqrt{2x_{n+1}} \geq \sqrt{2x_n},$$

i.e., $x_{n+2} \geq x_{n+1}$. Furthermore,

$$\sqrt{2} \leq x_n \leq 2 \implies \sqrt{2x_n} \leq \sqrt{4} = 2.$$

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

We have shown that the sequence (x_n) is bounded above and increasing, so by the Monotone Convergence Theorem (Theorem 2.4.2) we have $\lim x_n = x$ for some $x \in \mathbf{R}$. We may now take the limit on both sides of the recursive equation:

$$x_{n+1} = \sqrt{2x_n} \implies x = \sqrt{2x} \implies x^2 - 2x = 0 \iff x(x-2) = 0.$$

So $x = 2$ or $x = 0$. Since the sequence is increasing and $x_1 = \sqrt{2}$, we must have $x \geq \sqrt{2} > 0$ and thus $\lim x_n = 2$. See Figure F.12 for a graph of the first thirty terms of (x_n).

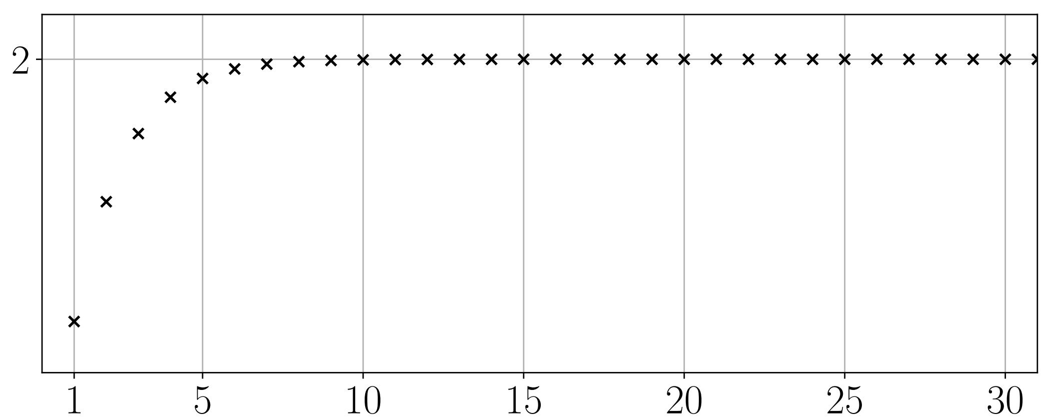


Figure F.12: x_n for $1 \leq n \leq 30$

Exercise 2.4.4. (a) In Section 1.4 we used the Axiom of Completeness (AoC) to prove the Archimedean Property of **R** (Theorem 1.4.2). Show that the Monotone Convergence Theorem can also be used to prove the Archimedean Property without making any use of AoC.

(b) Use the Monotone Convergence Theorem to supply a proof for the Nested Interval Property (Theorem 1.4.1) that doesn't make use of AoC.

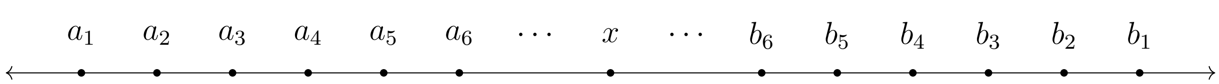
These two results suggest that we could have used the Monotone Convergence Theorem in place of AoC as our starting axiom for building a proper theory of the real numbers.

Solution. (a) Assuming that any bounded monotone sequence converges, we want to prove part (i) of Theorem 1.4.2: for any $x \in \mathbf{R}$, there exists an $n \in \mathbf{N}$ satisfying $n > x$. Part (ii) of Theorem 1.4.2 will then follow by taking $x = \frac{1}{y}$ in part (i). Let x be given. Seeking a contradiction, suppose that $n \leq x$ for each $n \in \mathbf{N}$. Then the sequence (n) is bounded above and clearly monotone increasing, so by assumption this sequence converges, say $\lim n = y$ for some $y \in \mathbf{R}$. There then exists an $N \in \mathbf{N}$ such that $|n - y| < \frac{1}{2}$ whenever $n \geq N$. Observe that

$$1 = |N + 1 - y + y - N| \leq |N + 1 - y| + |N - y| < \frac{1}{2} + \frac{1}{2} = 1,$$

i.e., $1 < 1$, which is a contradiction. We may conclude that there exists some $n \in \mathbf{N}$ such that $n > x$.

(b) Assuming that any bounded monotone sequence converges, we want to prove that any sequence of nested intervals $I_n = [a_n, b_n]$ has non-empty intersection. Consider the sequence (a_n) of left-hand endpoints. Because the intervals are nested, this is an increasing sequence which is bounded above by any right-hand endpoint, so by assumption this sequence converges, say $\lim a_n = x$ for some $x \in \mathbf{R}$. For any $n \in \mathbf{N}$ we have $a_n \leq a_m \leq b_m \leq b_n$ for all $m \geq n$. The Order Limit Theorem (Theorem 2.3.4) then implies that $x = \lim_{m\to\infty} a_m \leq b_n$ and $a_n \leq \lim_{m\to\infty} a_m = x$; it follows that $a_n \leq x \leq b_n$ for all $n \in \mathbf{N}$, i.e., $x \in \bigcap_{n=1}^{\infty} I_n$.



Exercise 2.4.5 (Calculating Square Roots). Let $x_1 = 2$, and define

$$x_{n+1} = \frac{1}{2}\left(x_n + \frac{2}{x_n}\right).$$

(a) Show that x_n^2 is always greater than or equal to 2, and then use this to prove that $x_n - x_{n+1} \geq 0$. Conclude that $\lim x_n = \sqrt{2}$.

(b) Modify the sequence (x_n) so that it converges to $\sqrt{c}$.

Solution. (a) Let $P(n)$ be the statement that $x_n \geq \sqrt{2}$. We will use induction to show 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 $n \in \mathbf{N}$. Observe that

$$\left(x_n - \sqrt{2}\right)^2 = x_n^2 - 2\sqrt{2}x_n + 2 \geq 0.$$

Our induction hypothesis guarantees that $x_n \geq \sqrt{2} > 0$ and so we may divide by x_n to obtain the inequality

$$x_n - 2\sqrt{2} + \frac{2}{x_n} \geq 0 \iff \frac{1}{2}\left(x_n + \frac{2}{x_n}\right) \geq \sqrt{2},$$

i.e., $x_{n+1} \geq \sqrt{2}$. This completes the induction step and thus $P(n)$ holds for all $n \in \mathbf{N}$; in particular, we have $x_n^2 \geq 2$ for each $n \in \mathbf{N}$. Given this, for any $n \in \mathbf{N}$ we have

$$\begin{aligned} x_n^2 - 2 \geq 0 \iff x_n - \frac{2}{x_n} \geq 0 \iff \frac{x_n}{2} - \frac{1}{x_n} \geq 0 \\ \iff x_n - \frac{1}{2}\left(x_n + \frac{2}{x_n}\right) \geq 0 \iff x_n - x_{n+1} \geq 0. \end{aligned}$$

It follows that the sequence (x_n) satisfies $x_{n+1} \leq x_n$ for all $n \in \mathbf{N}$.

We have now shown that the sequence (x_n) is decreasing and bounded below. The Monotone Convergence Theorem (Theorem 2.4.2) then implies that $\lim x_n = x$ for some $x \in \mathbf{R}$. Since $x_n \geq \sqrt{2}$ for all $n \in \mathbf{N}$, the Order Limit Theorem (Theorem 2.3.4) implies that $x \geq \sqrt{2} > 0$ and so we can use the Algebraic Limit Theorem (Theorem 2.3.3) to take the limit across the recursive equation:

$$x_{n+1} = \frac{1}{2}\left(x_n + \frac{2}{x_n}\right) \implies x = \frac{1}{2}\left(x + \frac{2}{x}\right) \implies x^2 = 2.$$

Since $x \geq \sqrt{2}$, we may conclude that $x = \sqrt{2}$. See Figure F.13 for a graph of the first thirty terms of the sequence (x_n).

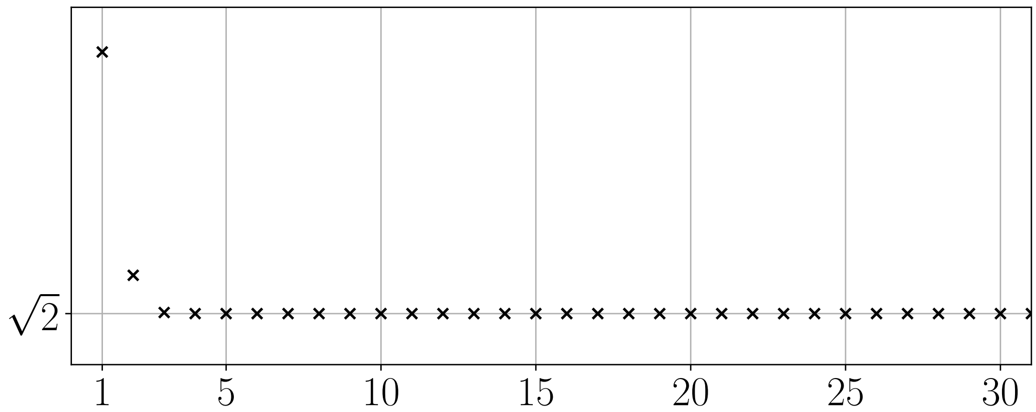


Figure F.13: x_n for $1 \le n \le 30$

(b) For $c \ge 0$, let $x_1 = 1 + c$ and define

$$x_{n+1} = \frac{1}{2}\left(x_n + \frac{c}{x_n}\right).$$

Repeating the argument given in part (a), replacing 2 with c where appropriate, shows that $\lim x_n = \sqrt{c}$. For the base case of the induction argument, note that

$$x_1 = 1 + c > 1 \implies x_1 = 1 + c > \sqrt{1+c} > \sqrt{c}.$$

Exercise 2.4.6 (Arithmetic-Geometric Mean). (a) Explain why $\sqrt{xy} \le (x+y)/2$ for any two positive real numbers x and y. (The geometric mean is always less than the arithmetic mean.)

(b) Now let $0 \le x_1 \le y_1$ and define

$$x_{n+1} = \sqrt{x_n y_n} \qquad \text{and} \qquad y_{n+1} = \frac{x_n + y_n}{2}.$$

Show $\lim x_n$ and $\lim y_n$ both exist and are equal.

Solution. (a) Observe that

$$0 \le (x-y)^2 \iff 0 \le x^2 - 2xy + y^2 \iff 4xy \le x^2 + 2xy + y^2 \iff 4xy \le (x+y)^2.$$

Since x and y are both positive, this implies that $\sqrt{xy} \le \frac{x+y}{2}$.

(b) By part (a), we have $x_n \le y_n$ for all $n \in \mathbf{N}$. It follows that

$$y_{n+1} = \frac{x_n + y_n}{2} \le \frac{y_n + y_n}{2} = y_n \qquad \text{and} \qquad x_{n+1} = \sqrt{x_n y_n} \ge \sqrt{x_n^2} = x_n.$$

Thus (x_n) is increasing and (y_n) is decreasing. Furthermore, (y_n) is bounded below: for any $n \in \mathbf{N}$, we have

$$y_n \ge x_n \ge \cdots \ge x_1.$$

It follows from the Monotone Convergence Theorem (Theorem 2.4.2) that $\lim y_n = y$ for some $y \in \mathbf{R}$. The Algebraic Limit Theorem (Theorem 2.3.3) then gives

$$x_n = 2y_{n+1} - y_n \implies \lim x_n = 2\lim y_{n+1} - \lim y_n = 2y - y = y.$$

Exercise 2.4.7 (Limit Superior). Let (a_n) be a bounded sequence.

(a) Prove that the sequence defined by $y_n = \sup\{a_k : k \ge n\}$ converges.

(b) The *limit superior* of (a_n), or $\limsup a_n$, is defined by

$$\limsup a_n = \lim y_n,$$

where y_n is the sequence from part (a) of this exercise. Provide a reasonable definition for $\liminf a_n$ and briefly explain why it always exists for any bounded sequence.

(c) Prove that $\liminf a_n \le \limsup a_n$ for every bounded sequence, and give an example of a sequence for which the inequality is strict.

(d) Show that $\liminf a_n = \limsup a_n$ if and only if $\lim a_n$ exists. In this case, all three share the same value.

Solution. (a) Suppose $M > 0$ is the bound for (a_n), i.e., $|a_n| \le M$ for all $n \in \mathbf{N}$. It follows that $y_n \ge a_n \ge -M$ for any $n \in \mathbf{N}$, so that the sequence (y_n) is bounded below. Furthermore, for any $n \in \mathbf{N}$ we have

$$\{a_k : k \ge n+1\} \subseteq \{a_k : k \ge n\} \implies \sup\{a_k : k \ge n+1\} \le \sup\{a_k : k \ge n\}$$
$$\iff y_{n+1} \le y_n,$$

i.e., the sequence (y_n) is decreasing. We may now invoke the Monotone Convergence Theorem (Theorem 2.4.2) to conclude that (y_n) converges.

(b) Let $z_n = \inf\{a_k : k \geq n\}$. Similarly to part (a), we can show that this sequence is bounded above, increasing, and hence convergent. We then define the limit inferior as $\liminf a_n = \lim z_n$.

(c) The infimum of a bounded set is always less than or equal to the supremum of that set, so we have $z_n \leq y_n$ for each $n \in \mathbf{N}$. The Order Limit Theorem (Theorem 2.3.4) then implies that $\lim z_n \leq \lim y_n$, i.e., $\liminf a_n \leq \limsup a_n$.

For an example of a bounded sequence where this inequality is strict, consider the sequence $a_n = (-1)^n$. For this sequence we have $y_n = (1, 1, 1, \ldots)$ and $z_n = (-1, -1, -1, \ldots)$, so that $\liminf a_n = -1 < 1 = \limsup a_n$.

(d) Suppose $\liminf a_n = \limsup a_n$. Since $z_n \leq a_n \leq y_n$ for all $n \in \mathbf{N}$, the Squeeze Theorem (Exercise 2.3.3) implies that (a_n) converges and that $\liminf a_n = \limsup a_n = \lim a_n$.

Now suppose that $\lim a_n = a$ for some $a \in \mathbf{R}$ and let $\epsilon > 0$ be given. Since $a_n \to a$, there is an $N \in \mathbf{N}$ such that

$$n \geq N \implies a - \frac{\epsilon}{2} < a_n < a + \frac{\epsilon}{2}.$$

This implies that $a - \frac{\epsilon}{2}$ is a lower bound for $\{a_k : k \geq N\}$ and that $a + \frac{\epsilon}{2}$ is an upper bound for $\{a_k : k \geq N\}$. It follows that $a - \frac{\epsilon}{2} \leq z_N \leq a_N \leq y_N \leq a + \frac{\epsilon}{2}$. Since (z_n) is increasing and (y_n) is decreasing, we then have

$$n \geq N \implies a - \epsilon < a - \frac{\epsilon}{2} \leq z_N \leq z_n \leq a_n \leq y_n \leq y_N \leq a + \frac{\epsilon}{2} < a + \epsilon,$$

i.e., $|z_n - a| < \epsilon$ and $|y_n - a| < \epsilon$ for all $n \geq N$. It follows that $\liminf a_n = \limsup a_n = \lim a_n = a$.

Exercise 2.4.8. For each series, find an explicit formula for the sequence of partial sums and determine if the series converges.

$$\text{(a)} \sum_{n=1}^{\infty} \frac{1}{2^n} \qquad \text{(b)} \sum_{n=1}^{\infty} \frac{1}{n(n+1)} \qquad \text{(c)} \sum_{n=1}^{\infty} \log\left(\frac{n+1}{n}\right)$$

(In (c), $\log(x)$ refers to the natural logarithm function from calculus.)

Solution. For each series, let (s_m) be its sequence of partial sums; see Figure F.14 for graphs of the first thirty terms of these partial sum sequences.

(a) Here we have

$$\begin{aligned} s_m &= \frac{1}{2} + \frac{1}{2^2} + \cdots + \frac{1}{2^{m-1}} + \frac{1}{2^m} \\ \implies 2s_m &= 1 + \frac{1}{2} + \cdots + \frac{1}{2^m} + \frac{1}{2^{m+1}} \\ \implies 2s_m &= \frac{1 - 2^{-(m+2)}}{1 - \frac{1}{2}} \\ \implies s_m &= 1 - \frac{1}{2^{m+2}}, \end{aligned}$$

where we have used the formula $(1-x)(1+x+x^2+\cdots+x^n) = 1 - x^{n+1}$. It follows that $\lim s_m = 1$.

(b) For this series,

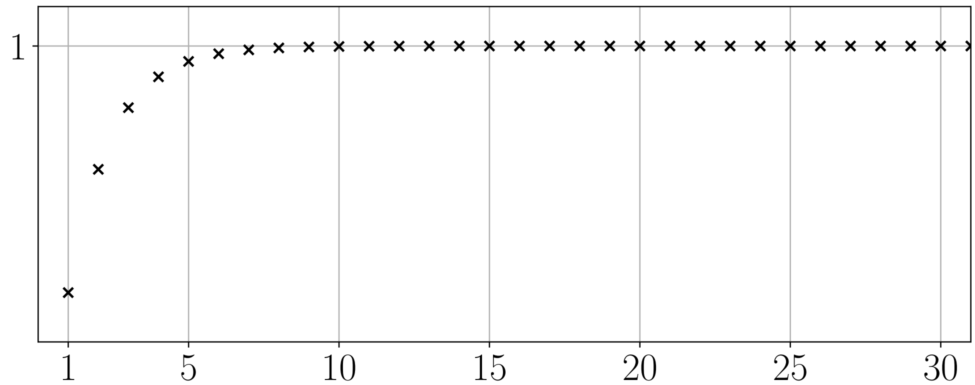
$$\begin{aligned} s_m = \sum_{n=1}^{m} \frac{1}{n(n+1)} &= \sum_{n=1}^{m} \left(\frac{1}{n} - \frac{1}{n+1} \right) \\ &= \left(1 - \frac{1}{2}\right) + \left(\frac{1}{2} - \frac{1}{3}\right) + \cdots + \left(\frac{1}{m} - \frac{1}{m+1}\right) = 1 - \frac{1}{m+1}. \end{aligned}$$

It follows that $\lim s_m = 1$.

