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Orderings and Functions

1.1 Basic Notation

Definition 1.1.1.

(1) The _natural numbers_ are defined as $\mathbf{N} = \{1, 2, 3, ...\}$,

(2) The _positive integers_ are defined as $\mathbf{N}_0 = \mathbf{Z}^+ = \{0, 1, 2, 3, ...\}$,

(3) The _integers_ are defined as $\mathbf{Z} = \{0, \pm 1, \pm 2, \pm 3, ...\}$,

(4) The _rational numbers_ are defined as $\mathbf{Q} = \{\frac{a}{b} \mid a, b \in \mathbf{Z}, b \neq 0\}$,

(5) The _real numbers_ are "defined" (we will get more into this later) as the set $(-\infty, \infty)$,

(6) The _complex numbers_ are defined as $\mathbf{C} = \{a + bi \mid a, b \in \mathbf{R}, i^2 = -1\}$.

Example 1.1.1. Note that $\sqrt{2}, \pi, e \notin \mathbf{Q}$, as they cannot be expressed as fractions.

Definition 1.1.2. Let A and B be sets. The _cartesian product_ is defined as $A \times B = \{(a, b) \mid a \in A, b \in B\}$.

Definition 1.1.3. A _relation_ from A to B is a subset $R \subseteq A \times B$. Typically, when one says "a relation on A" that means a relation from A to A; i.e., $R \subseteq A \times A$.

Definition 1.1.4. Let A be a set and R a relation on A. Then R is:

(1) _reflexive_ if $(a, a) \in R$ for all $a \in A$,

(2) _transitive_ if $(a, b), (b, c) \in R$ implies $(a, c) \in R$,

(3) _symmetric_ if $(a, b) \in R$ implies $(b, a) \in R$, and

(4) _antisymmetric_ if $(a, b), (b, a) \in R$ implies $a = b$.

1.2 Orderings

Definition 1.2.1. Let A be a set. An _ordering_ of A is a relation R on A that is reflexive, transitive, and antisymmetric. If this is the case, we write $(a, b) \in R$ as $a \leqslant_R b$. If A is an ordered set we write it as the ordered pair $(A, \leqslant_R)$ (or just A if the ordering is obvious by context).

Example 1.2.1.

(1) Let $m, n \in \mathbf{Z}$. The *algebraic ordering* $\leqslant_a$ is defined as follows: $m \leqslant_a n$ if and only if there exists an element $k \in \mathbf{N}_0$ with $m + k = n$.

(2) The set of natural numbers $\mathbf{N}$ equipped with the relation of divisibility form an ordering. Let $m, n \in \mathbf{N}$. Then $m \leqslant_d n$ if and only if $m \mid n$.

(3) Let S be any set. The subsets of S (i.e., elements of its power set) equipped with the relation of inclusion form an ordering. Let $A, B \in \mathcal{P}(S)$. Then $A \leqslant_{\mathcal{P}(S)} B$ if and only if $A \subseteq B$.

(4) The set of rational numbers $\mathbf{Q}$ form an algebraic ordering as follows: if $\frac{a}{b}, \frac{c}{d} \in \mathbf{Q}$, then $\frac{a}{b} \leqslant_a \frac{c}{d}$ if and only if $ad \leqslant_a bc$ (in $\mathbf{Z}$).

Definition 1.2.2. An ordered set $(A, \leqslant_R)$ is *total* (or *linear*) if for all $a, b \in A$ we have that $a \leqslant_R b$ or $b \leqslant_R a$.

Example 1.2.2. The ordered sets $(\mathbf{Z}, \leqslant_a)$ and $(\mathbf{Q}, \leqslant_a)$ are total orderings, whereas $(\mathbf{N}, \leqslant_d)$ and $(\mathcal{P}(S), \leqslant_{\mathcal{P}(S)})$ are not total orderings.

Definition 1.2.3. Let $(X, \leqslant)$ be an ordered set. Let $A \subseteq X$.

(1) A is called *bounded above* if there exists an element $u \in X$ with $a \leqslant u$ for all $a \in A$. Such a u (not necessarily unique) is called an *upperbound* for A.

(2) A is called *bounded below* if there exists an element $v \in X$ with $v \leqslant a$ for all $a \in A$. Such a v (not necessarily unique) is called a *lowerbound* for A.

(3) If A admits an upperbound u with $u \in A$, then u is called *the greatest element of A*.

(4) If A admits a lowerbound v with $v \in A$, then v is called *the least element of A*.

(5) Let A be bounded above. The *set of upperbounds of A* is defined as $\mathcal{U}_A = \{u \in X \mid u \text{ is an upperbound of } A\}$. If l is the least element of $\mathcal{U}_A$, we write $l = \sup(A)$ and call it *the supremum of A*.

(6) Let A be bounded below. The *set of lowerbounds of A* is defined as $\mathscr{L}_A = \{v \in X \mid v \text{ is a lowerbound of } A\}$. If g is the greatest element of $\mathscr{L}_A$, we write $g = \inf(A)$ and call it *the infimum of A*.

(7) A *maximal element of A* is an element $m \in A$ such that if $a \geqslant m$, then $a = m$ (not necessarily unique).

(8) A *minimal element of A* is an element $n \in A$ such that if $a \leqslant n$, then $a = n$ (not necessarily unique).

(9) If $(A, \leqslant)$ is a total ordering, then A is called a *chain*.

Proposition 1.2.1. *Let $(X, \leqslant)$ be an ordered set and $A \subseteq X$.*

(1) If A admits a greatest element, then it is unique,

(2) If A admits a least element, then it is unique,

(3) If A admits a least upper bound, then it is unique,

(4) If A admits a greatest lower bound, then it is unique.

Proof. Suppose u, u' are greatest elements of A, then $u, u' \in A$. Hence $u \leqslant u'$ and $u' \leqslant u$. By antisymmetry, $u = u'$, meaning the greatest element is unique. The proof for least elements being unique is identical, which establishes (1) and (2).

Note that $\mathcal{U}_A \subseteq X$. By definition the least element of $\mathcal{U}_A$ is defined to be the supremum of A, and since least elements are unique the supremum of A must be unique. Similarly, $\mathscr{L}_A \subseteq X$. By definition the greatest element of $\mathscr{L}_A$ is defined to be the infimum of A, and since greatest elements are unique the infimum of A must be unique. This establishes (3) and (4).   □

Lemma 1.2.2 (Zorn's Lemma)**.** *Let X be an ordered set with the property that every chain has an upperbound. Then X contains a maximal element.*

Example 1.2.3. Considered the ordered set $(\mathbf{N}, \leqslant_d)$ and the subset $A = \{4, 7, 12, 28, 35\}$.

- A is bounded above with $4 \times 7 \times 12 \times 28 \times 35$ as an upperbound.

- The supremum of A is lcm $(4, 7, 12, 28, 35)$.

- There does not exist a greatest element.

- $12, 28$, and 35 are maximal elements (no other element in A divides them).

Definition 1.2.4. Let $(X, \leqslant)$ be an ordered set and $A \subseteq X$. If A is bounded above and below, then we say A is *bounded*.

Definition 1.2.5. Let $(X, \leqslant)$ be an ordered set. Then $(X, \leqslant)$ is *complete* if, for every bounded set $A \subseteq X$, sup (A) and inf (A) exist.

1.3   Functions

Definition 1.3.1. Let X and Y be sets. A *function* from X to Y is a relation $f \subseteq X \times Y$ such that for all $x \in X$, there exists a unique $y_x \in Y$ with $(x, y_x) \in f$.

(1) The set X is the *domain* of f.

(2) The set Y is the *codomain* of f.

(3) The *image* of f is defined as $f(X) = \{f(x) \mid x \in X\} \subseteq Y$ (also sometimes denoted im (f)).

(4) The *preimage* of f is defined as $f^{-1}(Y) = \{x \in X \mid f(x) \in Y\} \subseteq X$.

(5) The *graph* of f is defined as Graph $(f) = \{(x, f(x)) \mid x \in X\} \subseteq X \times Y$.

If f is a function, we denote it by $f : X \to Y$ or $X \xrightarrow{f} Y$.

Example 1.3.1. Let X be a set.

(1) The *identity map* $\mathrm{id}_X : X \to X$ is defined by $\mathrm{id}_X(x) = x$.

(2) If $X \subseteq Y$, the *inclusion map* $\iota : X \to Y$ is defined by $\iota(x) = x$.

(3) If $A \subseteq X$ is a set, the *characteristic function* (or *step function*) $\mathbf{1}_A : X \to \mathbf{R}$ is defined by

$$\mathbf{1}_A(x) = \begin{cases} 1, & x \in A \\ 0, & x \notin A. \end{cases}$$

Definition 1.3.2. Given $f, g : X \to \mathbf{R}$ and $\alpha \in \mathbf{R}$, the *pointwise operations* on f and g are:

- $(f \pm g)(x) = f(x) \pm g(x)$,

- $(\alpha f)(x) = \alpha f(x)$,

- $(fg)(x) = f(x)g(x)$,

- $(f/g)(x) = f(x)/g(x)$.