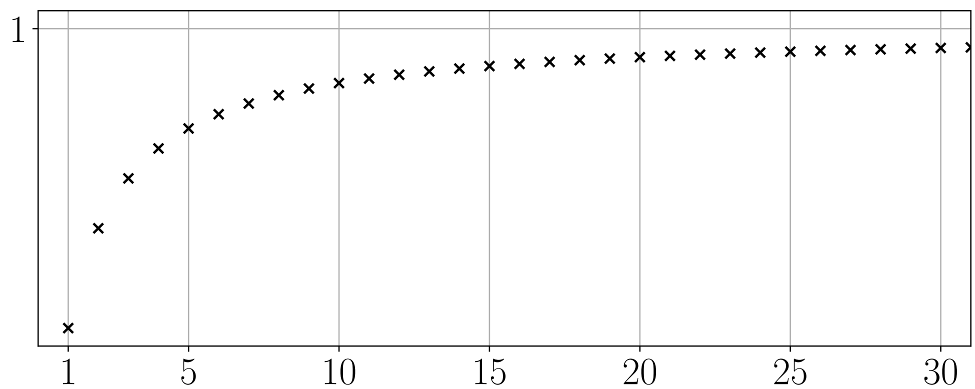
(c) We have

$$\begin{aligned} s_m &= \sum_{n=1}^{m} \log\left(\frac{n+1}{n}\right) \\ &= \sum_{n=1}^{m} (\log(n+1) - \log(n)) \\ &= (\log(2) - \log(1)) + (\log(3) - \log(2)) + \cdots + (\log(m+1) - \log(m)) \\ &= \log(m+1). \end{aligned}$$

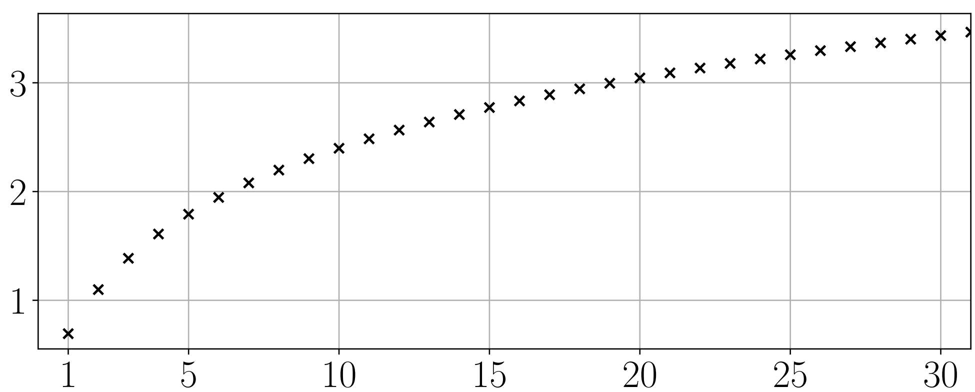
So $s_m = \log(m+1)$, which is unbounded and hence not convergent.



(a) $\sum_{n=1}^{m} \frac{1}{2^n}$ for $1 \le m \le 30$



(b) $\sum_{n=1}^{m} \frac{1}{n(n+1)}$ for $1 \le m \le 30$



(c) $\sum_{n=1}^{m} \log\left(\frac{n+1}{n}\right)$ for $1 \le m \le 30$

Figure F.14: Exercise 2.4.8 partial sums for $1 \le m \le 30$

Exercise 2.4.9. Complete the proof of Theorem 2.4.6 by showing that if the series $\sum_{n=0}^{\infty} 2^n b_{2^n}$ diverges, then so does $\sum_{n=1}^{\infty} b_n$. Example 2.4.5 may be a useful reference.

Solution. Define the sequences of partial sums

$$s_m = b_1 + b_2 + \cdots + b_m \qquad \text{and} \qquad t_m = b_1 + 2b_2 + \cdots + 2^m b_{2^m}.$$

We will use induction to show that $t_m \leq 2s_{2^m}$ for each $m \in \mathbf{N}$. For the base case $m = 1$ we have

$$t_1 = b_1 + 2b_2 \leq 2b_1 + 2b_2 = 2s_2,$$

where we have used that b_1 is non-negative. Suppose that the inequality holds for some $m \in \mathbf{N}$. Because the sequence (b_n) is decreasing, we have $b_{2^{m+1}} \leq b_{2^m+j}$ for each $1 \leq j \leq 2^m$. It follows that $2^m b_{2^{m+1}} \leq \sum_{j=1}^{2^m} b_{2^m+j}$. Combining this inequality with our induction hypothesis, we see that

$$t_{m+1} = t^m + 2^{m+1} b_{2^{m+1}} \leq 2s_{2^m} + 2\sum_{j=1}^{2^m} b_{2^m+j} = 2s_{2^{m+1}}.$$

This completes the induction step.

Since each b_n is non-negative, both sequences of partial sums (s_m) and (t_m) are increasing. It follows from the Monotone Convergence Theorem (Theorem 2.4.2) that the convergence of each series is equivalent to the boundedness of the respective sequence of partial sums. Given this, we want to show that if (t_m) is unbounded, then so is (s_m); this follows immediately from the inequality $t_m \leq 2s_{2^m}$.

Exercise 2.4.10 (Infinite Products). A close relative of infinite series is the *infinite product*

$$\prod_{n=1}^{\infty} b_n = b_1 b_2 b_3 \cdots$$

which is understood in terms of its sequence of *partial products*

$$p_m = \prod_{n=1}^{m} b_n = b_1 b_2 b_3 \cdots b_m.$$

Consider the special class of infinite products of the form

$$\prod_{n=1}^{\infty}(1 + a_n) = (1 + a_1)(1 + a_2)(1 + a_3) \cdots, \quad \text{where } a_n \geq 0.$$

(a) Find an explicit formula for the sequence of partial products in the case where $a_n = 1/n$ and decide whether the sequence converges. Write out the first few terms in the sequence of partial products in the case where $a_n = 1/n^2$ and make a conjecture about the convergence of this sequence.

(b) Show, in general, that the sequence of partial products converges if and only if $\sum_{n=1}^{\infty} a_n$ converges. (The inequality $1 + x \leq 3^x$ for positive x will be useful in one direction.)

Solution. (a) For $a_n = \frac{1}{n}$, observe that

$$p_m = \prod_{n=1}^{m}\left(1+\frac{1}{n}\right) = \prod_{n=1}^{m}\left(\frac{n+1}{n}\right) = 2 \cdot \frac{3}{2} \cdot \frac{4}{3} \cdots \frac{m}{m-1} \cdot \frac{m+1}{m}$$

$$= \frac{2}{2} \cdot \frac{3}{3} \cdot \frac{4}{4} \cdots \frac{m}{m} \cdot (m+1) = m+1.$$

It follows that (p_m) does not converge.

For $a_n = \frac{1}{n^2}$, the first few partial products are

$$\begin{aligned} p_1 &= 2, \\ p_2 &= 2(1+1/4) = 5/2 = 2.5, \\ p_3 &= (5/2)(1+1/9) = 25/9 \approx 2.778, \\ p_4 &= (25/9)(1+1/16) = 425/144 \approx 2.951. \end{aligned}$$

It looks like the partial products could be bounded; we conjecture that this infinite product converges. Indeed, part (b) proves our conjecture, since $\sum_{n=1}^{\infty} \frac{1}{n^2}$ is a convergent series; the Weierstrass factorization theorem can be used to show that

$$\prod_{n=1}^{\infty}\left(1+\frac{1}{n^2}\right) = \frac{\sinh(\pi)}{\pi}.$$

See Figure F.15 for a graph of the first thirty terms of the partial product sequence.

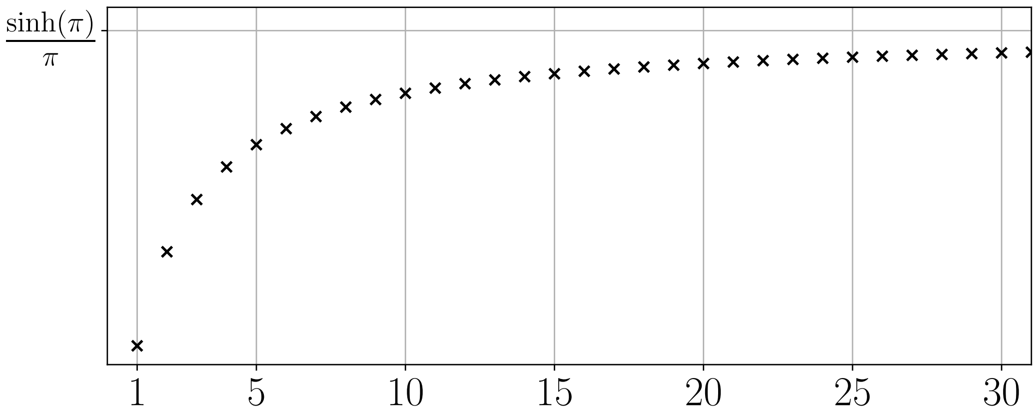


Figure F.15: $\prod_{n=1}^{m}\left(1+\frac{1}{n^2}\right)$ for $1 \leq m \leq 30$

(b) Let

$$s_m = \sum_{n=1}^{m} a_n \qquad \text{and} \qquad p_m = \prod_{n=1}^{m}(1+a_n).$$

Since $a_n \geq 0$ for all $n \in \mathbf{N}$, the sequence of partial sums and the sequence of partial products are both non-negative and increasing. It follows from the Monotone Convergence Theorem (Theorem 2.4.2) that the convergence of each sequence is equivalent to the boundedness of that sequence. By multiplying out the terms in the partial product p_m, we would obtain the sum s_m and some other non-negative terms; it follows that $s_m \leq p_m$. The hint gives us

$$p_m = \prod_{n=1}^{m}(1+a_n) \leq \prod_{n=1}^{m} 3^{a_n} = 3^{\sum_{n=1}^{m} a_n} = 3^{s_m}.$$

So we have the inequalities $s_m \leq p_m \leq 3^{s_m}$. It is then clear that (s_m) is bounded if (p_m) is bounded, and furthermore if (s_m) is bounded by some $M > 0$, then (p_m) is bounded by 3^M. It follows that for this special case, $\prod_{n=1}^{\infty}(1+a_n)$ converges if and only if $\sum_{n=1}^{\infty} a_n$ converges.

2.5 Subsequences and the Bolzano-Weierstrass Theorem

Exercise 2.5.1. Give an example of each of the following, or argue that such a request is impossible.

(a) A sequence that has a subsequence that is bounded but contains no subsequence that converges.

(b) A sequence that does not contain 0 or 1 as a term but contains subsequences converging to each of these values.

(c) A sequence that contains subsequences converging to every point in the infinite set

$$\{1, 1/2, 1/3, 1/4, 1/5, \ldots\}.$$

(d) A sequence that contains subsequences converging to every point in the infinite set

$$\{1, 1/2, 1/3, 1/4, 1/5, \ldots\},$$

and no subsequences converging to points outside of this set.

Solution. (a) This is impossible. If a sequence (a_n) has a bounded subsequence (a_{n_k}), then by the Bolzano-Weierstrass Theorem (Theorem 2.5.5) there must be a convergent sub-subsequence $\left(a_{n_{k_\ell}}\right)$; this is also a convergent subsequence of the original sequence (a_n).

(b) Consider the sequence

$$\left(\frac{1}{2}, \frac{1}{2}, \frac{1}{4}, \frac{3}{4}, \frac{1}{6}, \frac{5}{6}, \ldots\right),$$

i.e., the sequence (a_n) given by

$$a_n = \begin{cases} \frac{1}{n+1} & \text{if } n \text{ is odd,} \\ 1 - \frac{1}{n} & \text{if } n \text{ is even.} \end{cases}$$

This sequence does not contain 0 or 1 as a term, the subsequence (a_{2n-1}) converges to 0, and the subsequence (a_{2n}) converges to 1.

(c) Consider the following infinite array:

$$\begin{array}{cccccc}
1 & \frac{1}{2} & \frac{1}{3} & \frac{1}{4} & \frac{1}{5} & \cdots \\
1 & \frac{1}{2} & \frac{1}{3} & \frac{1}{4} & \frac{1}{5} & \cdots \\
1 & \frac{1}{2} & \frac{1}{3} & \frac{1}{4} & \frac{1}{5} & \cdots \\
1 & \frac{1}{2} & \frac{1}{3} & \frac{1}{4} & \frac{1}{5} & \cdots \\
1 & \frac{1}{2} & \frac{1}{3} & \frac{1}{4} & \frac{1}{5} & \cdots \\
\vdots & \vdots & \vdots & \vdots & \vdots & \ddots
\end{array}$$

Let (a_n) be the sequence obtained by following the diagonals of this array, i.e.,

$$(a_n) = \left(1, 1, \tfrac{1}{2}, 1, \tfrac{1}{2}, \tfrac{1}{3}, 1, \tfrac{1}{2}, \tfrac{1}{3}, \tfrac{1}{4}, 1, \ldots\right).$$

The subsequence given by the n^{th} column is $\left(\frac{1}{n}, \frac{1}{n}, \frac{1}{n}, \ldots\right)$, which converges to $\frac{1}{n}$.

(d) This is impossible. Suppose that (a_n) is a sequence that contains subsequences converging to every point in the infinite set

$$\left\{1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \frac{1}{5}, \ldots\right\}.$$

We claim that (a_n) must have a subsequence converging to 0. We will construct this subsequence recursively as follows. Since there is a subsequence converging to 1, there must be some index n_1 such that

$$|a_{n_1} - 1| < 1 \iff 0 < a_{n_1} < 2.$$

Since there is a subsequence converging to $\frac{1}{2}$, there must be some index $n_2 > n_1$ such that

$$\left|a_{n_2} - \frac{1}{2}\right| < \frac{1}{2} \iff 0 < a_{n_2} < 1.$$

We continue in this manner, obtaining a subsequence (a_{n_k}) satisfying $0 < a_{n_k} < \frac{2}{k}$. The Squeeze Theorem (Exercise 2.3.3) then implies that $\lim_{k\to\infty} a_{n_k} = 0$.

Exercise 2.5.2. Decide whether the following propositions are true or false, providing a short justification for each conclusion.

(a) If every proper subsequence of (x_n) converges, then (x_n) converges as well.

(b) If (x_n) contains a divergent subsequence, then (x_n) diverges.

(c) If (x_n) is bounded and diverges, then there exist two subsequences of (x_n) that converge to different limits.

(d) If (x_n) is monotone and contains a convergent subsequence, then (x_n) converges.

Solution. (a) This is true. By assumption, the subsequence $(x_2, x_3, x_4, \ldots)$ converges; it follows that (x_n) also converges to the same limit (see Exercise 2.4.1 (b)).

(b) This is true. Consider the contrapositive statement: if (x_n) converges, then all subsequences of (x_n) converge. This is implied by Theorem 2.5.2.

(c) This is true. Consider the sequences

$$y_n = \sup\{x_m : m \geq n\} \qquad \text{and} \qquad z_n = \inf\{x_m : m \geq n\}.$$

As shown in Exercise 2.4.7, these sequences both converge since (x_n) is bounded and their limits are denoted by

$$\limsup x_n = \lim y_n \qquad \text{and} \qquad \liminf x_n = \lim z_n.$$

We claim that there are subsequences of (x_n) converging to $\limsup x_n$ and $\liminf x_n$. First, we will recursively construct a subsequence converging to $\limsup x_n$. Let $n_0 = 0$. By Lemma 1.3.8, there exists an $n_1 \geq 1$ such that $y_1 - 1 < x_{n_1} \leq y_1$. There then exists an $n_2 \geq n_1 + 1$ such that $y_{n_1+1} - \frac{1}{2} < x_{n_2} \leq y_{n_1+1}$. Continuing in this fashion, we obtain indices $n_1 < \cdots < n_k < \cdots$ such that

$$y_{n_{k-1}+1} - \frac{1}{k} < x_{n_k} \leq y_{n_{k-1}+1}$$

for each $k \in \mathbf{N}$. The subsequence $(y_{n_{k-1}+1})$ converges to $\limsup x_n$ (Theorem 2.5.2) and hence by the Squeeze Theorem (Exercise 2.3.3) the subsequence (x_{n_k}) converges to $\limsup x_n$. Similarly, we can obtain another subsequence converging to $\liminf x_n$. As we showed in Exercise 2.4.7, the fact that (x_n) diverges implies that $\liminf x_n < \limsup x_n$ and so we have found two subsequences of (x_n) that converge to different limits.

(d) This is true. Suppose that (x_n) is decreasing; the case where (x_n) is increasing is handled similarly. By assumption, there is a subsequence (x_{n_k}), which must also be decreasing, converging to some $x \in \mathbf{R}$. By the Monotone Convergence Theorem (Theorem 2.4.2) and the uniqueness of limits (Theorem 2.2.7/Exercise 2.2.6), we have

$$\lim_{k\to\infty} x_{n_k} = x = \inf\{x_{n_k} : k \in \mathbf{N}\}.$$

Let $\epsilon > 0$ be given. Since $x_{n_k} \to x$, there is a $K \in \mathbf{N}$ such that $|x_{n_K} - x| < \epsilon$. Suppose that $n \in \mathbf{N}$ is such that $n \geq n_K$. Because (x_{n_k}) is a subsequence, there exists some $k \in \mathbf{N}$ such that $n_k \geq n$. Since (x_n) is decreasing, we then have

$$x \leq x_{n_k} \leq x_n \leq x_{n_K} < x + \epsilon \implies |x_n - x| < \epsilon.$$

Thus $\lim_{n\to\infty} x_n = x$.

Exercise 2.5.3. (a) Prove that if an infinite series converges, then the associative property holds. Assume $a_1 + a_2 + a_3 + a_4 + a_5 + \cdots$ converges to a limit L (i.e., the sequence of partial sums $(s_n) \to L$). Show that any regrouping of the terms

$$(a_1 + a_2 + \cdots + a_{n_1}) + (a_{n_1+1} + \cdots + a_{n_2}) + (a_{n_2+1} + \cdots + a_{n_3}) + \cdots$$

leads to a series that also converges to L.

(b) Compare this result to the example discussed at the end of Section 2.1 where infinite addition was shown not to be associative. Why doesn't our proof in (a) apply to this example?

Solution. (a) We have indices $n_1 < \cdots < n_k < \cdots$ and we want to show that $\sum_{k=1}^{\infty} b_k = L$, where $b_1 = a_1 + \cdots + a_{n_1} = s_{n_1}$ and

$$b_k = a_{n_{k-1}+1} + \cdots + a_{n_k} = s_{n_k} - s_{n_{k-1}}$$

for $k \geq 2$. Observe that for $m \geq 2$, the partial sums are

$$t_m = \sum_{k=1}^{m} b_k = s_{n_1} + \sum_{k=2}^{m} (s_{n_k} - s_{n_{k-1}}) = s_{n_1} + (s_{n_2} - s_{n_1}) + \cdots + (s_{n_m} - s_{n_{m-1}}) = s_{n_m}.$$

It follows from Theorem 2.5.2 that $\sum_{k=1}^{\infty} b_k = \lim_{m\to\infty} t_m = \lim_{m\to\infty} s_{n_m} = L$.

(b) Our proof does not apply to the series $\sum_{n=1}^{\infty}(-1)^n$ since this series does not converge: the sequence of partial sums is $(-1, 0, -1, 0, \ldots)$.

Exercise 2.5.4. The Bolzano-Weierstrass Theorem is extremely important, and so is the strategy employed in the proof. To gain some more experience with this technique, assume the Nested Interval Property is true and use it to provide a proof of the Axiom of Completeness. To prevent the argument from being circular, assume also that $(1/2^n) \to 0$. (Why precisely is this last assumption needed to avoid circularity?)

Solution. Let $E \subseteq \mathbf{R}$ be non-empty and bounded above by some $b_1 \in \mathbf{R}$; we will show that $\sup E$ exists. If E has a maximum x, then $\sup E = x$ and we are done. Otherwise, we shall use a recursive argument to construct a sequence $(I_n)_{n=1}^{\infty}$ of nested intervals. Pick some $a_1 \in E$; it must be the case that a_1 is not an upper bound of E since E has no maximum. Let $I_1 = [a_1, b_1]$ and note that:

- a_1 is not an upper bound of E;
- b_1 is an upper bound of E;
- $|I_1| = 2^0(b_1 - a_1)$.

Suppose that after N steps we have chosen intervals $I_n = [a_n, b_n], 1 \leq n \leq N$, such that

- $a_1 \leq \cdots \leq a_N$ are not upper bounds of E;
- $b_N \leq \cdots \leq b_1$ are upper bounds of E;
- $|I_n| = 2^{-(n-1)}(b_1 - a_1)$ for $1 \leq n \leq N$.

Let $m = \frac{a_N + b_N}{2}$, the midpoint of the interval I_N. If m is not an upper bound of E, let

$$a_{N+1} = m, \quad b_{N+1} = b_N, \qquad \text{and} \qquad I_{N+1} = [a_{N+1}, b_{N+1}].$$

If m is an upper bound of E, let

$$a_{N+1} = a_N, \quad b_{N+1} = m, \qquad \text{and} \qquad I_{N+1} = [a_{N+1}, b_{N+1}].$$

In either case, we have chosen intervals $I_n = [a_n, b_n], 1 \leq n \leq N + 1$, such that

- $a_1 \leq \cdots \leq a_{N+1}$ are not upper bounds of E;
- $b_{N+1} \leq \cdots \leq b_1$ are upper bounds of E;
- $|I_n| = 2^{-(n-1)}(b_1 - a_1)$ for $1 \leq n \leq N+1$.

In this way we obtain a sequence $(I_n)_{n=1}^{\infty}$ of intervals $I_n = [a_n, b_n]$ such that

- $a_1 \leq \cdots \leq a_n \leq \cdots$ are not upper bounds of E;
- $\cdots \leq b_n \leq \cdots \leq b_1$ are upper bounds of E;
- $|I_n| = 2^{-(n-1)}(b_1 - a_1)$ for all $n \in \mathbf{N}$.

Hence $(I_n)_{n=1}^{\infty}$ is a sequence of nested intervals. By assumption $\mathbf{R}$ has the Nested Interval Property (Theorem 1.4.1), so there exists an $x \in \mathbf{R}$ such that $x \in \bigcap_{n=1}^{\infty} I_n$; we claim that $x = \sup E$. For $y \in E$, let us seek a contradiction and suppose that $x < y$. Since $|I_n| = 2^{-(n-1)}(b_1 - a_1)$ for all $n \in \mathbf{N}$ and $(2^{-n}) \to 0$ (by assumption), there must exist an $N \in \mathbf{N}$ such that

$$|I_N| = b_N - a_N < y - x \implies x + (b_N - a_N) < y.$$

Since $x \in \bigcap_{n=1}^{\infty} I_n$, we have

$$a_N \leq x \implies 0 \leq x - a_N \implies b_N \leq x + (b_N - a_N) \implies b_N < y.$$

This is a contradiction since b_N is an upper bound of E. It follows that $y \leq x$ and thus x is an upper bound of E.

Now suppose that $z \in \mathbf{R}$ is such that $z < x$. Since $(|I_n|) \to 0$, there must be an $N \in \mathbf{N}$ such that

$$|I_N| = b_N - a_N < x - z \implies z < x - (b_N - a_N).$$

Since $x \in \bigcap_{n=1}^{\infty} I_n$, we have

$$x \leq b_N \implies x - b_N \leq 0 \implies x - (b_N - a_N) \leq a_N \implies z < a_N.$$

It follows that z is not an upper bound of E since a_N is not an upper bound of E. We may conclude that x is the least upper bound of E, i.e., $x = \sup E$.

We had to assume that $(2^{-n}) \to 0$ since the usual proof of this would involve the Archimedean Property (Theorem 1.4.2), which we proved using the Axiom of Completeness.

Exercise 2.5.5. Assume (a_n) is a bounded sequence with the property that every convergent subsequence of (a_n) converges to the same limit $a \in \mathbf{R}$. Show that (a_n) must converge to a.

Solution. Since (a_n) is bounded, $\limsup a_n$ and $\liminf a_n$ both exist. In the solution to Exercise 2.5.2 (c), we showed that there are subsequences (a_{n_k}) and (a_{n_ℓ}) such that

$$\lim_{k\to\infty} a_{n_k} = \limsup a_n \qquad \text{and} \qquad \lim_{\ell\to\infty} a_{n_\ell} = \liminf a_n.$$

By assumption we have $\lim_{k\to\infty} a_{n_k} = \lim_{\ell\to\infty} a_{n_\ell} = a$ and so by the uniqueness of limits (Theorem 2.2.7/Exercise 2.2.6) it follows that $\limsup a_n = \liminf a_n = a$; Exercise 2.4.7 then implies that $\lim a_n = a$.

Exercise 2.5.6. Use a similar strategy to the one in Example 2.5.3 to show $\lim b^{1/n}$ exists for all $b \geq 0$ and find the value of the limit. (The results in Exercise 2.3.1 may be assumed.)

Solution. If $b = 0$ then $b^{1/n} = 0$ for any $n \in \mathbf{N}$, so $\lim_{n\to\infty} b^{1/n} = 0$. Suppose that $b > 0$. If $0 < b < 1$, then

$$b < b^{1/2} < b^{1/3} < \cdots < 1.$$

If $b \geq 1$, then

$$b \geq b^{1/2} \geq b^{1/3} \geq \cdots \geq 1.$$

In either case, $(b^{1/n})$ is bounded and monotone and hence convergent by the Monotone Convergence Theorem (Theorem 2.4.2), say $\lim b^{1/n} = L \in \mathbf{R}$. It follows from Theorem 2.5.2 that $\lim b^{1/2n} = L$ also. Note that

$$\lim b^{1/2n} = \lim \sqrt{b^{1/n}} = \sqrt{\lim b^{1/n}} = \sqrt{L}$$

by Exercise 2.3.1. Since limits are unique (Theorem 2.2.7/Exercise 2.2.6), we must have $L = \sqrt{L}$, which implies that $L = 0$ or $L = 1$. If $0 < b < 1$ then the Order Limit Theorem (Theorem 2.3.4) gives $0 < b < L \leq 1$, whence $L = 1$, and if $b \geq 1$ then the Order Limit Theorem (Theorem 2.3.4) gives $L \geq 1$ so again we must have $L = 1$.

We may conclude that $\lim b^{1/n} = 0$ if $b = 0$ and $\lim b^{1/n} = 1$ if $b > 0$. See Figure F.16 for a graph of the first thirty terms of the sequence $(b^{1/n})$ for $b = 0, \frac{1}{2}, 1, 2$, demonstrating the behaviour of the sequence as b varies.

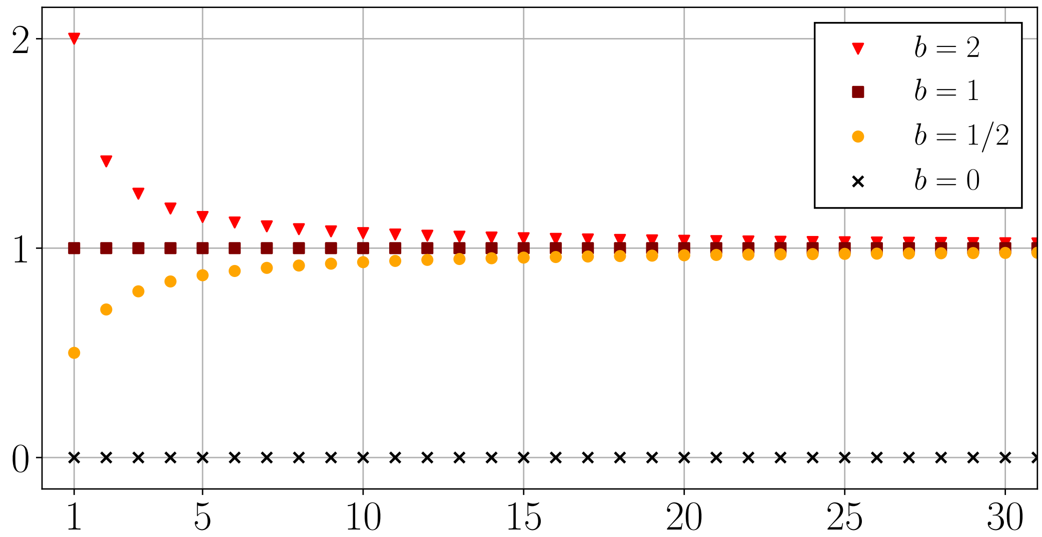


Figure F.16: $b^{1/n}$ for $1 \le n \le 30$ and $b = 0, \frac{1}{2}, 1, 2$

Exercise 2.5.7. Extend the result proved in Example 2.5.3 to the case $|b| < 1$; that is, show $\lim(b^n) = 0$ if and only if $-1 < b < 1$.

Solution. We will consider the following cases.

Case 1. $b > 1$. In this case, (b^n) is unbounded and hence divergent.

Case 2. $b = 1$. In this case, $(b^n) = (1, 1, 1, \ldots)$ and hence $\lim b^n = 1$.

Case 3. $0 < b < 1$. Example 2.5.3 shows that in this case we have $\lim b^n = 0$.

Case 4. $b = 0$. In this case, $(b^n) = (0, 0, 0, \ldots)$ and hence $\lim b^n = 0$.

Case 5. $-1 < b < 0$. Observe that $b = (-1)|b|$, so that $b^n = (-1)^n|b|^n$. Since $0 < |b| < 1$, we have $\lim|b|^n = 0$ by the $0 < b < 1$ case. Given this, and the boundedness of $(-1)^n$, it follows from Exercise 2.3.9 (a) that

$$\lim b^n = \lim[(-1)^n|b|^n] = 0.$$

Case 6. $b = -1$. In this case $b^n = (-1)^n$, which is divergent since it has two convergent subsequences with different limits:

$$\lim[(-1)^{2n}] = 1 \neq -1 = \lim[(-1)^{2n+1}].$$

Case 7. $b < -1$. We have $b^n = (-1)^n |b|^n$ with $|b| > 1$. Observe that the subsequence $(b^{2n}) = \left(|b|^{2n}\right)$ is divergent by the $b > 1$ case; it then follows from Exercise 2.5.2 (b) that the sequence (b^n) is divergent.

We may conclude that $\lim b^n = 0$ if and only if $-1 < b < 1$.

Exercise 2.5.8. Another way to prove the Bolzano-Weierstrass Theorem is to show that every sequence contains a monotone subsequence. A useful device in this endeavor is the notion of a *peak term*. Given a sequence (x_n), a particular term x_m is a peak term if no later term in the sequence exceeds it; i.e., if $x_m \geq x_n$ for all $n \geq m$.

(a) Find examples of sequences with zero, one, and two peak terms. Find an example of a sequence with infinitely many peak terms that is not monotone.

(b) Show that every sequence contains a monotone subsequence and explain how this furnishes a new proof of the Bolzano-Weierstrass Theorem.

Solution. (a) Any strictly increasing sequence will have zero peak terms; the sequence (n) for example. For sequences with one and two peak terms, consider (respectively)

$$\left(2, 0, \tfrac{1}{2}, \tfrac{2}{3}, \tfrac{3}{4}, \tfrac{4}{5} \ldots\right) \qquad \text{and} \qquad \left(3, 2, 0, \tfrac{1}{2}, \tfrac{2}{3}, \tfrac{3}{4}, \tfrac{4}{5} \ldots\right).$$

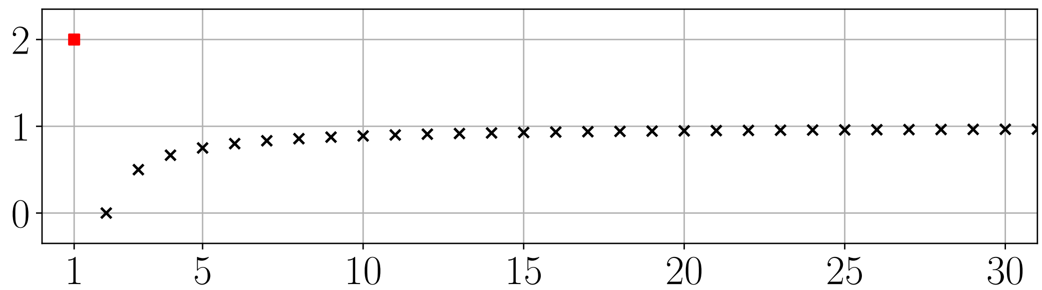
For a sequence with infinitely many peak terms but which is not monotone, consider

$$(0, 1, -2, -1, -4, -3, -6, -5, \ldots).$$

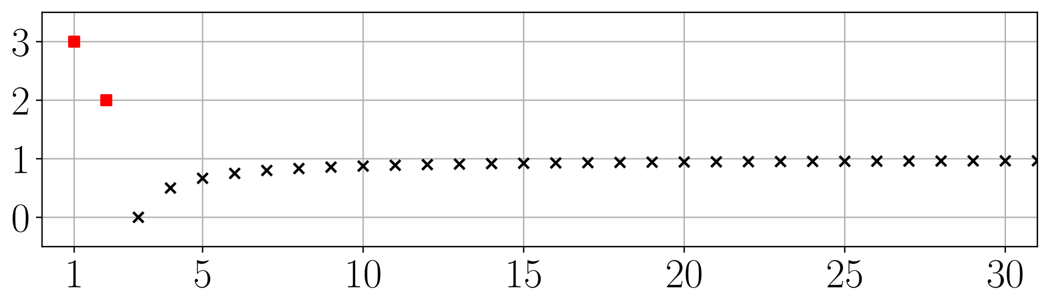
See Figure F.17 for a graph of the first thirty terms of these sequences.

(b) Let (x_n) be a sequence; we will show that (x_n) contains a monotone subsequence. First, suppose that (x_n) contains infinitely many peak terms, say $x_{n_1}, x_{n_2}, \ldots, x_{n_k}, \ldots$, where we may assume that $n_1 < n_2 < \cdots < n_k < \cdots$; the subsequence (x_{n_k}) is then a decreasing subsequence of (x_n). Next, suppose that (x_n) contains only finitely many peak terms. In this case, we are guaranteed the existence of a term x_{n_1} which is not a peak term and after which there are no peak terms. Since x_{n_1} is not a peak term, there exists an $n_2 > n_1$ such that $x_{n_2} > x_{n_1}$ and x_{n_2} is not a peak term. Since x_{n_2} is not a peak term, there exists an $n_3 > n_2$ such that $x_{n_3} > x_{n_2}$ and x_{n_3} is not a peak term. Continuing in this way, we recursively obtain an increasing subsequence (x_{n_k}) of (x_n). In either case, we have shown that (x_n) must contain a monotone subsequence.

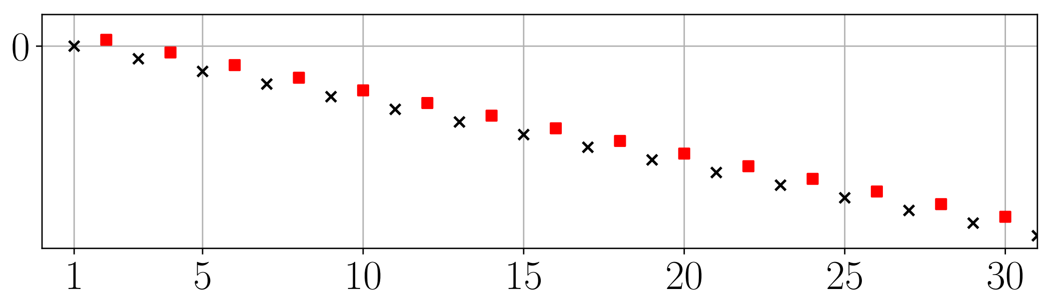
Now suppose that (x_n) is a bounded sequence. By the previous paragraph, there exists a monotone subsequence (x_{n_k}), which must also be bounded. The Monotone Convergence Theorem (Theorem 2.4.2) then implies that (x_{n_k}) is convergent; this provides another proof of the Bolzano-Weierstrass Theorem (Theorem 2.5.5).



(a) Sequence with one peak term



(b) Sequence with two peak terms



(c) Non-monotone sequence with infinitely many peak terms

Figure F.17: Exercise 2.5.8 (a) sequences with one, two, and infinitely many peak terms; the red squares indicate peak terms

Exercise 2.5.9. Let (a_n) be a bounded sequence, and define the set

$$S = \{x \in \mathbf{R} : x < a_n \text{ for infinitely many terms } a_n\}.$$

Show that there exists a subsequence (a_{n_k}) converging to $s = \sup S$. (This is a direct proof of the Bolzano-Weierstrass Theorem using the Axiom of Completeness.)

Solution. Since (a_n) is bounded, there is an $M > 0$ such that $-M \leq a_n \leq M$ for all $n \in \mathbf{N}$. It follows that $(-\infty, -M) \subseteq S$, so that S is non-empty, and for any $x \in S$ we have $x < a_n \leq M$ for some $n \in \mathbf{N}$, so that S is bounded above by M. The Axiom of Completeness then implies that $s := \sup S$ exists in $\mathbf{R}$.