Definition 1.3.3. Let $f : X \to Y$ and $g : Y \to Z$ be maps between sets. The *composition* of f and g is denoted $g \circ f : X \to Z$.

$$X \xrightarrow{\ f\ } Y \xrightarrow{\ g\ } Z$$
$$\underbrace{\qquad\qquad}_{g \circ f}$$

Definition 1.3.4. Let $f : X \to Y$ be a map between sets.

(1) f is *left-invertible* if there exists a map $g : Y \to X$ with $g \circ f = \mathrm{id}_X$.

(2) f is *right-invertible* if there exists a map $h : Y \to X$ with $f \circ h = \mathrm{id}_Y$.

(3) f is *invertible* if there exists a map $k : Y \to X$ with $k \circ f = \mathrm{id}_X$ and $f \circ k = \mathrm{id}_Y$.

Example 1.3.2. The *shift function* is a map $s : \mathbf{N} \to \mathbf{N}$ defined by $s(n) = n + 1$. Note that this function is left-invertible: define $g : \mathbf{N} \to \mathbf{N}$ by

$$g(n) = \begin{cases} n - 1, & n \geqslant 2 \\ n_0, & n = 1, \end{cases}$$

where n_0 is an arbitrary natural number, then $g \circ s = \mathrm{id}_{\mathbf{N}}$.

Suppose that s has a right inverse, that is, there exists a function $h : \mathbf{N} \to \mathbf{N}$ such that $s \circ h = \mathrm{id}_{\mathbf{N}}$. Observe that:

$$(s \circ h)(1) = s(h(1)) = h(1) + 1 = 1.$$

It must be the case that $h(1) = 0$, which is a contradiction. Hence s is not right-invertible.

Example 1.3.3. The function g defined above is right invertible, but not left invertible.

Proposition 1.3.1. *Let $f : X \to Y$ be a map between sets. The following are equivalent:*

(1) f is invertible,

(2) f is right-invertible and left-invertible.

Proof. Clearly (1) implies (2). Assume f to be left and right-invertible. Then there exists maps $h, g : Y \to X$ with $g \circ f = \text{id}_X$ and $f \circ h = \text{id}_Y$. Observe that:

$$\begin{aligned}
h &= \text{id}_X \circ h \\
&= (g \circ f) \circ h \\
&= g \circ (f \circ h) \\
&= g \circ \text{id}_Y \\
&= g,
\end{aligned}$$

establishing the proposition. $\square$

Definition 1.3.5. Let $f : X \to Y$ be a map between sets.

(1) f is <u>*injective*</u> if $f(x_1) = f(x_2)$ implies $x_1 = x_2$,

(2) f is <u>*surjective*</u> if im $(f) = Y$, and

(3) f is <u>*bijective*</u> if it is injective and surjective.

Proposition 1.3.2. *Let $f : X \to Y$ be a map between sets.*

1. f is injective if and only if f is left-invertible.

2. f is surjective if and only if f is right-invertible.

3. f is bijective if and only if f is invertible.

Proof. (1) Do the forward direction yourself! Now assume $f : X \to Y$ is injective. Define $g : Y \to X$ by

$$g(y) = \begin{cases} x_0, & y \notin \text{im}\,(f) \\ x_y, & y \in \text{im}\,(f), \end{cases}$$

where x_y is the unique element in x mapping to y; i.e., $f(x_y) = y$. By our construction, $(g \circ f)(x) = x$ for all $x \in X$.

(2) Do the forward direction yourself! Now assume $f : X \to Y$ is onto. Note that the preimage of f is nonempty, so we can define $h : Y \to X$ by $h(y) = x_y$, where $x_y \in f^{-1}(X)$. By our construction $(f \circ h)(y) = f(x_y) = y$ for all $y \in Y$.

(3) Do this yourself its easy! $\square$

Corollary 1.3.3. *Let A, B be sets. There exists an injection $A \hookrightarrow B$ if and only if there exists a surjection $B \twoheadrightarrow A$.*

Proof. If $f : A \to B$ is injective, then f is left invertible, that is, there exists a function $g : B \to A$ with $g \circ f = \text{id}_A$. But this means g is right invertible, so g is onto. The other direction follows identically. $\square$

1.4 Cardinality

Definition 1.4.1. Let A, B be sets. Then $\text{card}(A) = \text{card}(B)$ if there exists a bijection $A \hookrightarrow\!\!\!\!\to B$.

Example 1.4.1.

(1) Define $f : \mathbf{N}_0 \to \mathbf{N}$ by $f(n) = n + 1$. This is a bijection, hence $\text{card}(\mathbf{N}_0) = \text{card}(\mathbf{N})$.

(2) Let $[a, b]$ and $[c, d]$ be intervals with $a < b$ and $c < d$. Define $f : [a, b] \to [c, d]$ by $f(x) = (\frac{d-c}{b-a})(x - a) + c$.
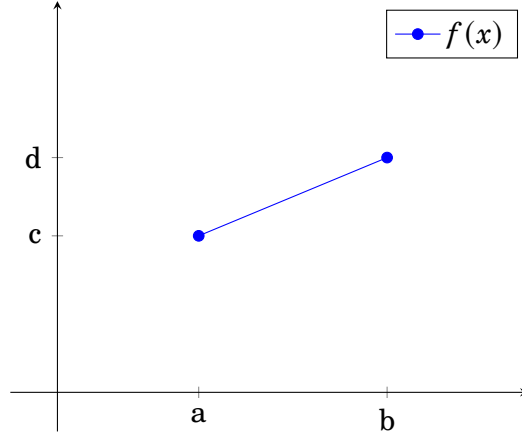
This is a bijection, hence $\text{card}([a, b]) = \text{card}([c, d])$. The result is the same had the intervals been open.

(3) Recall that $\tan : (-\frac{\pi}{2}, \frac{\pi}{2}) \to \mathbf{R}$ is a bijection. Consider the maps $(0, 1) \overset{g}{\hookrightarrow\!\!\!\!\to} (-\frac{\pi}{2}, \frac{\pi}{2}) \overset{\tan}{\hookrightarrow\!\!\!\!\to} \mathbf{R}$. Since g and $\tan$ are bijective, $\tan \circ g$ is bijective, hence $\text{card}((0, 1)) = \text{card}(\mathbf{R})$.

Definition 1.4.2. A set A is called *finite* if there exists an $N \in \mathbf{N}$ such that $\text{card}(A) = \text{card}(\{1, ..., N\})$. If not, then A is called *infinite*.

Proposition 1.4.1. *Given* $m, n \in \mathbf{N}$, $m \neq n$, *then* $\text{card}(\{1, ..., m\}) \neq \text{card}(\{1, ..., n\})$.

Proof. Without loss of generality, let $m > n$. By way of contradiction, if there exists a bijection $f : \{1, ..., m\} \to \{1, ..., n\}$, then there exists $i, j \in \{1, ..., m\}$ with $i \neq j$ and $f(i) = f(j)$. This is a contradiction (f is not injective). $\qquad\square$

Proposition 1.4.2. $\mathbf{N}$ *is infinite.*

Proof. Suppose towards contradiction there exists an $N \in \mathbf{N}$ and a bijection $f : \mathbf{N} \to \{1, ..., N\}$. Note that the inclusion map $\iota : \{1, ..., N, N + 1\} \to \mathbf{N}$ is injective. Now consider the maps $\{1, ..., N, N+1\} \overset{\iota}{\to} \mathbf{N} \overset{f}{\to} \{1, ..., N\}$. Then $f \circ \iota : \{1, ..., N, N+1\} \to \{1, ..., N\}$. But by the previous example this cannot be true, thus $\mathbf{N}$ is infinite. $\qquad\square$

Exercise 1.4.1. *If A is infinite, there exists an injection* $\mathbf{N} \hookrightarrow A$.

Proof. Let $\pi : \mathbf{N} \to A$ be a map. Let $a_1 \in A$. Define $\pi(1) = a_1$. Since A is infinite, $A - \{a_1\}$ is also infinite. Pick $a_2 \in A$ and let $\pi(2) = a_2$. Inductively, we have that an injection $\mathbf{N} \hookrightarrow A$.   □

Example 1.4.2.

(1) Define $k : \mathbf{Z} \to \mathbf{N}$ by $k(n) = (-1)^{n-1} \left\lfloor \frac{n}{2} \right\rfloor$. This is a bijection, hence $\mathrm{card}(\mathbf{Z}) = \mathrm{card}(\mathbf{N})$.

(2) Let X be any set. Recall that the *power set of X* is defined as $\mathcal{P}(X) = \{A \mid A \subseteq X\}$. Define $2^x = \{f \mid f : X \to \{0, 1\}\}$. Let $A \subseteq X$. Define $\varphi : \mathcal{P}(X) \to 2^X$ by $\varphi(A) = \mathbf{1}_A$, where $\mathbf{1}_A$ is the *characteristc function* defined in Example 1.3.1. Note that $\varphi(A) = \varphi(B)$ if and only if $\mathbf{1}_A = \mathbf{1}_B$. Recall that functions are equal if and only if $\mathbf{1}_A(x) = \mathbf{1}_B(x)$ for all $x \in X$. $x \in A$ if and only if $\mathbf{1}_A(x) = 1$ if and only if $\mathbf{1}_B(x) = 1$, giving $x \in B$. Thus $A = B$ which means φ is injective. Now let $f \in 2^X$. Let $A = \{x \in X \mid f(x) = 1\}$. Then $\mathbf{1}_A = f$. Thus φ is bijective and so $\mathrm{card}(\mathcal{P}(X)) = \mathrm{card}(2^X)$.