Let k be a positive integer. We claim that the set

$$C_k = \left\{n \in \mathbf{N} : s - \tfrac{1}{k} < a_n \leq s + \tfrac{1}{k}\right\}$$

is infinite. By Lemma 1.3.8, there exists an $x \in S$ such that $s - \frac{1}{k} < x \leq s$. Define the sets

$$E = \{n \in \mathbf{N} : x < a_n\}, \quad A_k = \left\{n \in \mathbf{N} : s + \tfrac{1}{k} < a_n\right\}$$
$$\text{and} \quad B_k = \left\{n \in \mathbf{N} : x < a_n \leq s + \tfrac{1}{k}\right\}.$$

Observe that E is the disjoint union of A_k and B_k and that E is infinite since $x \in S$. Furthermore, A_k must be finite, otherwise we would have $s + \frac{1}{k} \in S$. It follows that B_k is infinite and hence that C_k is infinite, since $B_k \subseteq C_k$.

Since C_1 is infinite, there exists some $n_1 \in \mathbf{N}$ such that $s - 1 < a_{n_1} \leq s + 1$. Since C_2 is infinite, there exists some $n_2 > n_1$ such that $s - \frac{1}{2} < a_{n_2} \leq s + \frac{1}{2}$. We continue this process recursively to obtain a subsequence (a_{n_k}) satisfying $s - \frac{1}{k} < a_{n_k} \leq s + \frac{1}{k}$. The Squeeze Theorem (Exercise 2.3.3) then implies that $\lim_{k\to\infty} a_{n_k} = s$.

2.6 The Cauchy Criterion

Exercise 2.6.1. Supply a proof for Theorem 2.6.2.

Solution. Suppose $x_n \to x$ for some $x \in \mathbf{R}$; we will show that (x_n) is Cauchy. Let $\epsilon > 0$ be given. There is an $N \in \mathbf{N}$ such that $n \geq N$ implies that $|x_n - x| < \frac{\epsilon}{2}$. For $m, n \geq N$ we then have

$$|x_n - x_m| \leq |x_n - x| + |x_m - x| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon.$$

It follows that (x_n) is a Cauchy sequence.

Exercise 2.6.2. Give an example of each of the following, or argue that such a request is impossible.

(a) A Cauchy sequence that is not monotone.

(b) A Cauchy sequence with an unbounded subsequence.

(c) A divergent monotone sequence with a Cauchy subsequence.

(d) An unbounded sequence containing a subsequence that is Cauchy.

Solution. (a) Consider the sequence (x_n) given by $x_n = \frac{(-1)^n}{n}$. The sequence is convergent ($\lim x_n = 0$) and hence Cauchy (Theorem 2.6.4), but is certainly not monotone.

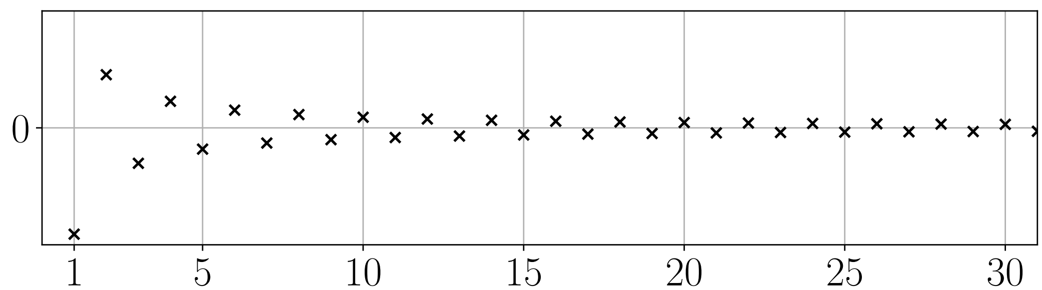


Figure F.18: $\frac{(-1)^n}{n}$ for $1 \leq n \leq 30$

(b) This is impossible. A Cauchy sequence (x_n) is necessarily convergent (Theorem 2.6.4) and hence all subsequences of (x_n) must be convergent (Theorem 2.5.2); each subsequence must then be bounded (Theorem 2.3.2).

(c) First, let us prove the following result.

Lemma L.8. If (x_n) is an unbounded monotone sequence, then all subsequences of (x_n) are also unbounded and monotone.

Proof. Suppose (x_n) is increasing (the case where (x_n) is decreasing is handled similarly) and let (x_{n_k}) be a subsequence of (x_n). If $k > \ell$, then $n_k > n_\ell$ and so $x_{n_k} \geq x_{n_\ell}$ since (x_n) is increasing; it follows that (x_{n_k}) is an increasing sequence. Now let $M > 0$ be given. Since

(x_n) is unbounded, there is an $N \in \mathbf{N}$ such that $x_N > M$, and since (x_{n_k}) is a subsequence of (x_n) we are guaranteed the existence of a $K \in \mathbf{N}$ such that $n_K > N$; it follows that $x_{n_K} \geq x_N > M$ since (x_n) is increasing. We may conclude that (x_{n_k}) is unbounded. $\square$

We can now show that the given request is impossible. If (x_n) is a divergent monotone sequence, then by the Monotone Convergence Theorem (Theorem 2.4.2) the sequence (x_n) must be unbounded. It follows from Lemma L.8 that all subsequences of (x_n) are unbounded, hence divergent (Theorem 2.3.2), and hence not Cauchy (Theorem 2.6.4).

(d) Consider the unbounded sequence $(0, 1, 0, 2, 0, 3, \ldots)$; the subsequence $(0, 0, 0, \ldots)$ is convergent and hence Cauchy (Theorem 2.6.4).

Exercise 2.6.3. If (x_n) and (y_n) are Cauchy sequences, then one easy way to prove that $(x_n + y_n)$ is Cauchy is to use the Cauchy Criterion. By Theorem 2.6.4, (x_n) and (y_n) must be convergent, and the Algebraic Limit Theorem then implies $(x_n + y_n)$ is convergent and hence Cauchy.

(a) Give a direct argument that $(x_n + y_n)$ is a Cauchy sequence that does not use the Cauchy Criterion or the Algebraic Limit Theorem.

(b) Do the same for the product $(x_n y_n)$.

Solution. (a) Let $\epsilon > 0$ be given. There are positive integers N_1 and N_2 such that

$$m, n \geq N_1 \implies |x_n - x_m| < \frac{\epsilon}{2} \qquad \text{and} \qquad m, n \geq N_2 \implies |y_n - y_m| < \frac{\epsilon}{2}.$$

Let $N = \max\{N_1, N_2\}$ and observe that for $m, n \geq N$ we have

$$|x_n + y_n - x_m - y_m| \leq |x_n - x_m| + |y_n - y_m| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon.$$

It follows that $(x_n + y_n)$ is a Cauchy sequence.

(b) Because Cauchy sequences are bounded (Lemma 2.6.3), there are positive real numbers M_1 and M_2 such that $|x_n| \leq M_1$ and $|y_n| \leq M_2$ for all $n \in \mathbf{N}$. Let $\epsilon > 0$ be given. There are positive integers N_1 and N_2 such that

$$m, n \geq N_1 \implies |x_n - x_m| < \frac{\epsilon}{2M_2} \qquad \text{and} \qquad m, n \geq N_2 \implies |y_n - y_m| < \frac{\epsilon}{2M_1}.$$

Let $N = \max\{N_1, N_2\}$ and observe that for $m, n \geq N$ we have

$$|x_n y_n - x_m y_m| = |x_n y_n - x_m y_n + x_m y_n - x_m y_m| \leq |y_n||x_n - x_m| + |x_m||y_n - y_m|$$
$$< M_2 \frac{\epsilon}{2M_2} + M_1 \frac{\epsilon}{2M_1} = \epsilon.$$

It follows that $(x_n y_n)$ is a Cauchy sequence.

Exercise 2.6.4. Let (a_n) and (b_n) be Cauchy sequences. Decide whether each of the following sequences is a Cauchy sequence, justifying each conclusion.

(a) $c_n = |a_n - b_n|$

(b) $c_n = (-1)^n a_n$

(c) $c_n = [[a_n]]$, where $[[x]]$ refers to the greatest integer less than or equal to x.

Solution. By the Cauchy Criterion (Theorem 2.6.4), we have $\lim a_n = a$ and $\lim b_n = b$ for some real numbers a and b. Again by the Cauchy Criterion, it will suffice to consider convergence of the given sequences (c_n).

(a) By Exercise 2.3.10 (b) and the Algebraic Limit Theorem (Theorem 2.3.3), we have

$$\lim c_n = \lim|a_n - b_n| = |\lim a_n - \lim b_n| = |a - b|.$$

So (c_n) is convergent and hence Cauchy.

(b) Suppose that $a = 0$. By Exercise 2.3.9 (a) we then have $\lim c_n = 0$ and it follows that (c_n) is Cauchy. If $a \neq 0$, then observe that

$$\lim c_{2n} = \lim a_{2n} = a \neq -a = \lim(-a_{2n-1}) = \lim c_{2n-1}.$$

So (c_n) has two subsequences which converge to different limits. It follows that (c_n) is not convergent (Theorem 2.5.2) and hence not Cauchy.

(c) Suppose that a is not an integer, so that $[[a]] < a < [[a]] + 1$. Let

$$\delta = \min\{a - [[a]], [[a]] + 1 - a\}.$$

Since $\lim a_n = a$, there is a positive integer N such that $n \geq N$ implies that $a_n \in (a-\delta, a+\delta)$. Observe that $[[a]] \leq a-\delta$ and $a+\delta \leq [[a]]+1$. For $n \geq N$ we then have $[[a]] < a_n < [[a]]+1$, which gives us $[[a_n]] = [[a]]$. Thus the sequence $[[a_n]]$ is eventually constant with value $[[a]]$; it follows that $[[a_n]]$ is convergent with limit $[[a]]$ and hence Cauchy.

If a is an integer, then the sequence $([[a_n]])$ may or may not be convergent (and so may or may not be Cauchy). For example, if (a_n) is the sequence $(0, 0, 0, \ldots)$ then clearly $\lim[[a_n]] = 0$. However, consider the sequence $a_n = \frac{(-1)^n}{n}$, which also satisfies $\lim a_n = 0$. This gives

$$([[a_n]]) = (-1, 0, -1, 0, -1, 0, \ldots),$$

which is divergent.

Exercise 2.6.5. Consider the following (invented) definition: A sequence (s_n) is *pseudo-Cauchy* if, for all $\epsilon > 0$, there exists an N such that if $n \geq N$, then $|s_{n+1} - s_n| < \epsilon$.

Decide which one of the following two propositions is actually true. Supply a proof for the valid statement and a counterexample for the other.

(i) Psuedo-Cauchy sequences are bounded.

(ii) If (x_n) and (y_n) are pseudo-Cauchy, then $(x_n + y_n)$ is pseudo-Cauchy as well.

Solution. (i) This statement is false: consider the sequence (s_n) given by $s_n = \sum_{m=1}^{n} \frac{1}{m}$. This sequence satisfies $s_{n+1} - s_n = \frac{1}{n+1} \to 0$, so that (s_n) is pseudo-Cauchy. However, as shown in Example 2.4.5, (s_n) is unbounded.

(ii) This statement is true. Let $\epsilon > 0$ be given. There are positive integers N_1 and N_2 such that

$$n \geq N_1 \implies |x_{n+1} - x_n| < \frac{\epsilon}{2} \qquad \text{and} \qquad n \geq N_2 \implies |y_{n+1} - y_n| < \frac{\epsilon}{2}.$$

Let $N = \max\{N_1, N_2\}$ and observe that for $n \geq N$ we have

$$|x_{n+1} + y_{n+1} - x_n - y_n| \leq |x_{n+1} - x_n| + |y_{n+1} - y_n| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon.$$

It follows that $(x_n + y_n)$ is pseudo-Cauchy.

Exercise 2.6.6. Let's call a sequence (a_n) *quasi-increasing* if for all $\epsilon > 0$ there exists an N such that whenever $n > m \geq N$ it follows that $a_n > a_m - \epsilon$.

(a) Give an example of a sequence that is quasi-increasing but not monotone or eventually monotone.

(b) Give an example of a quasi-increasing sequence that is divergent and not monotone or eventually monotone.

(c) Is there an analogue of the Monotone Convergence Theorem for quasi-increasing sequences? Give an example of a bounded, quasi-increasing sequence that doesn't converge, or prove that no such sequence exists.

Solution. (a) Consider the sequence (a_n) given by

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

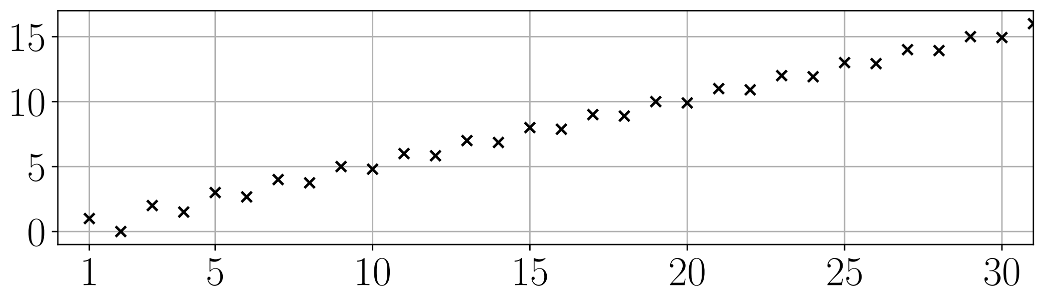


Figure F.19: a_n for $1 \leq n \leq 30$

Some calculations reveal that this sequence has the following properties.

(i) If $m \in \mathbf{N}$ is even, then $a_n > a_m$ for all $n > m$.

(ii) If $m \in \mathbf{N}$ is odd, then $a_n > a_m$ for all $n > m + 1$ and $a_m - a_{m+1} = \frac{2}{m+1} > 0$.

It follows that (a_n) is not eventually monotone, for if N is a positive integer, choose an odd integer m such that $m > N$; by property (ii) we then have $a_m > a_{m+1}$ and $a_m < a_{m+2}$. Furthermore, (a_n) is quasi-increasing. To see this, let $\epsilon > 0$ be given. Choose a positive integer N such that $\frac{2}{N+1} < \epsilon$ and suppose that $n > m \geq N$. By properties (i) and (ii), we have

$$a_m - a_n < 0 < \epsilon \implies a_n > a_m - \epsilon$$

unless m is odd and $n = m + 1$. In that case we have

$$a_m - a_{m+1} = \frac{2}{m+1} \leq \frac{2}{N+1} < \epsilon \implies a_n > a_m - \epsilon.$$

(b) The sequence (a_n) given in part (a) is unbounded and hence divergent.

(c) There is an analogue of the Monotone Convergence Theorem (Theorem 2.4.2) for bounded quasi-increasing sequences. Let (a_n) be such a sequence; we will show that (a_n) converges to $\limsup a_n$.

Let $s = \limsup a_n$ and $y_n = \sup\{a_\ell : \ell \geq n\}$, so that $\lim y_n = s$. By Exercise 2.5.2 (c), there is a subsequence (a_{n_k}) converging to s. Let $\epsilon > 0$ be given. There is an $N_1 \in \mathbf{N}$ such that $|y_n - s| < \epsilon$ whenever $n \geq N_1$. Since $a_n \leq y_n$ for all $n \in \mathbf{N}$, we have

$$n \geq N_1 \implies a_n < s + \epsilon. \tag{1}$$

Since (a_n) is quasi-increasing, there is an $N_2 \in \mathbf{N}$ such that

$$n > m \geq N_2 \implies a_m - \frac{\epsilon}{2} < a_n, \tag{2}$$

and since $(a_{n_k}) \to s$, there is a $K \in \mathbf{N}$ such that

$$k \geq K \implies |a_{n_k} - s| < \frac{\epsilon}{2}. \tag{3}$$

Because (a_{n_k}) is a subsequence, there must be some $k' \in \mathbf{N}$ such that both $k' \geq K$ and $n_{k'} \geq N_2$. It follows that

$$n > n_{k'} \implies a_{n_{k'}} - \frac{\epsilon}{2} < a_n \qquad \text{by (2)},$$

and $s - \epsilon < a_{n_{k'}} - \frac{\epsilon}{2}$ by (3). Combining these gives

$$n > n_{k'} \implies s - \epsilon < a_n. \tag{4}$$

Let $N = \max\{N_1, n_{k'}\}$. By (1) and (4), we then have

$$n > N \implies s - \epsilon < a_n < s + \epsilon.$$

It follows that $\lim a_n = s$.

Exercise 2.6.7. Exercises 2.4.4 and 2.5.4 establish the equivalence of the Axiom of Completeness and the Monotone Convergence Theorem. They also show that the Nested Interval Property is equivalent to these other two in the presence of the Archimedean Property.

(a) Assume the Bolzano-Weierstrass Theorem is true and use it to construct a proof of the Monotone Convergence Theorem without making any appeal to the Archimedean Property. This shows that BW, AoC, and MCT are all equivalent.

(b) Use the Cauchy Criterion to prove the Bolzano-Weierstrass Theorem, and find the point in the argument where the Archimedean Property is implicitly required. This establishes the final link in the equivalence of the five characterizations of completeness discussed at the end of Section 2.6.

(c) How do we know it is impossible to prove the Axiom of Completeness starting from the Archimedean Property?

Solution. (a) Suppose (x_n) is bounded and increasing (the case where (x_n) is decreasing is handled similarly). By assumption, there is a convergent subsequence (x_{n_k}), say $\lim_{k\to\infty} x_{n_k} = x$ for some $x \in \mathbf{R}$. Let $\epsilon > 0$ be given. There is a $K \in \mathbf{N}$ such that

$$k \geq K \implies |x_{n_k} - x| < \epsilon. \tag{1}$$

Suppose $n \in \mathbf{N}$ is such that $n \geq n_K$. Since (x_n) is increasing, we then have $x - \epsilon < x_{n_K} \leq x_n$. Furthermore, it must be the case that $x_n < x + \epsilon$. Indeed, if $x_n \geq x + \epsilon$, then since (x_{n_k}) is a subsequence there must be some $k \in \mathbf{N}$ such that $n_k \geq n \geq n_K$. This implies that $k \geq K$ and, since (x_n) is increasing, that $x_{n_k} \geq x_n \geq x + \epsilon$; this contradicts (1). So we have shown that

$$n \geq n_K \implies x - \epsilon < x_n < x + \epsilon.$$

It follows that $\lim x_n = x$.