Exercise 1.4.2. *Show that* $\mathrm{card}(\mathcal{P}(\{1, ..., N\})) = 2^N$.

Proof. do this   □

Theorem 1.4.3 (Cantor's Diagonal Argument). $\mathrm{card}(\mathbf{N}) < \mathrm{card}((0, 1))$.

Proof. Recall that every $\sigma \in (0, 1)$ has a decimal expansion $\sigma = 0.\sigma_1\sigma_2... = \sum_{k=1}^{\infty} \frac{\sigma_k}{10^k}$, where $\sigma_j \in \{0, 1, 2, ..., 9\}$ which does not terminate in 9's. By way of contradiction, suppose there exists a surjection $r : \mathbf{N} \to (0, 1)$ defined by $r(n) = 0.\sigma_1(n)\sigma_2(n)\sigma_3(n)...$, where $\sigma_j(n) \in \{0, 1, 2, ..., 9\}$ is the jth digit in the decimal expansion.

Consider the map $\tau : \mathbf{N} \to \{0, 1, ..., 9\}$ defined by:

$$\tau(n) = \begin{cases} 3, & \sigma_n(n) = 2 \\ 2, & \sigma_n(n) = 3, \end{cases}$$

and let $t = 0.\tau(1)\tau(2)\tau(3)...$ Observe the following:

$$r(1) = 0.\sigma_1(1)\sigma_2(1)\sigma_3(1)\sigma_4(1)...$$
$$r(2) = 0.\sigma_1(2)\sigma_2(2)\sigma_3(2)\sigma_4(2)...$$
$$r(3) = 0.\sigma_1(3)\sigma_2(3)\sigma_3(3)\sigma_4(3)...$$
$$r(4) = 0.\sigma_1(4)\sigma_2(4)\sigma_3(4)\sigma_4(4)...$$
$$\vdots$$
$$r(n) = 0.\sigma_1(n)\sigma_2(n)\sigma_3(n)\sigma_4(n) \ ... \ \sigma_n(n).$$

Since r is surjective, there is an $m \in \mathbf{N}$ with $r(m) = t$. It follows that:

$$r(m) = 0.\sigma_1(m)\sigma_2(m)\sigma_3(m)...\sigma_m(m)...$$
$$= 0.\tau(1)\tau(2)\tau(3)...\tau(m)...$$

which implies that $\sigma_m(m) = \tau(m)$. But recall how we defined $\tau(n)$ —if $\sigma_m(m) = 2$, then $\tau(2) = 3$ and if $\sigma_m(m) \neq 2$, then $\tau(2) = 2$. This is a contradiction, hence there does not exist a surjection $\mathbf{N} \xrightarrow{r} (0, 1)$.   □

Corollary 1.4.4. $\mathrm{card}(\mathbf{N}) \neq \mathrm{card}(\mathbf{R})$

Proof. It follows from Example 1.4.1 that $\mathrm{card}(\mathbf{N}) < \mathrm{card}((0,1)) = \mathrm{card}(\mathbf{R})$. $\qquad\square$

Definition 1.4.3. Let A and B be sets.

(1) We write $\mathrm{card}(A) \leqslant \mathrm{card}(B)$ if there exists an injection $A \hookrightarrow B$.

(2) We write $\mathrm{card}(A) < \mathrm{card}(B)$ if $\mathrm{card}(A) \leqslant \mathrm{card}(B)$ and $\mathrm{card}(A) \neq \mathrm{card}(B)$

Example 1.4.3.

(1) If $A \subseteq B$, then the inclusion map $\iota : A \to B$ gives $\mathrm{card}(A) \leqslant \mathrm{card}(B)$.

(2) If $m > n$, then $\mathrm{card}\{1, ..., n\} < \mathrm{card}\{1, ..., m\}$

Proposition 1.4.5. *Let A be a set. Then $\mathrm{card}(A) < \mathrm{card}(\mathcal{P}(A))$.*

Proof. Define $f : A \to \mathcal{P}(A)$ by $a \mapsto \{a\}$. This is clearly an injective map. Now suppose towards contradiction that there exists a surjection $g : A \to \mathcal{P}(A)$ defined by $a \mapsto g(a)$. Then $g(a) \subseteq A$ (by the definition of a power set).

Let $S = \{a \in A \mid a \notin g(a)\}$. Then $S \subseteq A$. Since g is onto, there exists an element $x \in A$ with $g(x) = S$. Case 1: $x \in S$. This implies that $x \notin g(x)$. But $g(x) = S$, so $x \notin S$, a contradiction. Case 2: $x \notin S$. This implies that $x \notin g(x)$. But by definition this means $x \in S$, a contradiction. Since we have exhausted all the necessary cases, it must be that there does not exist a surjection from $A \to \mathcal{P}(A)$. Hence $\mathrm{card}(A) < \mathrm{card}(\mathcal{P}(A))$. $\qquad\square$

Lemma 1.4.6. *Let A and B be sets. The following are equivalent:*

(1) $\mathrm{card}(A) \leqslant \mathrm{card}(B)$;

(2) there exists an injection $A \hookrightarrow B$;

(3) there exists a surjection $B \twoheadrightarrow A$.

Example 1.4.4.

(1) Define $\mathbf{N} \times \mathbf{Z} \to \mathbf{Q}$ by $(n, m) \mapsto \frac{m}{n}$. This is surjective, so $\mathrm{card}(\mathbf{Q}) \leqslant \mathrm{card}(\mathbf{N} \times \mathbf{Z})$.

(2) Define $\mathbf{N} \times \mathbf{N} \to \mathbf{N}$ by $(m, n) \mapsto 2^m \cdot 3^n$. Then g is injective by the fundamental theorem of arithmetic. So $\mathrm{card}(\mathbf{N} \times \mathbf{N}) \leqslant \mathrm{card}(\mathbf{N})$.

(3) Recall from Example 1.4.2 that $k : \mathbf{N} \to \mathbf{Z}$ defined by $k(n) = (-1)^{n-1} \left\lfloor \frac{n}{2} \right\rfloor$ is a bijection. Define $K : \mathbf{Z} \times \mathbf{N} \to \mathbf{N} \times \mathbf{N}$ by $(m, n) \mapsto (k^{-1}(m), n)$. This is a bijection, so $\mathrm{card}(\mathbf{Z} \times \mathbf{N}) = \mathrm{card}(\mathbf{N} \times \mathbf{N})$.

(4) From the previous examples, we've established that:

$$\mathrm{card}(\mathbf{N}) \leqslant \mathrm{card}(\mathbf{Q}) \leqslant \mathrm{card}(\mathbf{Z} \times \mathbf{N}) = \mathrm{card}(\mathbf{N} \times \mathbf{N}) \leqslant \mathrm{card}(\mathbf{N})$$

Theorem 1.4.7. *Let $\mathfrak{R}$ denote the class of cardinals. The pair $(\mathfrak{R}, \leqslant)$ forms a total ordering —where $\leqslant$ is defined by $\mathrm{card}(A) \leqslant \mathrm{card}(B)$ if and only if $A \hookrightarrow B$. In particular, if A, B, C are sets with $\mathrm{card}(A), \mathrm{card}(B), \mathrm{card}(C) \in \mathrm{obj}(\mathfrak{R})$, then we have the following:*

(1) $\mathrm{card}(A) \leqslant \mathrm{card}(A)$ (reflexive).

(2) If $\mathrm{card}(A) \leqslant \mathrm{card}(B) \leqslant \mathrm{card}(C)$, then $\mathrm{card}(A) \leqslant \mathrm{card}(C)$ (transitive).

(3) If $\mathrm{card}(A) \leqslant \mathrm{card}(B)$ and $\mathrm{card}(B) \leqslant \mathrm{card}(A)$, then $\mathrm{card}(A) = \mathrm{card}(B)$ (antisymmetric).

(4) Either $\mathrm{card}(A) \leqslant \mathrm{card}(B)$ or $\mathrm{card}(B) \leqslant \mathrm{card}(A)$ (total).

Proof. (1) and (2) follow by simply applying definitions. Note that any set bijects into itself, hence $A \hookrightarrow\!\!\!\rightarrow A$ implies $A \hookrightarrow A$, establishing $\mathrm{card}(A) \leqslant \mathrm{card}(A)$. Similarly, if there are bijections $A \hookrightarrow\!\!\!\rightarrow B \hookrightarrow\!\!\!\rightarrow C$, then clearly there is a bijection $A \hookrightarrow\!\!\!\rightarrow C$. Hence $\mathrm{card}(A) = \mathrm{card}(C)$.