(b) Let (x_n) be a sequence bounded by some $M > 0$. As in the proof of the Bolzano-Weierstrass Theorem (Theorem 2.5.5) given in the textbook, construct a sequence of nested intervals (I_k) with length $M \cdot 2^{-k+1}$ and a subsequence (x_{n_k}) such that $x_{n_k} \in I_k$. Let $\epsilon > 0$ be given. Assuming that $2^{-k} \to 0$ (this is equivalent to assuming the Archimedean Property (Theorem 1.4.2)), there is a $K \in \mathbf{N}$ such that $M \cdot 2^{-K+1} < \epsilon$. Suppose that $k > \ell \geq K$. Since the intervals are nested, both x_{n_k} and x_{n_ℓ} belong to I_K. It follows that x_{n_k} and x_{n_ℓ} are no further apart than the width of I_K, i.e.,

$$|x_{n_k} - x_{n_\ell}| \leq \frac{M}{2^{K-1}} < \epsilon.$$

This demonstrates that (x_{n_k}) is a Cauchy sequence. By assumption, this is equivalent to (x_{n_k}) being convergent.

(c) The ordered field $\mathbf{Q}$ has the Archimedean Property but does not satisfy the Axiom of Completeness (see Lemma L.4; the subset $A \subseteq \mathbf{Q}$ given there is non-empty and bounded above but has no supremum in $\mathbf{Q}$).

2.7 Properties of Infinite Series

Exercise 2.7.1. Proving the Alternating Series Test (Theorem 2.7.7) amounts to showing that the sequence of partial sums

$$s_n = a_1 - a_2 + a_3 - \cdots \pm a_n$$

converges. (The opening example in Section 2.1 includes a typical illustration of (s_n).) Different characterizations of completeness lead to different proofs.

(a) Prove the Alternating Series Test by showing that (s_n) is a Cauchy sequence.

(b) Supply another proof for this result using the Nested Interval Property (Theorem 1.4.1).

(c) Consider the subsequences (s_{2n}) and (s_{2n+1}), and show how the Monotone Convergence Theorem leads to a third proof for the Alternating Series Test.

Solution. First note that since (a_n) is decreasing and converges to zero, $a_n \geq 0$ and $a_n - a_{n+1} \geq 0$ for all $n \in \mathbf{N}$.

(a) Suppose $n > m$ are positive integers. If $n - m$ is even, then

$$s_n - s_m = \underbrace{a_{m+1} - a_{m+2}}_{\geq 0} + \underbrace{a_{m+3} - a_{m+4}}_{\geq 0} + \cdots + \underbrace{a_{n-1} - a_n}_{\geq 0} \geq 0,$$

and if $n - m$ is odd, then

$$s_n - s_m = \underbrace{a_{m+1} - a_{m+2}}_{\geq 0} + \underbrace{a_{m+3} - a_{m+4}}_{\geq 0} + \cdots + \underbrace{a_{n-2} - a_{n-1}}_{\geq 0} + \underbrace{a_n}_{\geq 0} \geq 0.$$

It follows that $|s_n - s_m| = s_n - s_m = a_{m+1} - a_{m+2} + \cdots \pm a_n$. If $n - m$ is even, then

$$|s_n - s_m| = a_{m+1} + \underbrace{(-a_{m+2} + a_{m+3})}_{\leq 0} + \cdots + \underbrace{(-a_{n-2} + a_{n-1})}_{\leq 0} + \underbrace{(-a_n)}_{\leq 0} \leq a_{m+1},$$

and if $n-m$ is odd, then

$$|s_n - s_m| = a_{m+1} + \underbrace{(-a_{m+2} + a_{m+3})}_{\leq 0} + \cdots + \underbrace{(-a_{n-1} + a_n)}_{\leq 0} \leq a_{m+1}.$$

It follows that $|s_n - s_m| \leq a_{m+1}$. Let $\epsilon > 0$ be given. Since $a_n \to 0$, there is an $N \in \mathbf{N}$ such that $|a_n| = a_n < \epsilon$ for all $n \geq N$. For $n > m \geq N$ we then have

$$|s_n - s_m| \leq a_{m+1} < \epsilon.$$

It follows that (s_n) is a Cauchy sequence.

(b) Let n be a positive integer. Observe that

$$s_{2n-1} - s_{2n} = a_{2n} \geq 0 \implies s_{2n} \leq s_{2n-1},$$

$$s_{2n-1} - s_{2n-3} = a_{2n-1} - a_{2n-2} \leq 0 \implies s_{2n-1} \leq s_{2n-3},$$

$$s_{2n} - s_{2n-2} = a_{2n-1} - a_{2n} \geq 0 \implies s_{2n-2} \leq s_{2n}.$$

Thus $(I_n = [s_{2n}, s_{2n-1}])_{n=1}^{\infty}$ is a sequence of nested intervals. It follows from the Nested Interval Property (Theorem 1.4.1) that there exists some $x \in \bigcap_{n=1}^{\infty} I_n$; we claim that $\lim s_n = x$. To see this, suppose that $n \in \mathbf{N}$. If n is even, then $s_n \in I_{n/2} = [s_n, s_{n-1}]$ and so

$$|s_n - x| \leq \left|I_{n/2}\right| = s_{n-1} - s_n = a_n.$$

If n is odd, then $s_n \in I_{(n+1)/2} = [s_{n+1}, s_n]$ and so

$$|s_n - x| \leq \left|I_{(n+1)/2}\right| = s_n - s_{n+1} = a_{n+1} \leq a_n.$$

It follows that for all $n \in \mathbf{N}$ we have $|s_n - x| \leq a_n$; since $a_n \to 0$, an application of the Squeeze Theorem (Exercise 2.3.3) then yields $\lim s_n = x$.

(c) As shown in (b), the sequence (s_{2n}) is increasing and bounded above by s_1, and the sequence (s_{2n+1}) is decreasing and bounded below by s_2. The Monotone Convergence Theorem (Theorem 2.4.2) then implies that $\lim s_{2n}$ and $\lim s_{2n+1}$ both exist. The relationship $s_{2n+1} - s_{2n} = a_{2n+1}$ gives

$$\lim(s_{2n+1} - s_{2n}) = \lim a_{2n+1} = 0,$$

so that (s_{2n}) and (s_{2n+1}) both converge to the same limit $x \in \mathbf{R}$ (Exercise 2.3.10 (c)). It follows that $\lim s_n = x$, as the next lemma shows.

Lemma L.9. If (x_n) is a sequence of real numbers such that

$$\lim x_{2n} = \lim x_{2n+1} = x$$

for some $x \in \mathbf{R}$, then $\lim x_n = x$.

Proof. Let $\epsilon > 0$ be given. There are positive integers N_1 and N_2 such that

$$n \geq N_1 \implies |x_{2n} - x| < \epsilon, \tag{1}$$
$$n \geq N_2 \implies |x_{2n+1} - x| < \epsilon. \tag{2}$$

Let $N = \max\{N_1, N_2\}$ and suppose that $n \in \mathbf{N}$ is such that $n \geq 2N + 1$. If n is even, then $\frac{n}{2} > N \geq N_1$ and so $|x_n - x| < \epsilon$ by (1). If n is odd, then $\frac{n-1}{2} \geq N \geq N_2$ and so $|x_n - x| < \epsilon$ by (2). Thus

$$n \geq 2N + 1 \implies |x_n - x| < \epsilon.$$

It follows that $\lim x_n = x$. □

Exercise 2.7.2. Decide whether each of the following series converges or diverges:

(a) $\sum_{n=1}^{\infty} \frac{1}{2^n+n}$ (b) $\sum_{n=1}^{\infty} \frac{\sin(n)}{n^2}$

(c) $1 - \frac{3}{4} + \frac{4}{6} - \frac{5}{8} + \frac{6}{10} - \frac{7}{12} + \cdots$

(d) $1 + \frac{1}{2} - \frac{1}{3} + \frac{1}{4} + \frac{1}{5} - \frac{1}{6} + \frac{1}{7} + \frac{1}{8} - \frac{1}{9} + \cdots$

(e) $1 - \frac{1}{2^2} + \frac{1}{3} - \frac{1}{4^2} + \frac{1}{5} - \frac{1}{6^2} + \frac{1}{7} - \frac{1}{8^2} + \cdots$

Solution. See Figure F.20 for graphs of the first thirty terms of relevant partial sums for each series.

(a) Observe that for each $n \in \mathbf{N}$ we have

$$0 < \frac{1}{2^n + n} < \frac{1}{2^n}.$$

Since $\sum_{n=1}^{\infty} \frac{1}{2^n} = 1$ (Example 2.7.5), the Comparison Test (Theorem 2.7.4) implies that $\sum_{n=1}^{\infty} \frac{1}{2^n+n}$ is convergent.

(b) Observe that for each $n \in \mathbf{N}$ we have

$$0 < \frac{|\sin(n)|}{n^2} \leq \frac{1}{n^2}.$$

Since $\sum_{n=1}^{\infty} \frac{1}{n^2}$ is convergent (Example 2.4.4), the Comparison Test (Theorem 2.7.4) implies that $\sum_{n=1}^{\infty} \frac{\sin(n)}{n^2}$ is absolutely convergent and hence convergent (Theorem 2.7.6).

(c) This is the series $\sum_{n=1}^{\infty} a_n$, where

$$a_n = (-1)^{n+1}\frac{n+1}{2n} = (-1)^{n+1}\left(\frac{1}{2} + \frac{1}{2n}\right).$$

The sequence (a_n) is divergent by Theorem 2.5.2:

$$\lim a_{2n} = -\frac{1}{2} \neq \frac{1}{2} = \lim a_{2n+1}.$$

It follows from Theorem 2.7.3 that $\sum_{n=1}^{\infty} a_n$ is divergent.

(d) For the series $1 + \frac{1}{2} - \frac{1}{3} + \frac{1}{4} + \frac{1}{5} - \frac{1}{6} + \frac{1}{7} + \frac{1}{8} - \frac{1}{9} + \cdots$, let (s_n) be the sequence of partial sums and consider the subsequence (s_{3n}). Observe that

$$\begin{aligned}
s_{3n} &= \left(1 + \frac{1}{2} - \frac{1}{3}\right) + \left(\frac{1}{4} + \frac{1}{5} - \frac{1}{6}\right) + \cdots + \left(\frac{1}{3n-2} + \frac{1}{3n-1} - \frac{1}{3n}\right) \\
&\geq \left(1 + \frac{1}{2} - \frac{1}{2}\right) + \left(\frac{1}{4} + \frac{1}{5} - \frac{1}{5}\right) + \cdots + \left(\frac{1}{3n-2} + \frac{1}{3n-1} - \frac{1}{3n-1}\right) \\
&= 1 + \frac{1}{4} + \cdots + \frac{1}{3n-2} \\
&= \frac{1}{3}\sum_{k=1}^{n} \frac{1}{k - \frac{2}{3}} \\
&\geq \frac{1}{3}\sum_{k=1}^{n} \frac{1}{k}.
\end{aligned}$$

So we have shown that $s_{3n} \geq \frac{1}{3}\sum_{k=1}^{n} \frac{1}{k}$ for all $n \in \mathbf{N}$. Since $\sum_{k=1}^{n} \frac{1}{k}$ is unbounded in n (Example 2.4.5), it follows that (s_{3n}) is unbounded. This implies that (s_n) is unbounded and hence divergent (Theorem 2.3.2).

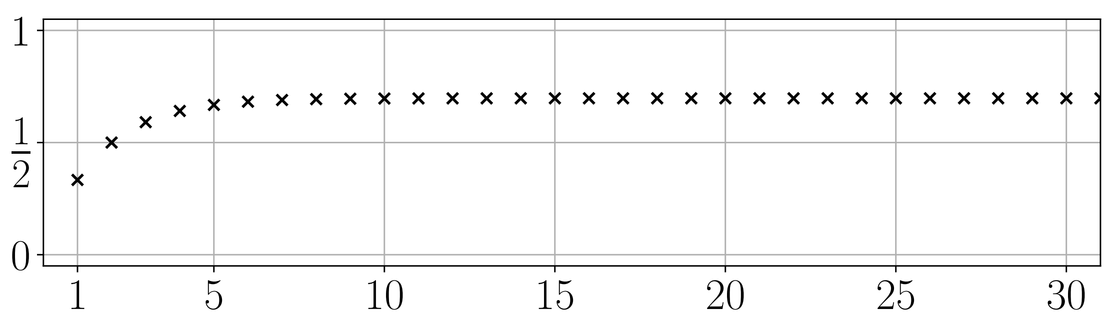
(e) For the series $1 - \frac{1}{2^2} + \frac{1}{3} - \frac{1}{4^2} + \frac{1}{5} - \frac{1}{6^2} + \frac{1}{7} - \frac{1}{8^2} + \cdots$, let (s_n) be the sequence of partial sums and consider the subsequence (s_{2n}). For any $m \geq 2$, we have

$$\frac{1}{m^2} \leq \frac{1}{m(m-1)} = \frac{1}{m-1} - \frac{1}{m} \implies -\frac{1}{m^2} \geq -\frac{1}{m-1} + \frac{1}{m}.$$

It follows that

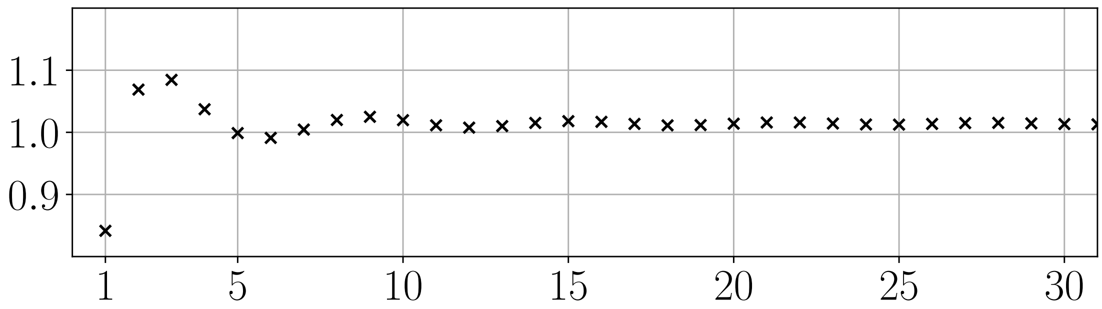
$$\begin{aligned} s_{2n} &= \left(1 - \frac{1}{2^2}\right) + \left(\frac{1}{3} - \frac{1}{4^2}\right) + \cdots + \left(\frac{1}{2n-1} - \frac{1}{(2n)^2}\right) \\ &\geq \left(1 - 1 + \frac{1}{2}\right) + \left(\frac{1}{3} - \frac{1}{3} + \frac{1}{4}\right) + \cdots + \left(\frac{1}{2n-1} - \frac{1}{2n-1} + \frac{1}{2n}\right) \\ &= \frac{1}{2} + \frac{1}{4} + \cdots + \frac{1}{2n} \\ &= \frac{1}{2}\sum_{k=1}^{n} \frac{1}{k}. \end{aligned}$$

So we have shown that $s_{2n} \geq \frac{1}{2}\sum_{k=1}^{n} \frac{1}{k}$ for all $n \in \mathbf{N}$. Since $\sum_{k=1}^{n} \frac{1}{k}$ is unbounded in n (Example 2.4.5), it follows that (s_{2n}) is unbounded. This implies that (s_n) is unbounded and hence divergent (Theorem 2.3.2).

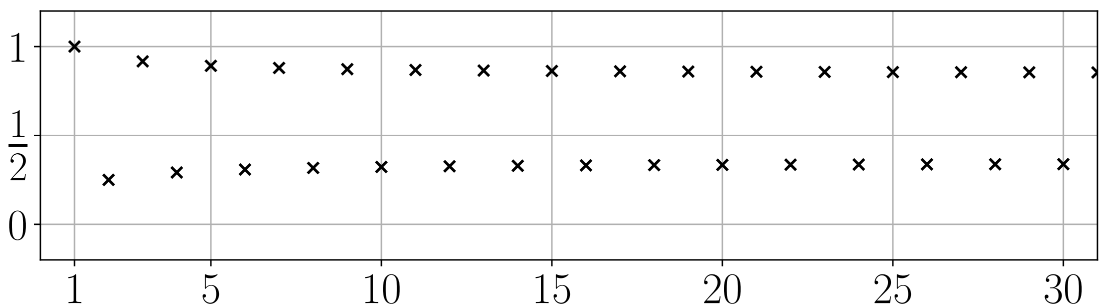


(a) $\sum_{k=1}^{n} \frac{1}{2^k+k}$ for $1 \leq n \leq 30$

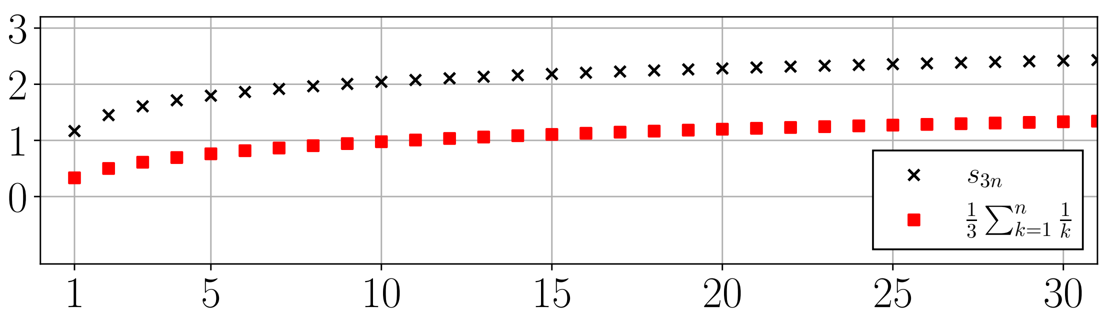
Figure F.20: Exercise 2.7.2 partial sums for $1 \leq n \leq 30$



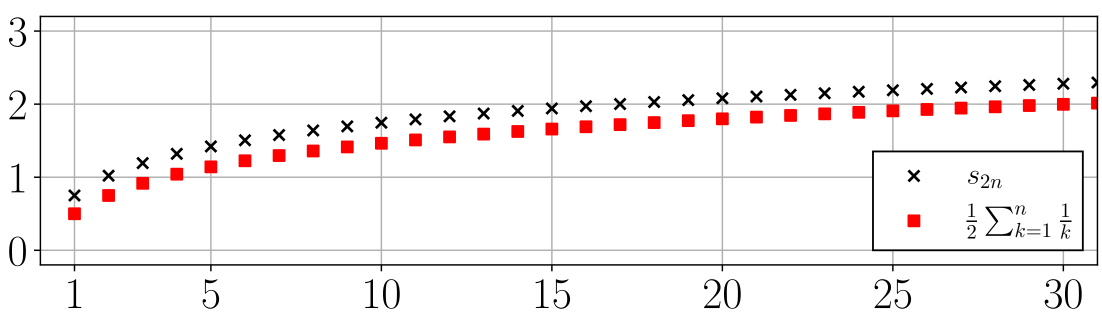
(b) $\sum_{k=1}^{n} \frac{\sin(k)}{k^2}$ for $1 \le n \le 30$



(c) $\sum_{k=1}^{n} (-1)^{k+1} \frac{k+1}{2k}$ for $1 \le n \le 30$



(d) s_{3n} and $\frac{1}{3}\sum_{k=1}^{n} \frac{1}{k}$ for $1 \le n \le 30$



(e) s_{2n} and $\frac{1}{2}\sum_{k=1}^{n} \frac{1}{k}$ for $1 \le n \le 30$

Figure F.20: Exercise 2.7.2 partial sums for $1 \le n \le 30$ (cont.)