(3) (Cantor-Shröder-Bernstein Theorem) We have injections $A \overset{f}{\hookrightarrow}$ and $B \overset{g}{\hookrightarrow} A$. Let:

$$
\begin{aligned}
A_0 &= \mathrm{im}\,(g)^{\complement} \\
A_1 &= (g \circ f)(A_0) \\
A_2 &= (g \circ f)(A_1) \\
&\vdots \\
A_n &= (g \circ f)(A_{n-1}).
\end{aligned}
$$

Note that $A_1 \cap A_0 = \emptyset$ because $A_1 \subseteq \mathrm{im}\,(g)$ and $A_0 = \mathrm{im}\,(g)^{\complement}$. We similarly have that $A_2 \cap A_0 = \emptyset$. Claim: $A_1 \cap A_2$. finish this

(4) Let $A \to B$ be a map. Let $\mathcal{F} = \{(D, f) \mid D \subseteq A, f : D \hookrightarrow B, \ f \text{ is injective}\}$. Note that $\mathcal{F} \neq \emptyset$ because $(\emptyset, k) \in \mathcal{F}$ for some map k. Define an ordering on $\mathcal{F}$ as follows: $(D, f) \leqslant_{\mathcal{F}} (E, g)$ if and only if $D \subseteq E$ and $g|_D = f$. Then $\mathcal{F}$ admits an upperbound of A. By Zorn's Lemma, there exists a maximal element $(M, h) \in \mathcal{F}$. Suppose towards contradiction there are elements $a \in A$, $a \notin M$ and $b \in B$, $b \notin h(M)$. Consider the map:

$$
h' : M \cup \{a\} \to B \text{ defined by } \begin{cases} h'(M) = h(M) \\ h'(a) = b \end{cases}.
$$

This set is clearly injective, and furthermore we have that $(M, h) \leqslant (M \cup \{a\}, h')$. This is a contradiction, hence $M = A$ or $h(M) = B$. If $M = A$, then the injection $A \overset{h}{\hookrightarrow} B$ implies $\mathrm{card}(A) \leqslant \mathrm{card}(B)$. If $h(M) = B$, then the map $B \hookrightarrow M \overset{\iota}{\hookrightarrow} A$ implies $\mathrm{card}(B) \leqslant \mathrm{card}(A)$. $\qquad\square$

Corollary 1.4.8. $\mathrm{card}(\mathbf{Q}) = \mathrm{card}(\mathbf{N})$.

Proof. This follows directly from Example 1.4.4 and Theorem 1.4.7 $\qquad\square$

Definition 1.4.4. A set A is *countable* if $\mathrm{card}(A) \leqslant \mathrm{card}(\mathbf{N})$. Equivalently, there exists an injection $A \hookrightarrow \mathbf{N}$ and a surjection $\mathbf{N} \twoheadrightarrow A$. If A is countable and infinite, A is called *denumerable* (or more commonly referred to as *countably infinity*).

Definition 1.4.5. We say $\text{card}(\mathbf{N}) = \text{card}(\mathbf{Z}) = \text{card}(\mathbf{Q}) := \aleph_0$, called *aleph naught*. We also define $\text{card}(\mathbf{R}) = \mathfrak{c}$, called the *continuum*.

Example 1.4.5. By Theorem 1.4.3, $\aleph_0 < \mathfrak{c}$.

Corollary 1.4.9. *There does not exist an infinite set A with $\text{card}(A) < \aleph_0$. In particular, if A is infinite and countable, then $\text{card}(A) = \aleph_0$.*

Proof. By Exercise 1.4.1, $\text{card}(\mathbf{N}) \leqslant \text{card}(A)$, and by definition (since A is countable), $\text{card}(A) \leqslant \text{card}(\mathbf{N})$. So by Theorem 1.4.7, $\text{card}(A) = \text{card}(\mathbf{N}) = \aleph_0$. $\qquad\square$

Example 1.4.6. $\text{card}(\mathcal{P}(\mathbf{N})) > \text{card}(\mathbf{N}) = \aleph_0$.

Proposition 1.4.10. *The countable union of countable sets is countable. More precisely, if A_i is countable for all $i \in \mathbf{N}$, then $\bigcup_{i=1}^{\infty} A_i$ is countable.*

Proof. By definition, there exist surjections $\pi_i : \mathbf{N} \to A_i$. Define $\pi : \mathbf{N} \times \mathbf{N} \to \bigcup_{i=1}^{\infty} A_i$ by $\pi(i, j) = \pi_i(j)$. Claim: π is onto. Let $x \in \bigcup_{i=1}^{\infty} A_i$, then there exists an i_0 with $x \in A_{i_0}$. Since π_{i_0} is onto, there exists a $j_0 \in \mathbf{N}$ with $\pi_{i_0}(j_0) = x$. So $\pi(i_0, j_0) = x$, establishing that π is surjective as well. Therefore $\text{card}(\bigcup_{i=1}^{\infty} A_i) \leqslant \text{card}(\mathbf{N} \times \mathbf{N}) = \text{card}(\mathbf{N})$. $\qquad\square$

Lemma 1.4.11. $\text{card}([0, 1]) \leqslant \text{card}(2^{\mathbf{N}})$.

Proof. Recall that every $\sigma \in [0, 1]$ has a binary expansion $\sigma = \sum_{k=1}^{\infty} \frac{\sigma_k}{2^k}$, where $\sigma_k \in \{0, 1\}$. Consider the map $\varphi : 2^{\mathbf{N}} \to [0, 1]$ defined by $\varphi(f) = \sum_{k=1}^{\infty} \frac{f(k)}{2^k}$. Letting $f(k) = \sigma_k$ gives φ is surjective. $\qquad\square$

Lemma 1.4.12. $\text{card}(\mathbf{R}) = \text{card}([0, 1])$.

Proof. By inclusion $[0, 1] \overset{\iota}{\hookrightarrow} \mathbf{R}$, which implies that $\text{card}([0, 1]) \leqslant \text{card}(\mathbf{R})$. Recall that $\mathbf{R} \overset{\tan}{\twoheadrightarrow} (0, 1) \overset{\iota}{\hookrightarrow} [0, 1]$, which implies that $\text{card}(\mathbf{R}) \leqslant \text{card}([0, 1])$. Then Theorem 1.4.7 gives the desired result. $\qquad\square$

Lemma 1.4.13. $\text{card}(2^{\mathbf{N}}) \leqslant \text{card}([0, 1])$.

Proof. Consider the map $\lambda : 2^{\mathbf{N}} \to [0, 1]$ defined by $\lambda(f) = \sum_{k=1}^{\infty} \frac{f(k)}{3^k}$. Claim: λ is injective. Let $f, g \in 2^{\mathbf{N}}$ with $f \neq g$. Let k_0 be the *smallest point k where f and g are different*. So in particular:

$$f(1) = g(1)$$
$$f(2) = g(2)$$
$$\vdots$$
$$f(k_0 - 1) = g(k_0 - 1)$$
$$f(k_0) \neq g(k_0).$$

Let:

$$t_1 = \sum_{k > k_0} \frac{f(k)}{3^k} \quad \text{sum past } k_0$$

$$t_2 = \sum_{k > k_0} \frac{g(k)}{3^k} \quad \text{sum past } k_0$$

$$s_1 = \sum_{k=1}^{k_0-1} \frac{f(k)}{3^k} \quad \text{sum before } k_0$$

$$s_1 = \sum_{k=1}^{k_0-1} \frac{g(k)}{3^k} \quad \text{sum before } k_0$$

We have that:

$$\lambda(f) = s_1 + \frac{f(k_0)}{3^{k_0}} + t_1$$

$$\lambda(g) = s_2 + \frac{g(k_0)}{3^{k_0}} + t_2$$

Because f and g differ at k_0, without loss of generality let $f(k_0) = 0$ and $g(k_0) = 1$. Then $\lambda(g) - \lambda(f) = \frac{1}{3^{k_0}} + t_2 - t_1$. Observe that:

$$\begin{aligned}
|t_2 - t_2| &= \left| \sum_{k > k_0} \frac{g(k) - f(k)}{3^k} \right| \\
&\leqslant \sum_{k > k_0} \frac{|g(k) - f(k)|}{3^k} \quad \text{By triangle inequality} \\
&\leqslant \sum_{k > k_0} \frac{1}{3^k} \quad \text{By comparison test} \\
&= \frac{1}{3^{k_0+1}} \sum_{k \geqslant 0} \frac{1}{3^k} \\
&= \frac{1}{3^{k_0+1}} \cdot \frac{1}{1 - \frac{1}{3}} \\
&= \frac{3}{2 \cdot 3^{k_0+1}} \\
&= \frac{1}{2 \cdot 3^{k_0}} \\
&< \frac{1}{3^{k_0}}.
\end{aligned}$$

Since $|t_2 - t_2| < \frac{1}{3^{k_0}}$, $\lambda(g) - \lambda(f) \neq 0$, establishing λ as an injection. Thus $\text{card}(2^{\mathbf{N}}) \leqslant \text{card}([0,1])$. $\square$

Theorem 1.4.14. $\text{card}(2^{\mathbf{N}}) = \text{card}(\mathcal{P}(\mathbf{N})) = \text{card}(\mathbf{R})$.

Proof. This follows from Lemma 1.4.11, Lemma 1.4.12, and Lemma 1.4.13. $\square$

2

Ordered Fields

2.1 Ordering of $\mathbb{Z}$

Definition 2.1.1. Define $\mathbf{Z}^+ = \{n \in \mathbf{Z} \mid n \geqslant_a 0\}$, where $\geqslant_a$ is the *algebraic ordering* from Example 1.2.1. We call $\mathbf{Z}^+$ the *cone of positive integers*, and they admit the following axioms:

(1) If $m, n \in \mathbf{Z}^+$, then $m + n \in \mathbf{Z}^+$ and $mn \in \mathbf{Z}^+$.

(2) For all $m \in \mathbf{Z}$, $m \in \mathbf{Z}^+$ or $-m \in \mathbf{Z}^+$.

(3) If $m \in \mathbf{Z}^+$ and $-m \in \mathbf{Z}^+$, then $m = 0$.

Proposition 2.1.1 (Properties of $\leqslant_a$)**.**

(1) $m \leqslant_a n$ if and only if $n - m \in \mathbf{Z}^+$.

(2) If $m \leqslant_a n$ and $p \leqslant_a q$, then $m + p \leqslant_a n + q$.

(3) If $m \leqslant_a n$ and $p \in \mathbf{Z}^+$, then $pm \leqslant_a pn$.

(4) If $m \leqslant_a n$ then $-n \leqslant_a -m$.

(5) $(\mathbf{Z}, \leqslant_a)$ forms a total ordering.

(6) If $m >_a 0$ and $mn >_a 0$, then $n >_a 0$.

(7) If $m >_a 0$ and $mn \geqslant_a mp$, then $n \geqslant_a p$.

Proof. (5) Let $m, n \in \mathbf{Z}$, since $\mathbf{Z}$ is closed under subtraction $m - n \in \mathbf{Z}$. So either $m - n \in \mathbf{Z}^+$ or $n - m \in \mathbf{Z}^+$. Then by (1) $n \leqslant_a m$ or $m \leqslant_a n$. Thus $(\mathbf{Z}, \leqslant_a)$ is a total ordering.

(6) We have $mn >_a 0$ with $m >_a 0$. If $n = 0$, we are done. So now assume $n \neq 0$. Then either $n \in \mathbf{Z}^+$ or $-n \in \mathbf{Z}^+$. If $-n \in \mathbf{Z}^+$, then $m(-n) = -(mn) \in \mathbf{Z}^+$. But we had assumed $mn >_a 0$; i.e., $mn \in \mathbf{Z}^+$, hence it must be the case that $mn = 0$, a contradiction. Therefore it must be that $n \in \mathbf{Z}^+$. $\qquad\square$

2.2 Ordering of $\mathbb{Q}$

Proposition 2.2.1. *Define $Q := \mathbf{Z} \times \mathbf{N}$. Show that $\sim$ forms an equivalence relation, where $(a, b) \sim (c, d)$ if and only if $ad = bc$.*

Proof. I dont wanna do this $\qquad\square$

Definition 2.2.1. The set of equivalence classes of Q is $\mathbf{Q} = Q/\!\sim\, = \{[(a, b)] \mid (a, b) \in Q\}$. We call this set the *rational numbers*, and denote the equivalence classes $[(a, b)]$ as $\frac{a}{b}$.

Proposition 2.2.2. *The operations*

$$+ : \mathbf{Q} \times \mathbf{Q} \to \mathbf{Q} \text{ defined by } [(a, b)] + [(c, d)] = [(ad + bc, bd)]$$
$$\cdot : \mathbf{Q} \times \mathbf{Q} \to \mathbf{Q} \text{ defined by } [(a, b)] \cdot [(c, d)] = [(ac, bd)]$$

are well-defined. Furthermore, $(\mathbf{Q}, +, \cdot)$ forms a field.

Proof. I dont wana □

Lemma 2.2.3. *There is an injective map $\mathbf{Z} \xhookrightarrow{j} \mathbf{Q}$ defined by $j(n) = \frac{n}{1}$ satisfying the properties*

$$j(n + m) = j(n) + j(m)$$
$$j(nm) = j(n)j(m).$$

Proof. Note that $j(n) = j(m)$ if and only if $\frac{n}{1} + \frac{m}{1}$. By definition this is equivalent to $n = m$, hence j is injective.

Observe that $j(n + m) = \frac{n+m}{1} = \frac{n}{1} + \frac{m}{1} = j(n) + j(m)$ and $j(nm) = \frac{nm}{1} = \frac{n}{1} \cdot \frac{m}{1} = j(n)j(m)$. □

Theorem 2.2.4. *$(\mathbf{Q}, \leqslant_Q)$ is a total ordering, where $\leqslant_Q$ is a well-defined ordering defined by $\frac{a}{b} \leqslant_Q \frac{c}{d}$ if and only if $ad \leqslant_a bc$ in $(\mathbf{Z}, \leqslant_a)$. Furthermore, the map $j : \mathbf{Z} \hookrightarrow \mathbf{Q}$ is order preserving, that is, if $n \leqslant_a m$ in $(\mathbf{Z}, \leqslant_a)$, then $j(n) \leqslant_Q j(m)$ in $(\mathbf{Q}, \leqslant_Q)$.*

Proof. i REALLY dont □

Definition 2.2.2. Define $\mathbf{Q}_+ := \{q \in \mathbf{Q} \mid q \geqslant_Q 0\}$ as the *cone of positive rationals*, and they admit the following axioms:

(1) If $q_1, q_2 \in \mathbf{Q}^+$, then $q_1 + q_2 \in \mathbf{Z}^+$ and $q_1 q_2 \in \mathbf{Z}^+$.

(2) For all $q \in \mathbf{Q}$, $q \in \mathbf{Q}^+$ or $-q \in \mathbf{Q}^+$.

(3) If $q \in \mathbf{Q}^+$ and $-q \in \mathbf{Q}^+$, then $q = 0$.

(4) $q_1 \leqslant_Q q_2$ if and only if $q_2 - q_1 \in \mathbf{Q}^+$.

Proposition 2.2.5. *Let $r, s, t, u \in \mathbf{Q}$*

(1) If $r \leqslant_Q s$ and $t \leqslant_Q u$, then $r + t \leqslant_Q s + u$.

(2) If $r \leqslant_Q s$ and $t \geqslant_Q 0$, then $tr \leqslant_Q ts$.

Proof. do this shi later □

2.3   Rings and Fields

Definition 2.3.1. A _ring_ is a non-empty set R equipped with two binary operations:

$$R \times R \xrightarrow{a} R \text{ defined by } a(r, s) = r + s$$
$$R \times R \xrightarrow{m} R \text{ defined by } m(r, s) = rs,$$

such that they admit the following axioms:

(1) R is an _abelian group_ under addition:

    (i) $r + (s + t) = (r + s) + t$ for all $r, s, t \in R$,

    (ii) there exists an element $0_R \in R$ with $r + 0_R = r = 0_R = r$ for all $r \in R$,

    (iii) For all $r \in R$ there exists an $s \in R$ such that $r + s = 0_R = s + r$ (such an s is unique, and is denoted $-r$),

    (iv) $r + s = s + r$ for all $r, s \in R$.

(2) $r(st) = (rs)t$ for all $r, s, t \in R$,

(3) $(r + s)t = rt + rs$ and $r(s + t) = rs + rt$ for all $r, s, t \in R$.

If R contains an element 1_R such that $1_R r = r = r 1_R$, then we say R is _unital_. If $rs = sr$ for all $r, s \in R$, then we say R is _commutative_. If R is a unital ring such that $1_R \neq 0_R$ _and_ for all $r \in R$ there exists an $s \in R$ such that $rs = 1_R = sr$ (such an s is unique, and denoted r^{-1}), then we say R is a _division ring_.

Definition 2.3.2. A _field_ is a commutative division ring.

Example 2.3.1.

(1) $\mathbf{Q}$ is a field.

(2) $\mathbf{Z}/p\mathbf{Z}$ is a field.

(3) $\mathbf{C_Q} = \{r + si \mid r, s \in \mathbf{Q}, i^2 = -1\}$ with addition and multiplication defined by

$$(r + si) + (t + ui) := (r + t) + (s + u)i$$
$$(r + si)(t + ui) := (rt - su) + (ru + st)i$$

is a field. We call this set the _complex rationals_.

Definition 2.3.3. An _ordered field_ is a field F equipped with a total ordering $\leqslant_F$ such that:

(1) If $x \leqslant_F y$ and $u \leqslant_F v$, then $x + u \leqslant_F y + v$.

(2) If $x \leqslant_F y$ and $z \geqslant_F 0$, then $xz \leqslant_F zy$.

We similarly define $F^+ = \{x \in F \mid x \geqslant_F 0\}$ as the _cone of positive elements_.

Proposition 2.3.1. *Let $(F, \leqslant_F)$ be an ordered field.*

(1) If $x, y \in F^+$, then $x + y \in F^+$ and $xy \in F^+$.

(2) If $x \in F$, then $-x \in F^+$ or $x \in F^+$.

(3) If $x, -x \in F^+$, then $x = 0$.

Proof. need to do □

Example 2.3.2.

(1) **Q** is an ordered field.