Exercise 2.7.3. (a) Provide the details for the proof of the Comparison Test (Theorem 2.7.4) using the Cauchy Criterion for Series.

(b) Give another proof for the Comparison Test, this time using the Monotone Convergence Theorem.

Solution. (a) Since $0 \leq a_k \leq b_k$ for all $k \in \mathbf{N}$, for any $n > m$ we have

$$|a_{m+1} + \cdots + a_n| = a_{m+1} + \cdots + a_n \leq b_{m+1} + \cdots + b_n = |b_{m+1} + \cdots + b_n|. \tag{1}$$

Suppose that $\sum_{k=1}^{\infty} b_k$ is convergent and let $\epsilon > 0$ be given. By the Cauchy Criterion for Series (Theorem 2.7.2), there exists an $N \in \mathbf{N}$ such that

$$n > m \geq N \implies |b_{m+1} + \cdots + b_n| < \epsilon.$$

It then follows from inequality (1) that $|a_{m+1} + \cdots + a_n| < \epsilon$ for all $n > m \geq N$. The Cauchy Criterion for Series (Theorem 2.7.2) allows us to conclude that $\sum_{k=1}^{\infty} a_k$ is convergent.

Now suppose that $\sum_{k=1}^{\infty} a_k$ is divergent. By the Cauchy Criterion for Series (Theorem 2.7.2), there must exist an $\epsilon > 0$ such that for all $N \in \mathbf{N}$ there are positive integers n and m such that

$$n > m \geq N \qquad \text{and} \qquad |a_{m+1} + \cdots + a_n| \geq \epsilon.$$

Let $N \in \mathbf{N}$ be given and let n and m be the positive integers obtained above. Inequality (1) then gives us $|b_{m+1} + \cdots + b_n| \geq \epsilon$; it follows from the Cauchy Criterion for Series (Theorem 2.7.2) that $\sum_{k=1}^{\infty} b_k$ is divergent.

(b) Define the sequences of partial sums

$$s_n = a_1 + \cdots + a_n \qquad \text{and} \qquad t_n = b_1 + \cdots + b_n.$$

Since $0 \leq a_k \leq b_k$ for all $k \in \mathbf{N}$, both sequences of partial sums are increasing and satisfy $0 \leq s_n \leq t_n$ for all $n \in \mathbf{N}$. It follows from the Monotone Convergence Theorem (Theorem 2.4.2) that the convergence of each sequence is equivalent to the boundedness of that sequence. From the inequality $0 \leq s_n \leq t_n$, it is clear that (s_n) is bounded if (t_n) is bounded and that (t_n) is unbounded if (s_n) is unbounded.

Exercise 2.7.4. Give an example of each or explain why the request is impossible referencing the proper theorem(s).

(a) Two series $\sum x_n$ and $\sum y_n$ that both diverge but where $\sum x_n y_n$ converges.

(b) A convergent series $\sum x_n$ and a bounded sequence (y_n) such that $\sum x_n y_n$ diverges.

(c) Two sequences (x_n) and (y_n) where $\sum x_n$ and $\sum(x_n + y_n)$ both converge but $\sum y_n$ diverges.

(d) A sequence (x_n) satisfying $0 \leq x_n \leq 1/n$ where $\sum(-1)^n x_n$ diverges.

Solution. (a) If we let (x_n) and (y_n) be the sequences given by $x_n = y_n = \frac{1}{n}$, then $\sum_{n=1}^{\infty} x_n = \sum_{n=1}^{\infty} y_n = \sum_{n=1}^{\infty} \frac{1}{n}$ is the divergent harmonic series (Example 2.4.5), but $\sum_{n=1}^{\infty} x_n y_n = \sum_{n=1}^{\infty} \frac{1}{n^2}$ is convergent (Example 2.4.4).

(b) Let (x_n) be the sequence given by $x_n = \frac{(-1)^{n+1}}{n}$ and (y_n) be the bounded sequence given by $y_n = (-1)^{n+1}$. It then follows from the Alternating Series Test (Theorem 2.7.7) that $\sum_{n=1}^{\infty} x_n$ is convergent, but $\sum_{n=1}^{\infty} x_n y_n = \sum_{n=1}^{\infty} \frac{1}{n}$ is the divergent harmonic series (Example 2.4.5).

(c) This is impossible; by Theorem 2.7.1 we must have

$$\sum_{n=1}^{\infty} y_n = \sum_{n=1}^{\infty} (x_n + y_n) - \sum_{n=1}^{\infty} x_n.$$

(d) Let (x_n) be the sequence given by

$$x_n = \begin{cases} \frac{1}{2(n+1)} & \text{if } n \text{ is odd,} \\ \frac{1}{n} & \text{if } n \text{ is even,} \end{cases} \qquad \text{i.e., } (x_n) = \left(\frac{1}{4}, \frac{1}{2}, \frac{1}{8}, \frac{1}{4}, \frac{1}{12}, \frac{1}{6}, \dots\right),$$

so that $0 \leq x_n \leq \frac{1}{n}$ for all $n \in \mathbf{N}$, and let (s_n) be the sequence of partial sums for the series $\sum_{n=1}^{\infty}(-1)^n x_n$. Observe that

$$\begin{aligned} s_{2n} &= \left(-\frac{1}{4} + \frac{1}{2}\right) + \left(-\frac{1}{8} + \frac{1}{4}\right) + \cdots + \left(-\frac{1}{4n} + \frac{1}{2n}\right) \\ &= \frac{1}{4} + \frac{1}{8} + \cdots + \frac{1}{4n} \\ &= \frac{1}{4} \sum_{k=1}^{n} \frac{1}{k}. \end{aligned}$$

It follows that (s_{2n}) is unbounded (Example 2.4.5) and hence that $\sum_{n=1}^{\infty}(-1)^n x_n$ is divergent.

Exercise 2.7.5. Now that we have proved the basic facts about geometric series, supply a proof for Corollary 2.4.7.

Solution. We want to show that the series $\sum_{n=1}^{\infty}\frac{1}{n^p}$ converges if and only if $p>1$. If $p\le 0$, then $\frac{1}{n^p}$ does not converge to zero; it follows that $\sum_{n=1}^{\infty}\frac{1}{n^p}$ diverges (Theorem 2.7.3). Suppose that $p>0$ and notice that the sequence $\frac{1}{n^p}$ is positive and decreasing. The Cauchy Condensation Test (Theorem 2.4.6) then implies that $\sum_{n=1}^{\infty}\frac{1}{n^p}$ is convergent if and only if the series

$$\sum_{n=0}^{\infty}\frac{2^n}{(2^n)^p}=\sum_{n=0}^{\infty}\left(2^{1-p}\right)^n$$

is convergent. This is a geometric series with common ratio 2^{1-p}, so by Example 2.7.5 this series is convergent if and only if

$$\left|2^{1-p}\right|<1 \iff 1-p<0 \iff p>1.$$

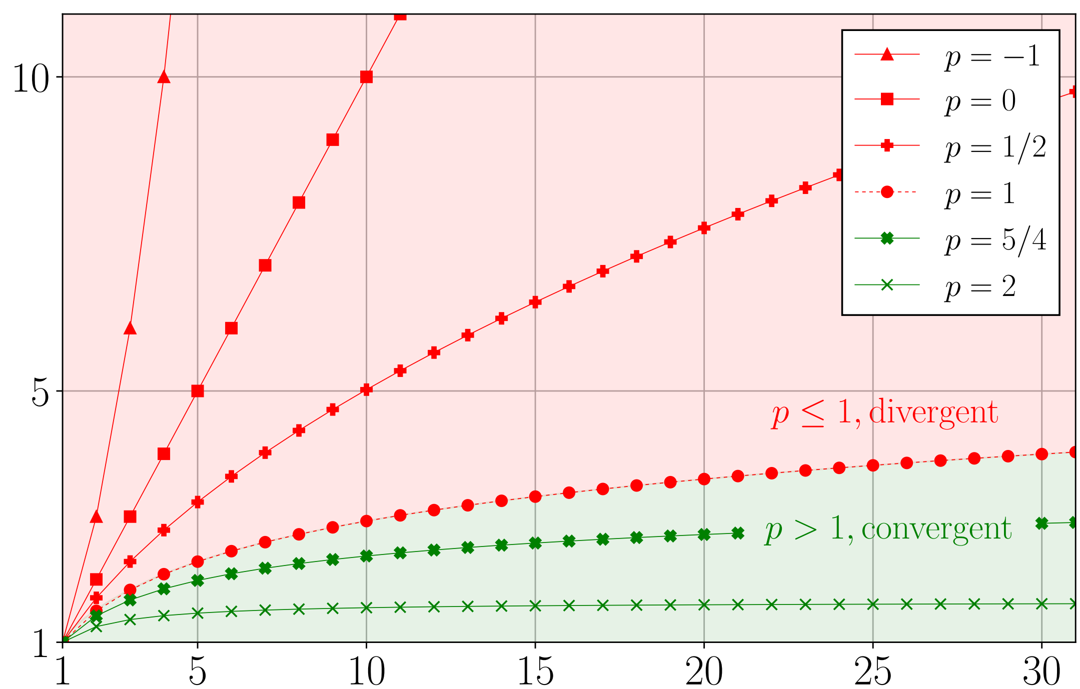


Figure F.21: $\sum_{n=1}^{\infty}\frac{1}{n^p}$ partial sums for various values of p

Exercise 2.7.6. Let's say that a series subverges if the sequence of partial sums contains a subsequence that converges. Consider this (invented) definition for a moment, and then decide which of the following statements are valid propositions about subvergent series:

(a) If (a_n) is bounded, then $\sum a_n$ subverges.

(b) All convergent series are subvergent.

(c) If $\sum |a_n|$ subverges, then $\sum a_n$ subverges as well.

(d) If $\sum a_n$ subverges, then (a_n) has a convergent subsequence.

Solution. (a) This is false in general. For the bounded sequence $(a_n) = (1, 1, 1, \ldots)$, the sequence of partial sums for the series $\sum_{n=1}^{\infty} a_n$ is $(1, 2, 3, \ldots)$. This sequence is unbounded and monotone and hence contains no convergent subsequence (Lemma L.8).

(b) This is true. If the sequence of partial sums (s_n) is convergent then any subsequence of (s_n) is convergent; (s_n) itself, for example.

(c) This is true; we will prove the contrapositive statement. Define the sequences of partial sums

$$s_n = |a_1| + \cdots + |a_n| \quad \text{and} \quad t_n = a_1 + \cdots + a_n.$$

We want to show that if (t_n) has no convergent subsequence, then neither does (s_n). By the Bolzano-Weierstrass Theorem (Theorem 2.5.5) it must be the case that (t_n) is unbounded and, since $t_n \leq s_n$ for all $n \in \mathbf{N}$, it follows that (s_n) is unbounded. Thus (s_n) is an increasing unbounded sequence; such sequences do not have convergent subsequences, as shown in Lemma L.8.

(d) This is false in general. Consider the sequence $(a_n) = (1, -1, 2, -2, 3, -3, \ldots)$. The sequence of partial sums is $(s_n) = (1, 0, 2, 0, 3, 0, \ldots)$, which has the convergent subsequence $(0, 0, 0, \ldots)$; it follows that $\sum_{n=1}^{\infty} a_n$ subverges. However, (a_n) has no convergent subsequence. To see this, observe that for any sequence (x_n) we have

$$(x_n) \text{ has a convergent subsequence} \implies (|x_n|) \text{ has a convergent subsequence},$$

since if $\lim_k x_{n_k} = x$ then $\lim_k |x_{n_k}| = |x|$ (Exercise 2.3.10 (b)). Because $(|a_n|) = (1, 1, 2, 2, 3, 3, \ldots)$ has no convergent subsequence (see Lemma L.8), it follows that (a_n) has no convergent subsequence.

Exercise 2.7.7. (a) Show that if $a_n > 0$ and $\lim(na_n) = l$ with $l \neq 0$, then the series $\sum a_n$ diverges.

(b) Assume $a_n > 0$ and $\lim(n^2 a_n)$ exists. Show that $\sum a_n$ converges.

Solution. The condition that $a_n > 0$ can be relaxed to $a_n \geq 0$ for both parts of this exercise.

(a) Because $na_n \geq 0$ for all $n \in \mathbf{N}$, the Order Limit Theorem (Theorem 2.3.4) and the assumption $l \neq 0$ imply that $l > 0$. Since $na_n \to l$, there exists an $N \in \mathbf{N}$ such that

$$n \geq N \implies 0 < \frac{l}{2} < na_n \implies 0 < \frac{l}{2n} < a_n.$$

Thus the series $\sum_{n=1}^{\infty} a_n$ diverges by comparison (Theorem 2.7.4) with the divergent series $\sum_{n=1}^{\infty} \frac{l}{2n}$ (Example 2.4.5).

(b) Suppose that $\lim(n^2 a_n) = L$; the Order Limit Theorem (Theorem 2.3.4) implies that $L \geq 0$. There is an $N \in \mathbf{N}$ such that

$$n \geq N \implies 0 \leq n^2 a_n < L + 1 \implies 0 \leq a_n < \frac{L+1}{n^2}.$$

Since the series $\sum_{n=1}^{\infty} \frac{L+1}{n^2}$ is convergent (Corollary 2.4.7), the Comparison Test (Theorem 2.7.4) implies that $\sum_{n=1}^{\infty} a_n$ is also convergent.

Exercise 2.7.8. Consider each of the following propositions. Provide short proofs for those that are true and counterexamples for any that are not.

(a) If $\sum a_n$ converges absolutely, then $\sum a_n^2$ also converges absolutely.

(b) If $\sum a_n$ converges and (b_n) converges, then $\sum a_n b_n$ converges.

(c) If $\sum a_n$ converges conditionally, then $\sum n^2 a_n$ diverges.

Solution. (a) This is true. Since the series $\sum_{n=1}^{\infty} |a_n|$ converges, we must have $\lim|a_n| = 0$ (Theorem 2.7.3). There is then an $N \in \mathbf{N}$ such that $0 \leq |a_n| \leq 1$ for $n \geq N$; it follows that $0 \leq |a_n|^2 = a_n^2 \leq |a_n|$ for $n \geq N$. We may now apply the Comparison Test (Theorem 2.7.4) to conclude that $\sum_{n=1}^{\infty} a_n^2$ converges absolutely.

(b) This is false. Let $a_n = b_n = \frac{(-1)^n}{\sqrt{n}}$, so that $\lim b_n = 0$. Notice that $\sum_{n=1}^{\infty} a_n$ converges by the Alternating Series Test (Theorem 2.7.7), but $\sum_{n=1}^{\infty} a_n b_n = \sum_{n=1}^{\infty} \frac{1}{n}$, which is divergent (Example 2.4.5).

(c) This is true; we will prove that

$$\sum_{n=1}^{\infty}|a_n| \text{ diverges } \implies \sum_{n=1}^{\infty} n^2 a_n \text{ diverges,}$$

by proving the contrapositive statement

$$\sum_{n=1}^{\infty} n^2 a_n \text{ converges } \implies \sum_{n=1}^{\infty}|a_n| \text{ converges.}$$

By Theorem 2.7.3 we have $\lim(n^2 a_n) = 0$, which implies that $\lim(n^2|a_n|) = 0$. We may now apply Exercise 2.7.7 (b) to conclude that $\sum_{n=1}^{\infty}|a_n|$ is convergent.

Exercise 2.7.9 (Ratio Test). Given a series $\sum_{n=1}^{\infty} a_n$ with $a_n \neq 0$, the Ratio Test states that if (a_n) satisfies

$$\lim\left|\frac{a_{n+1}}{a_n}\right| = r < 1,$$

then the series converges absolutely.

(a) Let r' satisfy $r < r' < 1$. Explain why there exists an N such that $n \geq N$ implies $|a_{n+1}| \leq |a_n|r'$.

(b) Why does $|a_N|\sum(r')^n$ converge?

(c) Now, show that $\sum|a_n|$ converges, and conclude that $\sum a_n$ converges.

Solution. (a) Since $\lim\left|\frac{a_{n+1}}{a_n}\right| = r$ and $r' - r > 0$, there is an $N \in \mathbf{N}$ such that

$$n \geq N \implies \left|\left|\frac{a_{n+1}}{a_n}\right| - r\right| < r' - r \implies \frac{|a_{n+1}|}{|a_n|} < r' \implies |a_{n+1}| < |a_n|r'.$$

(b) Since $0 < r' < 1$, the geometric series $\sum_{n=0}^{\infty}(r')^n$ converges (Example 2.7.5).

(c) By part (a) we have

$$|a_{N+n}| < |a_{N+n-1}|r' < |a_{N+n-2}|(r')^2 < \cdots < |a_N|(r')^n$$

for any $n \in \mathbf{N}$. It then follows from part (b) and the Comparison Test (Theorem 2.7.4) that the series

$$\sum_{n=0}^{\infty}|a_{N+n}| = \sum_{n=N}^{\infty}|a_n|$$

is convergent. Since a finite number of terms do not affect convergence, we see that the series $\sum_{n=1}^{\infty}|a_n|$ is convergent; the convergence of $\sum_{n=1}^{\infty} a_n$ is then given by Theorem 2.7.6.

Exercise 2.7.10 (Infinite Products). Review Exercise 2.4.10 about infinite products and then answer the following questions:

(a) Does $\frac{2}{1} \cdot \frac{3}{2} \cdot \frac{5}{4} \cdot \frac{9}{8} \cdot \frac{17}{16} \cdots$ converge?

(b) The infinite product $\frac{1}{2} \cdot \frac{3}{4} \cdot \frac{5}{6} \cdot \frac{7}{8} \cdot \frac{9}{10} \cdots$ certainly converges. (Why?) Does it converge to zero?