(2) Is $\mathbf{C_Q}$ an ordered field?

Proposition 2.3.2. *Let $(F, \leqslant)$ be an ordered field with $1_F \neq 0_F$.*

(1) For all $a \in F$, $a^2 \in F$.

(2) $0, 1 \in F^+$.

(3) If $n \in \mathbf{N}$, then $n \cdot 1_F := \underbrace{1_F + 1_F + \ldots + 1_F}_{n \text{ times}}$, implying $n \cdot 1_F \in F^+$.

(4) If $x \in F^+$ and $x \neq 0$, then $x^{-1} \in F^+$.

(5) If $xy \in F^+$ and $xy \neq 0$, then $x, y \in F^+$ or $-x, -y \in F^+$.

(6) If $0 < x \leqslant y$, then $y^{-1} \leqslant x^{-1}$.

(7) If $x \leqslant y$, then $-y \leqslant -x$.

(8) If $x \geqslant 1_F$, then $x^2 \geqslant x$.

(9) If $x \leqslant 1_F$, then $x^2 \leqslant x$.

Proof. (1) If $a \in F^+$, then $a \cdot a = a^2 \in F^+$. If $-a \in F^+$, then $(-a) \cdot (-a) = a^2 \in F^+$.

(2) From part (1) we have that $0 = 0 \cdot 0 \in F^+$. Similarly, $1 = 1 \cdot 1 \in F^+$ and $(-1) \cdot (-1) \in F^+$

(3) Since F^+ is closed under addition, we can inductively show that $n \cdot 1 = 1 + 1 + \ldots + 1 \in F^+$.

(4) Suppose towards contradiction $x^{-1} \notin F^+$. Then $-(x^{-1}) \in F^+$, so $(-(x^{-1})) \cdot x = -1(x^{-1} \cdot x) = -1 \in F^+$. But $-1, 1 \in F^+$ implies $1 = 0$, a contradiction. Thus $x^{-1} \in F^+$.

(6) $y \geqslant x > 0$ implies $x, y \in F^+$. So $x^{-1}, y^{-1} \in F^+$. Then $y^{-1}xx^{-1} \leqslant y^{-1}yx^{-1}$, and simplifying yields $y^{-1} \leqslant x^{-1}$. finish the rest (i'm not going to) □

3

The Real Numbers

3.1 The Completion of $\mathbb{Q}$

Definition 3.1.1. A _Dedekind cut_ is a nonempty subset D of $\mathbf{Q}$ with the following properties:

(1) $D \neq \mathbf{Q}$;

(2) If $b \in D$, then $a \in D$ for all $a \in \mathbf{Q}$ with $a < b$;

(3) D does not contain a largest element.

Example 3.1.1. The following examples are Dedekind cuts:

(1) $\{a \in \mathbf{Q} \mid a < 3\}$ (the set of all rational numbers less than 3).

(2) $\{a \in \mathbf{Q} \mid a < 0 \text{ or } a^2 < 2\}$ (the set of all rational numbers less than $\sqrt{2}$).

(3) $\{a \in \mathbf{Q} \mid a < 1 + \frac{1}{1!} + \frac{1}{2!} + \ldots + \frac{1}{n!} \text{ for some } n \in \mathbf{Z}^+\}$ (the set of all rational numbers less than e).

Definition 3.1.2. Let C and D be Dedekind cuts.

will probably not finish this

3.2 Ordering of $\mathbb{R}$

Axiom 1. $\mathbf{R}$ _is an ordered field._

Proposition 3.2.1. $\mathbf{Q}^+ \subseteq \mathbf{R}^+$.

Proof. If $x \in \mathbf{Q}^+$, then $x = \frac{p}{q}$ with $p \in \mathbf{Z}^+$ and $q \in \mathbf{N}$. Write $p = \underbrace{1 + 1 + \ldots + 1}_{p \text{ times}}$, then $p \in \mathbf{R}^+$.

Similarly, write $q = \underbrace{1 + 1 + \ldots + 1}_{q \text{ times}}$. Then $q \in \mathbf{R}^+$, which implies that $q^{-1} \in \mathbf{R}^+$. Hence $\frac{p}{q} \in \mathbf{R}^+$, establishing $\mathbf{Q}^+ \subseteq \mathbf{R}^+$. $\qquad\square$

Proposition 3.2.2. _The maps_ $Z \xrightarrow{j} \mathbf{Q} \xrightarrow{i} \mathbf{R}$ _are order embeddings (defined in Lemma_ 2.2.3 _and Theorem_ 2.2.4_)._

Proof. Suppose $i(q_1) \leqslant_Q i(g_2)$. Then $q_1 \leqslant_\mathbf{R} q_2$, hence $q_2 - q_1 \in \mathbf{R}^+$. Now If $q_2 - q_2 \in \mathbf{Q}^+$, then $q_2 - q_1 \in \mathbf{R}^+$. Hence $q_1 \leqslant_\mathbf{R} q_2$. wtf is this saying? $\qquad\square$

Proposition 3.2.3. _Let_ $a, b \in \mathbf{R}$. _If_ $a \leqslant b$ _(or_ $a < b$_), then_ $a \leqslant \frac{1}{2}(a+b) \leqslant b$ _(or_ $a < \frac{1}{2}(a+b) < b$_)._

Proof. By the order axioms, $a \leqslant b$ implies $a + a \leqslant a + b$. So $2a \leqslant a + b$, which is equivalent to $a \leqslant \frac{1}{2}(a + b)$. Similarly, $a + b \leqslant b + b$, which similarly gives $\frac{1}{2}(a + b) \leqslant b$, establishing the proposition. $\qquad\square$

Corollary 3.2.4. *Given $b > 0$, we have $0 < \frac{1}{2}b < b$.*

Proof. From Proposition 3.2.3, setting $a = 0$ yields the desired result. $\qquad\square$

Proposition 3.2.5. *Suppose $a \in \mathbf{R}$. For all $\epsilon > 0$, if $0 \leqslant a \leqslant \epsilon$, then $a = 0$.*

Proof. If $a = 0$ we are done. If $a > 0$, by Corollary 3.2.4 $0 \leqslant \frac{1}{2}a \leqslant a$. Pick $\epsilon = \frac{1}{2}a$, then $a \leqslant \frac{1}{2}a$, a contradiction. Thus $a = 0$. $\qquad\square$

Definition 3.2.1. Let $a_1, a_2, ..., a_n > 0$. The <u>*arithmetic mean*</u> is $\frac{1}{2}\left(\sum_{j=1}^{n} a_j\right)$. The <u>*geometric mean*</u> is $\left(\prod_{j=1}^{n} a_j\right)^{\frac{1}{n}}$.

Proposition 3.2.6 (AM-GM Inequality)**.** *For all $a_1, a_2, ..., a_n \geqslant 0$, then $\left(\prod_{j=1}^{n} a_j\right)^{\frac{1}{n}} \leqslant \frac{1}{2}\left(\sum_{j=1}^{n} a_j\right)$.*

Proof. We will only prove the $n = 2$ case. Consider the fact that $(a_1 - a_2)^2 \geqslant 0$, and expanding gives $a_1^2 - 2a_1a_2 + a_2^2$. So $2a_1a_2 \leqslant a_1^2 + a_2^2$. Adding $2a_1a_2$ to both sides yields $4a_1a_2 \leqslant a_1^2 + 2a_1a_2 + a_2^2$, which is equivalent to $4a_1a_2 \leqslant (a_1 + a_2)^2$. Then simplifying yields the desired result of $(a_1a_2)^{\frac{1}{2}} \leqslant \frac{1}{2}(a_1 + a_2)$. $\qquad\square$

Proposition 3.2.7 (Bernoulli's Inequality)**.** *If $x > -1$, then $(1 + x)^n \geqslant 1 + nx$ for all $n \in \mathbf{N}_0$.*

Proof. We proceed with induction with base case $n = 0$ and $n = 1$; these hold by inspection. Assume the inequality holds true for $n = k$. For $n = k + 1$:

$$\begin{aligned}
(1 + x)^{k+1} &= (1 + x)^k(1 + x) \\
&\geqslant (1 + nx)(1 + x)^{[1]} \\
&= 1 + (n + 1)x + nx^2 \\
&\geqslant 1 + (n + 1)x.
\end{aligned}$$

$\qquad\square$

Proposition 3.2.8 (Cauchy-Schwartz Inequality)**.** *Let $a_1, ..., a_n$, $b_1, ..., b_n \in \mathbf{R}^n$. Then:*

$$\left|\sum_{j=1}^{n} a_j b_j\right| \leqslant \left(\sum_{j=1}^{n} a_j^2\right)^{\frac{1}{2}} \left(\sum_{j=1}^{n} b_j^2\right)^{\frac{1}{2}}.$$

---

[1]Because order is preserved under multiplication by positive elements.

Proof. Consider the map $F : \mathbb{R}^n \to \mathbb{R}^n$ defined by $F(t) = \sum_{j=1}^{n}(a_j - b_j t)^2$. Note that $\sum_{j=1}^{n}(a_j - b_j t)^2 \geqslant 0$. Observe that:

$$\sum_{j=1}^{n}(a_j - b_j t)^2 = \sum_{j=1}^{n}(a_j^2 - 2a_j b_j t + b_j^2 t^2)$$

$$= \sum_{j=1}^{n} a_j^2 - \sum_{j=1}^{n} 2a_j b_j t + \sum_{j=1}^{n} b_j^2 t^2.$$

This is a quadratic equation, and since $F(t) \geqslant 0$, the discriminant will be less than or equal to 0. Hence:

$$\Delta = \left(\sum_{j=1}^{n} 2a_j b_j\right)^2 - 4\left(\sum_{j=1}^{n} b_j^2\right)\left(\sum_{j=1}^{n} a_j^2\right) \leqslant 0.$$

Simplifying gives:

$$\left(\sum_{j=1}^{n} 2a_j b_j\right)^2 \leqslant 4\left(\sum_{j=1}^{n} b_j^2\right)\left(\sum_{j=1}^{n} a_j^2\right).$$

Pulling 2 out from the left-hand side, dividing both sides by 4, and then square-rooting gives the desired result. $\qquad\square$

Question. When do we have equality?

Answer. When $\Delta = 0$, there exists a $t_0 \in \mathbb{R}$ with $F(t_0) = 0$. So $\sum_{j=1}^{n}(a_j - b_j t_0) = 0$ implies $a_j - b_j t_0 = 0$ for all j. Hence there is equality only when $a_j = b_j t_0$ for all j.

Proposition 3.2.9 (Triangle Inequality). *Let $a_1, ..., a_n, b_1, ..., b_n \in \mathbb{R}^n$. Then:*

$$\left(\sum_{j=1}^{n}(a_j + b_j)^2\right)^{\frac{1}{2}} \leqslant \left(\sum_{j=1}^{n} a_j^2\right)^{\frac{1}{2}} + \left(\sum_{j=1}^{n} b_j^2\right)^{\frac{1}{2}}.$$

Proof. Observe that:

$$\sum_{j=1}^{n}(a_j + b_j)^2 = \sum_{j=1}^{n}(a_j^2 + 2a_j b_j + b_j^2)$$

$$= \sum_{j=1}^{n} a_j^2 + \sum_{j=1}^{n} 2a_j b_j + \sum_{j=1}^{n} b_j^2$$

$$\leqslant \sum_{j=1}^{n} a_j^2 + 2\left(\sum_{j=1}^{n} a_j^2\right)^{\frac{1}{2}}\left(\sum_{j=1}^{n} b_j^2\right)^{\frac{1}{2}} + \sum_{j=1}^{n} b_j^2.$$

$$= \left(\left(\sum_{j=1}^{n} a_j^2\right)^{\frac{1}{2}} + \left(\sum_{j=1}^{n} b_j^2\right)^{\frac{1}{2}}\right)^2.$$

Squaring both sides gives the desired result. $\qquad\square$

3.3 Metrics and Norms on $\mathbb{R}^n$

Definition 3.3.1. The _absolute value_ is a function $|\cdot| : \mathbf{R} \to \mathbf{R}$ defined by:

$$|x| = \begin{cases} x, & x \in \mathbf{R}^+ \\ -x, & -x \in \mathbf{R}^+. \end{cases}$$

Proposition 3.3.1. _Let_ $a, b \in \mathbf{R}$ _and_ $\delta > 0$.

(1) $|ab| = |a||b|$.

(2) $|a|^2 = |a^2|$.

(3) $|-a| = |a|$.

(4) $|a| \in \mathbf{R}+$.

(5) $-|a| \leqslant a \leqslant |a|$.

(6) $|a| \leqslant \delta$ _if and only if_ $-\delta \leqslant a \leqslant \delta$.

(7) $|a + b| \leqslant |a| + |b|$.

(8) $|a - b| \leqslant |a| + |b|$.

(9) $||a| - |b|| \leqslant |a - b|$.

Proof. do later □

Lemma 3.3.2. $\pm x \leqslant \delta$ _if and only if_ $|x| \leqslant \delta$.

Proof. do lter □

Lemma 3.3.3. $A \subseteq \mathbf{R}$ _is bounded if and only if there exists an_ $r > 0$ _such that_ $|a| < r$ _for all_ $a \in A$.

Proof. Suppose $A \subseteq \mathbf{R}$ is bounded. Then there exists an $l, u \in \mathbf{R}$ with $l \leqslant a \leqslant u$ for all $a \in A$. We have that:

$$-|l| \leqslant l \leqslant a \leqslant u \leqslant |u|.$$

Let $r = \max\{|l|, |u|\} \geqslant 0$. So $-r \leqslant |l| \leqslant a \leqslant |u| \leqslant r$. Thus $|a| \leqslant r$.

Conversely, suppose there exists an $r > 0$ with $|a| \leqslant r$ for all $a \in A$. Then $-r \leqslant a \leqslant r$ for all $a \in A$, hence A is bounded. □

Definition 3.3.2. A function $f : D \to \mathbf{R}$ is _bounded_ if im $(f) \subseteq \mathbf{R}$ is a bounded subset. Equivalently, there exists a $c > 0$ such that $|f(x)| < c$ for all $x \in D$.

Example 3.3.1. Consider the function $f : [3, 7] \to \mathbf{R}$ defined by $f(x) = \frac{x^2+2x+1}{x-1}$. Since $3 \leqslant x \leqslant 7$, observe that:

$$|x^2 + 2x + 1| \leqslant |x^2| + |2x| + 1$$
$$= |x|^2 + 2|x| + 1 \quad \text{Evaluate at 7}$$
$$= 64$$

Likewise, $3 \leqslant x \leqslant 7$ implies $|x - 1| \geqslant 2$, hence $\frac{1}{|x-1|} \leqslant \frac{1}{2}$. Together, we have that:

$$\left| \frac{x^2 + 2x + 1}{x - 1} \right| \leqslant \frac{64}{2} = 32.$$

Definition 3.3.3. Let $s, t \in \mathbf{R}$. We define the _distance_ between s and t as $d(s, t) = |s - t|$.

Definition 3.3.4. Let X be a nonempty set equipped with a map $d : X \times X \to \mathbf{R}^+$. We say (X, d) is a _semi-metric_ if for all $x, y, z \in X$,

(1) $d(x, y) = d(y, x)$,

(2) $d(x, z) \leqslant d(x, y) + d(y, z)$, and

(3) $d(x, x) = 0$.

We say (X, d) is a _metric space_ if it satisfies the additional axiom:

(4) $d(x, y) = 0$ implies $x = y$.

Proposition 3.3.4.

(1) $(\mathbf{R}, d_1(s, t) = |s - t|)$ _is a metric space._

(2) $\left(\mathbf{R}^n, d_1(\vec{x}, \vec{y}) = \sum_{j=1}^{n} |y_j - x_j| \right)$ _is a metric space._

(3) $\left(\mathbf{R}^n, d_\infty(\vec{x}, \vec{y}) = \max_{j=1}^{n} \{|y_j - x_j|\} \right)$ _is a metric space._

(4) $\left(\mathbf{R}^n, d_2(\vec{x}, \vec{y}) = \left(\sum_{j=1}^{n} |y_j - x_j|^2 \right)^{\frac{1}{2}} \right)$ _is a metric space._

(5) $\left(\mathbf{R}^n, d_p(\vec{x}, \vec{y}) = \left(\sum_{j=1}^{n} |y_j - x_j|^p \right)^{\frac{1}{p}} \right)$ _for some $p \in \mathbf{Q}$ is a metric space._

Proof. (1) We have $d(s, t) = |s - t| = |t - s| = d(t, s)$. Similarly, $d(s, r) = |s - r| = |s - t + t - r| \leqslant |s - t| + |t - r| = d(s, t) + d(t, r)$. Clearly $d(s, s) = |s - s| = 0$. Lastly, if $d(s, t) = 0$, then $|s - t| = 0$, which is equivalent to $s - t = 0$; i.e., $s = t$. Thus $(\mathbf{R}, d_1)$ is a metric space.

(4) Axioms 2 and 3 of metric spaces are clearly satisfied. If $d_2(\vec{x}, \vec{y}) = 0$ then $|y_j - x_j|^2 = 0$ for all j. Hence $y_j - x_j = 0$; i.e., $y_j = x_j$ for all j, establishing axiom 4. Observe that:

$$d_2(\vec{x}, \vec{z}) = \left(\sum_{j=1}^{n} |z_j - x_j|^2 \right)^{\frac{1}{2}}$$

$$= \left(\sum_{j=1}^{n} |z_j - y_j + y_j - x_j|^2 \right)^{\frac{1}{2}}$$

$$= \left(\sum_{j=1}^{n} (z_j - y_j + y_j - x_j)^2 \right)^{\frac{1}{2}}$$

$$\leqslant \left(\sum_{j=1}^{n} (z_j - y_j)^2 \right)^{\frac{1}{2}} + \left(\sum_{j=1}^{n} (y_j - x_j)^2 \right)^{\frac{1}{2}}$$

$$= \left(\sum_{j=1}^{n} |z_j - y_j|^2 \right)^{\frac{1}{2}} + \left(\sum_{j=1}^{n} |y_j - x_j|^2 \right)^{\frac{1}{2}}$$

$$= d_2(\vec{x}, \vec{y}) + d_2(\vec{y}, \vec{z}).$$

Thus $(\mathbf{R}^n, d_2)$ is a metric space. $\square$

Definition 3.3.5. Let (X, d) be a metric space.