(c) In 1655, John Wallis famously derived the formula

$$\left(\frac{2 \cdot 2}{1 \cdot 3}\right)\left(\frac{4 \cdot 4}{3 \cdot 5}\right)\left(\frac{6 \cdot 6}{5 \cdot 7}\right)\left(\frac{8 \cdot 8}{7 \cdot 9}\right) \cdots = \frac{\pi}{2}.$$

Show that the left side of this identity at least converges to something. (A complete proof of this result is taken up in Section 8.3.)

Solution. (a) This is the infinite product

$$\prod_{n=0}^{\infty} \frac{2^n + 1}{2^n} = \prod_{n=0}^{\infty}\left(1 + \frac{1}{2^n}\right).$$

By Exercise 2.4.10, this infinite product converges if and only if the series $\sum_{n=0}^{\infty} \frac{1}{2^n}$ converges. This series is geometric with common ratio $r = \frac{1}{2}$ and hence convergent by Example 2.7.5; it follows that the infinite product converges.

(b) This is the infinite product

$$\prod_{n=1}^{\infty} \frac{2n - 1}{2n} = \prod_{n=1}^{\infty}\left(1 - \frac{1}{2n}\right).$$

The sequence of partial products is positive and decreasing, since each term in the partial product satisfies $0 < 1 - \frac{1}{2n} < 1$; the Monotone Convergence Theorem (Theorem 2.4.2) then implies that the infinite product converges.

Indeed, this infinite product converges to zero. To see this, let (p_m) be the sequence of partial products:

$$p_m = \frac{1}{2} \cdot \frac{3}{4} \cdots \frac{2m - 1}{2m}.$$

As stated above, (p_m) is decreasing and satisfies $0 < p_m < 1$ for all $m \in \mathbf{N}$, so we can look at the sequence of reciprocals (p_m^{-1}):

$$\begin{aligned}\frac{1}{p_m} &= \frac{2}{1}\cdot\frac{4}{3}\cdots\frac{2m}{2m-1}\\ &= \left(1+\frac{1}{1}\right)\left(1+\frac{1}{3}\right)\cdots\left(1+\frac{1}{2m-1}\right)\\ &\geq \sum_{n=1}^{m}\frac{1}{2n-1}\\ &\geq \frac{1}{2}\sum_{n=1}^{m}\frac{1}{n}.\end{aligned}$$

It follows from Example 2.4.5 that (p_m^{-1}) is unbounded above. Thus, for any $\epsilon > 0$, there is an $M \in \mathbf{N}$ such that $p_M^{-1} > \epsilon^{-1}$, and since (p_m) is decreasing we then have

$$m \geq M \implies |p_m| = p_m \leq p_M < \epsilon.$$

Hence $\lim p_m = 0$.

(c) This is the infinite product

$$\prod_{n=1}^{\infty}\frac{(2n)^2}{(2n-1)(2n+1)} = \prod_{n=1}^{\infty}\left(1+\frac{1}{(2n-1)(2n+1)}\right) = \prod_{n=1}^{\infty}\left(1+\frac{1}{4n^2-1}\right).$$

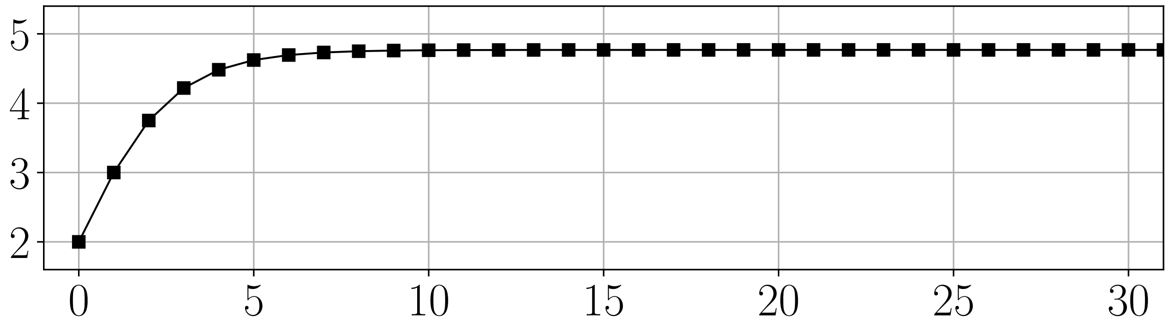
By Exercise 2.4.10, this infinite product converges if and only if the series $\sum_{n=0}^{\infty}\frac{1}{4n^2-1}$ converges. Observe that for all $n \in \mathbf{N}$ we have

$$n^2 - 1 \geq 0 \implies 4n^2 - 1 \geq 3n^2 \implies \frac{1}{4n^2-1} \leq \frac{1}{3n^2}.$$

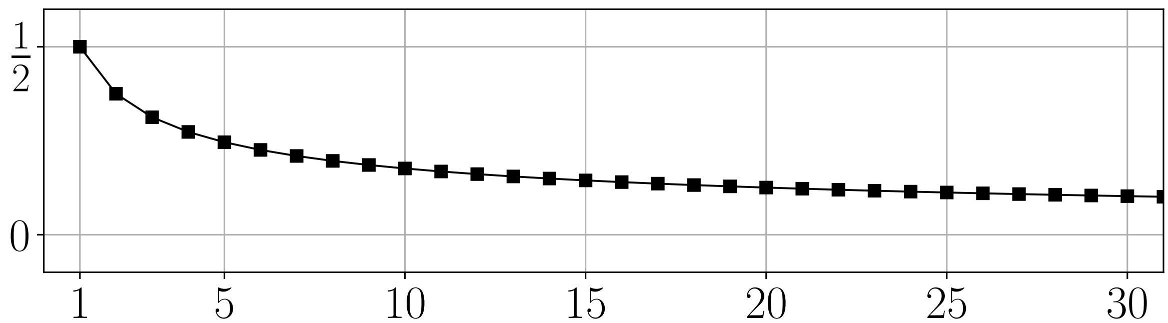
The series $\sum_{n=1}^{\infty}\frac{1}{3n^2}$ is convergent (Corollary 2.4.7), so the Comparison Test (Theorem 2.7.4) implies that the series $\sum_{n=0}^{\infty}\frac{1}{4n^2-1}$ is also convergent; it follows that the infinite product

$$\left(\frac{2\cdot 2}{1\cdot 3}\right)\left(\frac{4\cdot 4}{3\cdot 5}\right)\left(\frac{6\cdot 6}{5\cdot 7}\right)\left(\frac{8\cdot 8}{7\cdot 9}\right)\cdots$$

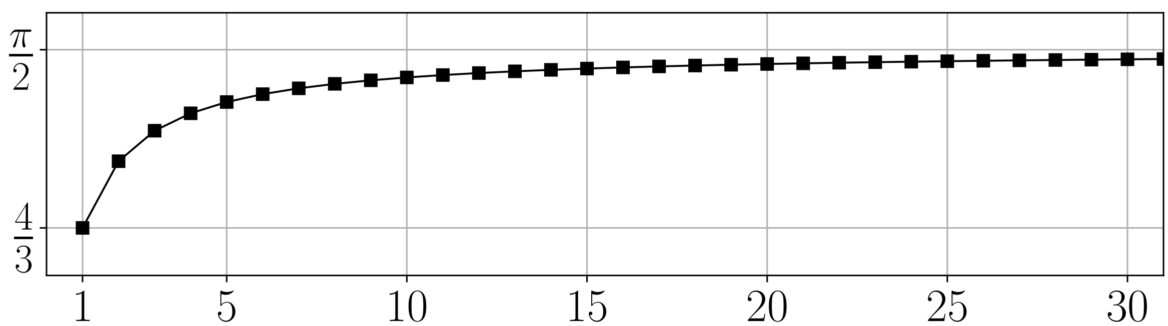
converges.



(a) $\prod_{n=0}^{m}\left(1+\frac{1}{2^n}\right)$ for $0 \le m \le 30$



(b) $\prod_{n=1}^{m}\left(1-\frac{1}{2n}\right)$ for $1 \le m \le 30$



(c) $\prod_{n=1}^{m}\left(1+\frac{1}{4n^2-1}\right)$ for $1 \le m \le 30$

Figure F.22: Exercise 2.7.10 partial products

Exercise 2.7.11. Find examples of two series $\sum a_n$ and $\sum b_n$ both of which diverge but for which $\sum \min\{a_n, b_n\}$ converges. To make it more challenging, produce examples where (a_n) and (b_n) are strictly positive and decreasing.

Solution. Consider the series

$$\sum_{n=1}^{\infty} a_n = \underbrace{\frac{1}{1^2}}_{\substack{\text{1 term} \\ \text{sum} = 1}} + \frac{1}{2^2} + \cdots + \frac{1}{5^2} + \underbrace{\frac{1}{6^2} + \cdots + \frac{1}{6^2}}_{\substack{6^2 \text{ terms} \\ \text{sum} = 1}} + \frac{1}{42^2} + \cdots + \frac{1}{1805^2} + \cdots$$

$$\sum_{n=1}^{\infty} b_n = \frac{1}{1^2} + \underbrace{\frac{1}{2^2} + \cdots + \frac{1}{2^2}}_{\substack{2^2 \text{ terms} \\ \text{sum} = 1}} + \frac{1}{6^2} + \cdots + \frac{1}{41^2} + \underbrace{\frac{1}{42^2} + \cdots + \frac{1}{42^2}}_{\substack{42^2 \text{ terms} \\ \text{sum} = 1}} + \cdots$$

Both (a_n) and (b_n) are strictly positive and decreasing and

$$\sum_{n=1}^{\infty} \min\{a_n, b_n\} = \sum_{n=1}^{\infty} \frac{1}{n^2},$$

which is a convergent series. Furthermore, both $\sum a_n$ and $\sum b_n$ diverge since their respective sequences of partial sums are unbounded; we can find arbitrarily many groupings of terms which sum to 1 as shown above.

Exercise 2.7.12 (Summation by parts). Let (x_n) and (y_n) be sequences, let $s_n = x_1 + x_2 + \cdots + x_n$ and set $s_0 = 0$. Use the observation that $x_j = s_j - s_{j-1}$ to verify the formula

$$\sum_{j=m}^{n} x_j y_j = s_n y_{n+1} - s_{m-1} y_m + \sum_{j=m}^{n} s_j (y_j - y_{j+1}).$$

Solution. For positive integers $n > m$,

$$\begin{aligned}
\sum_{j=m}^{n} x_j y_j &= \sum_{j=m}^{n} (s_j - s_{j-1}) y_j \\
&= \sum_{j=m}^{n} s_j y_j - \sum_{j=m}^{n} s_{j-1} y_j \\
&= \sum_{j=m}^{n} s_j y_j - \sum_{j=m-1}^{n-1} s_j y_{j+1}
\end{aligned}$$

$$= \sum_{j=m}^{n} s_j y_j - \sum_{j=m}^{n} s_j y_{j+1} + s_n y_{n+1} - s_{m-1} y_m$$
$$= s_n y_{n+1} - s_{m-1} y_m + \sum_{j=m}^{n} s_j (y_j - y_{j+1}).$$

Exercise 2.7.13 (Abel's Test). Abel's Test for convergence states that if the series $\sum_{k=1}^{\infty} x_k$ converges, and if (y_k) is a sequence satisfying

$$y_1 \geq y_2 \geq y_3 \geq \cdots \geq 0,$$

then the series $\sum_{k=1}^{\infty} x_k y_k$ converges.

(a) Use Exercise 2.7.12 to show that

$$\sum_{k=1}^{n} x_k y_k = s_n y_{n+1} + \sum_{k=1}^{n} s_k (y_k - y_{k+1}),$$

where $s_n = x_1 + x_2 + \cdots + x_n$.

(b) Use the Comparison Test to argue that $\sum_{k=1}^{\infty} s_k (y_k - y_{k+1})$ converges absolutely, and show how this leads directly to a proof of Abel's Test.

Solution. (a) This follows immediately from Exercise 2.7.12, taking $m = 1$ and remembering that $s_0 := 0$.

(b) By assumption the sequence (s_k) is convergent and hence, by Theorem 2.3.2, bounded by some $M > 0$, so that for each $k \in \mathbf{N}$ we have the inequality

$$0 \leq |s_k (y_k - y_{k+1})| = |s_k| (y_k - y_{k+1}) \leq M (y_k - y_{k+1}). \tag{1}$$

Notice that since (y_k) is decreasing and bounded below, the limit $y := \lim_{k\to\infty} y_k$ exists by the Monotone Convergence Theorem (Theorem 2.4.2). It follows that the series $\sum_{k=1}^{\infty}(y_k - y_{k+1})$ is convergent since, letting t_m be the m^{th} partial sum, we have

$$t_m = (y_1 - y_2) + (y_2 - y_3) + \cdots + (y_m - y_{m+1}) = y_1 - y_{m+1} \to y_1 - y \text{ as } m \to \infty.$$

Inequality (1) and the Comparison Test (Theorem 2.7.4) then imply that $\sum_{k=1}^{\infty} s_k (y_k - y_{k+1})$ is absolutely convergent and hence convergent (Theorem 2.7.6). From part (a) we have $\sum_{k=1}^{n} x_k y_k = s_n y_{n+1} + \sum_{k=1}^{n} s_k (y_k - y_{k+1})$; it follows that

$$\sum_{k=1}^{\infty} x_k y_k = \lim_{n\to\infty} \left(s_n y_{n+1} + \sum_{k=1}^{n} s_k (y_k - y_{k+1}) \right) = y \sum_{k=1}^{\infty} x_k + \sum_{k=1}^{\infty} s_k (y_k - y_{k+1}).$$

Exercise 2.7.14 (Dirichlet's Test). Dirichlet's Test for convergence states that if the partial sums of $\sum_{k=1}^{\infty} x_k$ are bounded (but not necessarily convergent), and if (y_k) is a sequence satisfying $y_1 \geq y_2 \geq y_3 \geq \cdots \geq 0$ with $\lim y_k = 0$, then the series $\sum_{k=1}^{\infty} x_k y_k$ converges.

(a) Point out how the hypothesis of Dirichlet's Test differs from that of Abel's Test in Exercise 2.7.13, but show that essentially the same strategy can be used to provide a proof.

(b) Show how the Alternating Series Test (Theorem 2.7.7) can be derived as a special case of Dirichlet's Test.

Solution. (a) Abel's Test has the stronger hypothesis that the sequence of partial sums of $\sum_{k=1}^{\infty} x_k$ is convergent (and hence bounded), but the weaker hypothesis that (y_k) only satisfies $y_1 \geq y_2 \geq y_3 \geq \cdots \geq 0$ without necessarily converging to zero.

The proof of Dirichlet's Test is almost identical to the proof of Abel's Test given in Exercise 2.7.13 (b). Letting (s_k) be the k^{th} partial sum of $\sum_{n=1}^{\infty} x_n$, we are given that (s_k) is bounded by some $M > 0$. It follows that

$$0 \leq |s_k(y_k - y_{k+1})| = |s_k|(y_k - y_{k+1}) \leq M(y_k - y_{k+1}) \tag{1}$$

for each $k \in \mathbf{N}$. The series $\sum_{k=1}^{\infty}(y_k - y_{k+1})$ is convergent since it has m^{th} partial sum

$$(y_1 - y_2) + (y_2 - y_3) + \cdots + (y_m - y_{m+1}) = y_1 - y_{m+1} \to y_1 \text{ as } m \to \infty.$$

Inequality (1) and the Comparison Test (Theorem 2.7.4) then imply that $\sum_{k=1}^{\infty} s_k(y_k - y_{k+1})$ is absolutely convergent and hence convergent. Since (s_k) is bounded and $\lim y_k = 0$, we have $\lim(s_k y_{k+1}) = 0$ also (Exercise 2.3.9 (b)). It follows that

$$\sum_{k=1}^{\infty} x_k y_k = \lim_{n\to\infty}\left(s_n y_{n+1} + \sum_{k=1}^{n} s_k(y_k - y_{k+1})\right) = \sum_{k=1}^{\infty} s_k(y_k - y_{k+1}).$$

(b) The Alternating Series Test (Theorem 2.7.7) can be recovered from Dirichlet's Test by taking $x_k = (-1)^{k+1}$; the sequence of partial sums of $\sum_{k=1}^{\infty} x_k$ is then $(1, 0, 1, 0, \ldots)$, which is certainly bounded.

2.8 Double Summations and Products of Infinite Series

Exercise 2.8.1. Using the particular array (a_{ij}) from Section 2.1, compute $\lim_{n\to\infty} s_{nn}$. How does this value compare to the two iterated values for the sum already computed?

Solution. The array in question is

$$\begin{bmatrix} -1 & \frac{1}{2} & \frac{1}{4} & \frac{1}{8} & \frac{1}{16} & \cdots \\ 0 & -1 & \frac{1}{2} & \frac{1}{4} & \frac{1}{8} & \cdots \\ 0 & 0 & -1 & \frac{1}{2} & \frac{1}{4} & \cdots \\ 0 & 0 & 0 & -1 & \frac{1}{2} & \cdots \\ 0 & 0 & 0 & 0 & -1 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix},$$

where $a_{ij} = 2^{i-j}$ if $j > i, a_{ij} = -1$ if $j = i$, and $a_{ij} = 0$ if $j < i$. If we let $f(j)$ be the sum of the first row up to the j^{th} column, then using the formula for the partial sums of a geometric series, we find that

$$\begin{aligned} f(j) &= \begin{cases} -1 & \text{if } j = 1, \\ -1 + \frac{1}{2} + \cdots + \frac{1}{2^{j-1}} = -\frac{1}{2^{j-1}} & \text{if } j \geq 2 \end{cases} \\ &= -\frac{1}{2^{j-1}}. \end{aligned}$$

Since subsequent rows are simply the first row shifted along, it is clear that $s_{11} = f(1), s_{22} = f(1) + f(2), s_{33} = f(1) + f(2) + f(3)$, and in general

$$s_{nn} = \sum_{j=1}^{n} f(j) = \sum_{j=1}^{n} \frac{-1}{2^{j-1}} = -\sum_{j=0}^{n-1} \frac{1}{2^j}.$$

It follows that

$$\lim_{n\to\infty} s_{nn} = -\sum_{j=0}^{\infty} \frac{1}{2^j} = -2.$$

At the beginning of Section 2.1, we found that summing along the rows first gave a value of 0 for the double sum, whereas summing down the columns first gave a value of -2.

Exercise 2.8.2. Show that if the iterated series

$$\sum_{i=1}^{\infty} \sum_{j=1}^{\infty} |a_{ij}|$$

converges (meaning for each fixed $i \in \mathbf{N}$ the series $\sum_{j=1}^{\infty} |a_{ij}|$ converges to some real number b_i, and the series $\sum_{i=1}^{\infty} b_i$ converges as well), then the iterated series

$$\sum_{i=1}^{\infty} \sum_{j=1}^{\infty} a_{ij}$$

converges.

Solution. For each $i \in \mathbf{N}$, Theorem 2.7.6 implies that the series $\sum_{j=1}^{\infty} a_{ij}$ converges to some real number c_i. Observe that

$$0 \leq |c_i| = \left| \sum_{j=1}^{\infty} a_{ij} \right| \leq \sum_{j=1}^{\infty} |a_{ij}| = b_i.$$

Since $\sum_{i=1}^{\infty} b_i$ converges, the Comparison Test (Theorem 2.7.4) implies that the series $\sum_{i=1}^{\infty} c_i$ is absolutely convergent and hence convergent (Theorem 2.7.6).

Exercise 2.8.3. (a) Prove that (t_{nn}) converges.

(b) Now, use the fact that (t_{nn}) is a Cauchy sequence to argue that (s_{nn}) converges.

Solution. (a) Since $|a_{ij}| \geq 0$ for all positive integers i and j, the sequence (t_{nn}) is increasing and bounded above by the real number $\sum_{i=1}^{\infty} \sum_{j=1}^{\infty} |a_{ij}|$. Thus (t_{nn}) converges by the Monotone Convergence Theorem (Theorem 2.4.2).

(b) Suppose $n > m$ are positive integers. By examining the array

$$\begin{array}{ccc|ccc}
a_{11} & \cdots & a_{1m} & a_{1,m+1} & \cdots & a_{1n} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
a_{m1} & \cdots & a_{mm} & a_{m,m+1} & \cdots & a_{mn} \\
\hline
a_{m+1,1} & \cdots & a_{m+1,m} & a_{m+1,m+1} & \cdots & a_{m+1,n} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
a_{n1} & \cdots & a_{nm} & a_{n,m+1} & \cdots & a_{nn}
\end{array}$$

we see that

$$\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} - \sum_{i=1}^{m} \sum_{j=1}^{m} a_{ij} = \sum_{i=1}^{m} \sum_{j=m+1}^{n} a_{ij} + \sum_{i=m+1}^{n} \sum_{j=1}^{n} a_{ij}.$$

(The sum of the top right "square" (in red) and the bottom "rectangle" (in blue) of the array.) Let $\epsilon > 0$ be given. Since (t_{nn}) is a Cauchy sequence, there exists an $N \in \mathbf{N}$ such that $n > m \geq N$ implies

$$|t_{nn} - t_{mm}| = t_{nn} - t_{mm} < \epsilon.$$

For such n and m, observe that

$$\begin{aligned} |s_{nn} - s_{mm}| &= \left|\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij} - \sum_{i=1}^{m}\sum_{j=1}^{m} a_{ij}\right| \\ &= \left|\sum_{i=1}^{m}\sum_{j=m+1}^{n} a_{ij} + \sum_{i=m+1}^{n}\sum_{j=1}^{n} a_{ij}\right| \\ &\leq \sum_{i=1}^{m}\sum_{j=m+1}^{n} |a_{ij}| + \sum_{i=m+1}^{n}\sum_{j=1}^{n} |a_{ij}| \\ &= t_{nn} - t_{mm} \\ &< \epsilon. \end{aligned}$$

It follows that (s_{nn}) is a Cauchy sequence and hence convergent.

Exercise 2.8.4. (a) Let $\epsilon > 0$ be arbitrary and argue that there exists an $N_1 \in \mathbf{N}$ such that $m, n \geq N_1$ implies $B - \frac{\epsilon}{2} < t_{mn} \leq B$.

(b) Now, show that there exists an N such that

$$|s_{mn} - S| < \epsilon$$

for all $m, n \geq N$.

Solution. (a) By Lemma 1.3.8, there exist positive integers m', n' such that $B - \frac{\epsilon}{2} < t_{m'n'} \leq B$. Set $N_1 = \max\{m', n'\}$. Since each $|a_{ij}|$ is positive, (t_{mn}) is increasing in both m and n; it follows that for $m, n \geq N_1$ we have $B - \frac{\epsilon}{2} < t_{mn} \leq B$.

(b) Since $\lim_{n\to\infty} s_{nn} = S$, there is an $N_2 \in \mathbf{N}$ such that $|s_{nn} - S| < \frac{\epsilon}{2}$ for all $n \geq N_2$. Set $N = \max\{N_1, N_2\}$ and suppose that $m, n > N$. Similarly to Exercise 2.8.3 (b), we have

$$|s_{mn} - s_{NN}| = \left|\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij} - \sum_{i=1}^{N}\sum_{j=1}^{N} a_{ij}\right|$$

$$
\begin{aligned}
&= \left| \sum_{i=1}^{N} \sum_{j=N+1}^{n} a_{ij} + \sum_{i=N+1}^{m} \sum_{j=1}^{n} a_{ij} \right| \\
&\leq \sum_{i=1}^{N} \sum_{j=N+1}^{n} |a_{ij}| + \sum_{i=N+1}^{m} \sum_{j=1}^{n} |a_{ij}| \\
&= t_{mn} - t_{NN} \\
&\leq B - t_{NN} \\
&< \frac{\epsilon}{2}.
\end{aligned}
$$

It follows that

$$|s_{mn} - S| \leq |s_{mn} - s_{NN}| + |s_{NN} - S| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon.$$

Exercise 2.8.5. (a) Show that for all $m \geq N$

$$|(r_1 + r_2 + \cdots + r_m) - S| \leq \epsilon.$$

Conclude that the iterated sum $\sum_{i=1}^{\infty} \sum_{j=1}^{\infty} a_{ij}$ converges to S.

(b) Finish the proof by showing that the other iterated sum, $\sum_{j=1}^{\infty} \sum_{i=1}^{\infty} a_{ij}$, converges to S as well. Notice that the same argument can be used once it is established that, for each fixed column j, the sum $\sum_{i=1}^{\infty} a_{ij}$ converges to some real number c_j.

Solution. (a) Suppose that $n \geq N$. Then

$$
\begin{aligned}
|(r_1 + \cdots + r_m) - S| &\leq |(r_1 + \cdots + r_m) - s_{mn}| + |s_{mn} - S| \\
&< \left| (r_1 + \cdots + r_m) - \left(\sum_{j=1}^{n} a_{1j} + \cdots + \sum_{j=1}^{n} a_{mj} \right) \right| + \epsilon \\
&\leq \left| r_1 - \sum_{j=1}^{n} a_{1j} \right| + \cdots + \left| r_m - \sum_{j=1}^{n} a_{mj} \right| + \epsilon.
\end{aligned}
$$

Since this is true for any $n \geq N$ and for any given i we have $\sum_{j=1}^{\infty} a_{ij} = r_i$, taking the limit in n on both sides of the inequality

$$|(r_1 + r_2 + \cdots + r_m) - S| < \left| r_1 - \sum_{j=1}^{n} a_{1j} \right| + \left| r_2 - \sum_{j=1}^{n} a_{2j} \right| + \cdots + \left| r_m - \sum_{j=1}^{n} a_{mj} \right| + \epsilon$$

gives us

$$|(r_1 + r_2 + \cdots + r_m) - S| \le \epsilon.$$

It follows that $\lim_{m\to\infty}(\sum_{i=1}^{m} r_i) = S$, i.e., $\sum_{i=1}^{\infty}\sum_{j=1}^{\infty} a_{ij} = S$.

(b) Fix $j \in \mathbf{N}$ and let (x_n) be the sequence of partial sums of the series $\sum_{i=1}^{\infty}|a_{ij}|$, i.e.,

$$x_n = |a_{1j}| + |a_{2j}| + \cdots + |a_{nj}|.$$

Since each $|a_{ij}|$ is a term of the convergent series $\sum_{j=1}^{\infty}|a_{ij}| = r_i$, which has only non-negative terms, we see that $|a_{ij}| \le r_i$, so that

$$x_n \le r_1 + r_2 + \cdots + r_n \le \sum_{i=1}^{\infty} r_i,$$

where the last inequality follows since each r_i is non-negative. So (x_n) is an increasing and bounded sequence and hence converges by the Monotone Convergence Theorem (Theorem 2.4.2). It follows that $\sum_{i=1}^{\infty} a_{ij}$ converges to some (non-negative) real number c_j.

Let $\epsilon > 0$ be given. As in Exercise 2.8.4, there is an $N \in \mathbf{N}$ such that $|s_{mn} - S| < \epsilon$ for all $m, n \ge N$. We can write s_{mn} as

$$s_{mn} = \sum_{i=1}^{m} a_{i1} + \sum_{i=1}^{m} a_{i2} + \cdots + \sum_{i=1}^{m} a_{in}.$$

Suppose that $m, n \ge N$. Then

$$\begin{aligned}
|(c_1 + \cdots + c_n) - S| &\le |(c_1 + \cdots + c_n) - s_{mn}| + |s_{mn} - S| \\
&< \left|(c_1 + \cdots + c_n) - \left(\sum_{i=1}^{m} a_{i1} + \cdots + \sum_{i=1}^{m} a_{in}\right)\right| + \epsilon \\
&\le \left|c_1 - \sum_{i=1}^{m} a_{i1}\right| + \cdots + \left|c_n - \sum_{i=1}^{m} a_{in}\right| + \epsilon.
\end{aligned}$$

Since this is true for any $m \ge N$ and for any given j we have $\sum_{i=1}^{\infty} a_{ij} = c_j$, taking the limit in m on both sides of the inequality

$$|(c_1 + c_2 + \cdots + c_n) - S| < \left|c_1 - \sum_{i=1}^{m} a_{i1}\right| + \left|c_2 - \sum_{i=1}^{m} a_{i2}\right| + \cdots + \left|c_n - \sum_{i=1}^{m} a_{in}\right| + \epsilon$$

gives us

$$|(c_1 + c_2 + \cdots + c_n) - S| \le \epsilon.$$

It follows that $\lim_{n\to\infty} \left(\sum_{j=1}^{n} c_j\right) = S$, i.e., $\sum_{j=1}^{\infty} \sum_{i=1}^{\infty} a_{ij} = S$.

Exercise 2.8.6. (a) Assuming the hypothesis—and hence the conclusion—of Theorem 2.8.1, show that $\sum_{k=2}^{\infty} d_k$ converges absolutely.

(b) Imitate the strategy in the proof of Theorem 2.8.1 to show that $\sum_{k=2}^{\infty} d_k$ converges to $S = \lim_{n\to\infty} s_{nn}$.

Solution. (a) Observe that

$$|d_2| = |a_{11}| = \sum_{i=1}^{1} \sum_{j=1}^{2-i} |a_{ij}|,$$

$$|d_2| + |d_3| = |a_{11}| + |a_{12} + a_{21}| \le (|a_{11}| + |a_{12}|) + |a_{21}| = \sum_{i=1}^{2} \sum_{j=1}^{3-i} |a_{ij}|,$$

$$\begin{aligned} |d_2| + |d_3| + |d_4| &= |a_{11}| + |a_{12} + a_{21}| + |a_{13} + a_{22} + a_{31}| \\ &\le (|a_{11}| + |a_{12}| + |a_{13}|) + (|a_{21}| + |a_{22}|) + |a_{31}| = \sum_{i=1}^{3} \sum_{j=1}^{4-i} |a_{ij}|, \end{aligned}$$

and in general for $n \ge 2$,

$$\sum_{k=2}^{n} |d_k| \le \sum_{i=1}^{n-1} \sum_{j=1}^{n-i} |a_{ij}| \le \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} |a_{ij}|,$$

where the last inequality follows since each $|a_{ij}|$ is non-negative. By assumption $\sum_{i=1}^{\infty} \sum_{j=1}^{\infty} |a_{ij}|$ is finite, so the sequence $\sum_{k=2}^{n} |d_k|$ is increasing and bounded above and hence converges by the Monotone Convergence Theorem (Theorem 2.4.2).

(b) By considering Figure F.23, which shows the special case $n = 6$, we see that for each $n \ge 2$,

$$s_{nn} - \sum_{k=2}^{n} d_k = \sum_{i=1}^{n} \sum_{j=n+1-i}^{n} a_{ij}.$$

a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}
a_{21}	a_{22}	a_{23}	a_{24}	a_{25}	a_{26}
a_{31}	a_{32}	a_{33}	a_{34}	a_{35}	a_{36}
a_{41}	a_{42}	a_{43}	a_{44}	a_{45}	a_{46}
a_{51}	a_{52}	a_{53}	a_{54}	a_{55}	a_{56}
a_{61}	a_{62}	a_{63}	a_{64}	a_{65}	a_{66}

Figure F.23: $s_{66} - \sum_{k=2}^{6} d_k = \sum_{i=1}^{6} \sum_{j=7-i}^{6} a_{ij}$

Similarly, letting

$$e_k = |a_{1,k-1}| + |a_{2,k-2}| + \cdots + |a_{k-1,1}|$$

for $k \geq 2$, we find that

$$t_{nn} - \sum_{k=2}^{n} e_k = \sum_{i=1}^{n} \sum_{j=n+1-i}^{n} |a_{ij}|$$

for each $n \geq 2$. It follows that

$$\left| s_{nn} - \sum_{k=2}^{n} d_k \right| = \left| \sum_{i=1}^{n} \sum_{j=n+1-i}^{n} a_{ij} \right| \leq \sum_{i=1}^{n} \sum_{j=n+1-i}^{n} |a_{ij}| = t_{nn} - \sum_{k=2}^{n} e_k. \tag{1}$$

Let $\epsilon > 0$ be given. Since $\lim_{n\to\infty} s_{nn} = S$ and (t_{nn}) is an increasing Cauchy sequence, there are positive integers N_1, N_2 such that

$$n \geq N_1 \implies |s_{nn} - S| < \frac{\epsilon}{2} \quad \text{and} \quad n > m \geq N_2 \implies t_{nn} - t_{mm} < \frac{\epsilon}{2}. \tag{2}$$

Set $N = \max\{N_1, 2N_2\}$ and suppose $n \geq N$. Since $n \geq 2N_2$, each term of $t_{N_2N_2}$ appears in $\sum_{k=2}^{n} e_k$ (see Figure F.24, which has the special case $n = 6$ and $N_2 = 3$).

$\lvert a_{11}\rvert$	$\lvert a_{12}\rvert$	$\lvert a_{13}\rvert$	$\lvert a_{14}\rvert$	$\lvert a_{15}\rvert$	$\lvert a_{16}\rvert$
$\lvert a_{21}\rvert$	$\lvert a_{22}\rvert$	$\lvert a_{23}\rvert$	$\lvert a_{24}\rvert$	$\lvert a_{25}\rvert$	$\lvert a_{26}\rvert$
$\lvert a_{31}\rvert$	$\lvert a_{32}\rvert$	$\lvert a_{33}\rvert$	$\lvert a_{34}\rvert$	$\lvert a_{35}\rvert$	$\lvert a_{36}\rvert$
$\lvert a_{41}\rvert$	$\lvert a_{42}\rvert$	$\lvert a_{43}\rvert$	$\lvert a_{44}\rvert$	$\lvert a_{45}\rvert$	$\lvert a_{46}\rvert$
$\lvert a_{51}\rvert$	$\lvert a_{52}\rvert$	$\lvert a_{53}\rvert$	$\lvert a_{54}\rvert$	$\lvert a_{55}\rvert$	$\lvert a_{56}\rvert$
$\lvert a_{61}\rvert$	$\lvert a_{62}\rvert$	$\lvert a_{63}\rvert$	$\lvert a_{64}\rvert$	$\lvert a_{65}\rvert$	$\lvert a_{66}\rvert$

Figure F.24: $t_{33} \leq \sum_{k=2}^{6} e_k$

It follows that $t_{N_2N_2} \leq \sum_{k=2}^{n} e_k$ and thus by (1) and (2) we have

$$\left| s_{nn} - \sum_{k=2}^{n} d_k \right| \leq t_{nn} - t_{N_2N_2} < \frac{\epsilon}{2},$$

which implies

$$\left| \sum_{k=2}^{n} d_k - S \right| \leq |s_{nn} - S| + \left| s_{nn} - \sum_{k=2}^{n} d_k \right| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon.$$

We may conclude that $\lim_{n\to\infty} \sum_{k=2}^{n} d_k = S$.

Exercise 2.8.7. Assume that $\sum_{i=1}^{\infty} a_i$ converges absolutely to A, and $\sum_{j=1}^{\infty} b_j$ converges absolutely to B.

(a) Show that the iterated sum $\sum_{i=1}^{\infty} \sum_{j=1}^{\infty} |a_i b_j|$ converges so that we may apply Theorem 2.8.1.

(b) Let $s_{nn} = \sum_{i=1}^{n} \sum_{j=1}^{n} a_i b_j$, and prove that $\lim_{n\to\infty} s_{nn} = AB$. Conclude that

$$\sum_{i=1}^{\infty} \sum_{j=1}^{\infty} a_i b_j = \sum_{j=1}^{\infty} \sum_{i=1}^{\infty} a_i b_j = \sum_{k=2}^{\infty} d_k = AB,$$

where, as before, $d_k = a_1 b_{k-1} + a_2 b_{k-2} + \cdots + a_{k-1} b_1$.

Solution. (a) Let $A' = \sum_{i=1}^{\infty} |a_i|$ and $B' = \sum_{j=1}^{\infty} |b_j|$. Notice that for a fixed $i \in \mathbf{N}$ we have

$$\sum_{j=1}^{n} |a_i b_j| = |a_i| \sum_{j=1}^{n} |b_j| \to |a_i| B' \text{ as } n \to \infty.$$

It follows that

$$\sum_{i=1}^{n} |a_i| B' = B' \sum_{i=1}^{n} |a_i| \to A'B' \text{ as } n \to \infty,$$

i.e.,

$$\sum_{i=1}^{\infty} \sum_{j=1}^{\infty} |a_i b_j| = A'B'.$$

(b) For each $n \in \mathbf{N}$ we have

$$s_{nn} = \sum_{i=1}^{n} \sum_{j=1}^{n} a_i b_j = \left(\sum_{i=1}^{n} a_i \right) \left(\sum_{j=1}^{n} b_j \right).$$

The Algebraic Limit Theorem (Theorem 2.3.3) now implies that $\lim_{n \to \infty} s_{nn} = AB$, and Theorem 2.8.1 then gives the desired result.