(1) The _open ball_ centered at x_0 with radius $\delta > 0$ is $U(x_0, \delta) = \{y \in X \mid d(y, x_0) < \delta\}$.

(2) The _closed ball_ centered at x_0 with radius $\delta > 0$ is $B(x_0, \delta) = \{y \in X \mid d(y, x_0) \leqslant \delta\}$.

(3) A subset $A \subseteq X$ is called _open_ if for all $a \in A$, there exists a $\delta > 0$ such that $U(a, \delta) \subseteq A$.

(4) A subset $C \subseteq X$ is called _closed_ if $\text{compl}(C) = X \setminus C$ is open.

Example 3.3.2. Consider $X = \mathbf{R}$ and $d(s, t) = |s - t|$. Observe that:

$$U(t, \delta) = \{s \in \mathbf{R} \mid d(s, t) < \delta\}$$
$$= \{s \in \mathbf{R} \mid |s - t| < \delta\}$$
$$= \{s \in \mathbf{R} \mid -\delta < s - t < \delta\}$$
$$= \{s \in \mathbf{R} \mid -\delta + t < s < \delta + t\}$$
$$= (t - \delta, t + \delta).$$

It follows similarly that $B(t, \delta) = [t - \delta, t + \delta]$.

Proposition 3.3.5. *If I is an open interval, then I is open.*

Proof. Let $I = (a, b)$. Let $x \in I$. Let $\delta_x = \min\{x - a, b - x\} > 0$. Now let $t \in V_\delta(x)$. Then $t \in (x - \delta, x + \delta)$. Case 1: $\min\{x - a, b - x\} = x - a$. Then $x - (x - a) < t < x + x - a$, idk how to do this $\square$

4

Supremum, Infimum, and Completeness

4.1 Supremum and Infimum

Theorem 4.1.1. *Let $\emptyset \neq A \subseteq \mathbf{R}$. Let u be an upperbound for A. The following are equivalent:*

(1) $u = \sup(A)$.

(2) If $t < u$, then there exists an $a_t \in A$ with $t < a_t$.

(3) For all $\epsilon > 0$, there exists an $a_\epsilon \in A$ such that $u - \epsilon < a_\epsilon$.

Proof. $[(1) \implies (2)]$ Assume $u = \sup(A)$. Let $t < u$. Suppose towards contradiction there does not exist and $a \in A$ with $a > t$. Then $a \leqslant t$ for all $a \in A$. But this implies t is an upperbound of A less than u, which is a contradiction because u is the least upper bound. $[(2) \implies (3)]$ Given $\epsilon > 0$, let $t = u - \epsilon$. Then applying (2) gives the desired result. $[(3) \implies (1)]$ We know u is an upperbound of A, we aim to show that it is the least upperbound. Let v be an upperbound for A with $v < u$. Pick $\epsilon = u - v > 0$. By (3), there exists an $a_\epsilon \in A$ such that $u - (u - v) < a_\epsilon$. So $v < a_\epsilon$, which is a contradiction (v is an upperbound, how can it be smaller than an element of A?). $\square$

Example 4.1.1. Claim: $\sup([0, 1)) = 1$. If $s \in [0, 1)$, by definition $s < 1$, so 1 is an upper bound for $[0, 1)$. Given $t < 1$, set $\delta = 1 - t > 0$. Then $0 < \frac{\delta}{2} < \delta$ this is not trivial, have to show $\delta - \delta/2$ is positive. This gives:

$$t < t + \frac{\delta}{2} < t + \delta = 1.$$

Pick $a_t = t + \frac{\delta}{2}$. By (2) of Theorem 4.1.1, $a_t \in [0, 1)$, hence $1 = \sup([0, 1))$.

Proposition 4.1.2. *Let $A, B \subseteq \mathbf{R}$ and $a \leqslant b$ for all $a \in A$ and $b \in B$. Then $\sup(A) \leqslant \inf(B)$.*

Proof. Fix a point $b_0 \in B$. Then $a \leqslant b_0$ for all $a \in A$. Then b_0 is an upperbound for A. This gives $u := \sup(A) \leqslant b_0$. But since b_0 was arbitrary, we have $u \leqslant b$ for all $b \in B$. So u is a lower bound for B, therefore $u \leqslant \inf(B)$. $\square$

Axiom 2 (Completeness of **R**)**.** *Given any nonempty subset $A \subseteq \mathbf{R}$ which is bounded above, $\sup(A)$ exists.*

Lemma 4.1.3. *For $A \subseteq \mathbf{R}$ which is bounded below, $\sup(-A) = -\inf(A)$.*

Proof. If A is bounded below, then $-A$ is bounded above. Then $\sup(-A)$ exists, define it as u. So for all $a \in A$, $-a \leqslant u$. Hence $-u$ is a lower bound for A. Suppose v is another lower bound for A. Then $v \leqslant a$ for all $a \in A$. So $-v \geqslant -a$ for all $a \in A$. Thus $-v$ is an upper bound of $-A$. Therefore, since u is the least upper bound, $-v \geqslant u$; i.e., $-u \geqslant v$. Thus $-u = \inf(A)$. $\square$

Axiom 3 (Well-Ordering Princple)**.** *Every nonempty subset $A \subseteq \mathbf{N}$ contains a least element.*

Proposition 4.1.4 (Arcimedean Property 1)**.** *If $x \in \mathbf{R}$, then there exists $n_x \in \mathbf{N}$ with $x < n_x$.*

Proof. Suppose not. That is, suppose $n \leqslant x$ for all $n \in \mathbf{N}$. Then x is an upper bound for $\mathbf{N}$. Thus $\sup(A) := u$ exists. From part (3) of Theorem 4.1.1, take $\epsilon = 1$. Then there exists an $n \in \mathbf{N}$ such that $u - 1 < n$. So $u < n + 1 \in \mathbf{N}$, which is a contradiction. ◻

Proposition 4.1.5 (Archimedean Property 2)**.** *If $t > 0$, there exists $n_t \in \mathbf{N}$ with $\frac{1}{n_t} < t$.*

Proof. From Arcimedean Property 1, pick $x = \frac{1}{t}$. ◻

Corollary 4.1.6. *Given $t > 0$, there exists $m \in \mathbf{N}$ with $\frac{1}{2^m} < t$.*

Proof. By Archimedean Property 2 there exists an $n \in \mathbf{N}$ with $\frac{1}{n} < t$. Claim: $\frac{1}{2^n} < \frac{1}{n}$. It suffices to show that $2^n > n$. Proposition 1.4.5 gives $\mathrm{card}(\{1, 2, ..., n\}) < \mathrm{card}\left(\mathcal{P}\left(\{1, 2, ..., n\}\right)\right)$. Then Exercise 1.4.2 gives:

$$n = \mathrm{card}(\{1, 2, ..., n\}) < \mathrm{card}\left(\mathcal{P}\left(\{1, 2, ..., n\}\right)\right) = 2^n.$$

Alternatively, Bernoulli's Inequality gives $(1 + 1)^n \geqslant 1 + n$. Hence $2^n > n$. ◻

Example 4.1.2.

(1) Claim: $\inf\left\{\frac{1}{n} \mid n \in N\right\} = 0$. Note that 0 is indeed a lower bound because $0 < \frac{1}{n}$ for all $n \in \mathbf{N}$. Suppose t is another lower bound. If $t \leqslant 0$, then we are done. If $t > 0$, by the Archimedean Property there exists an $n_t \in \mathbf{N}$ such that $\frac{1}{n_t} < t$, which is a contradiction (because we asserted that t is a lower bound, and $\frac{1}{n_t} \in \inf\{\frac{1}{n} \mid n \in N\}$). Thus $\inf\left\{\frac{1}{n} \mid n \in N\right\} = 0$.

(2) Claim: $\inf\left\{\frac{1}{2^m} \mid m \in N\right\} = 0$. This follows from the above example and previous corollary.

Corollary 4.1.7. *Let $x \in \mathbf{R}$, Then there exists $n_x \in \mathbf{Z}$ with $n_x - 1 \leqslant x < n_x$.*

Proof. Case 1: $x \geqslant 0$. Let $S_x = \{n \in \mathbf{N} \mid x < n\}$. By Arcimedean Property 1 $S_x \neq 0$. By the Well-Ordering Princple, there exists a least element in this set, call it n_x. Since $n_x \in S_x$, it must be the case that $x < n_x$. But since n_x is the least element, $n_x - 1 \notin S_x$. Since S_x is the set of all natural numbers with lower bound x, $n_x - 1$ is not bounded below by x. Whence $n_x - 1 \leqslant x$.

Case 2: $x < 0$. Define $S_{-x} = \{n \in \mathbf{N} \mid n < -x\}$. As a consequence of the Well-Ordering Princple, any subset of the integers which is bounded above admits a greatest element, define it to be $n_{-x} \in \mathbf{Z}$. Then $n_{-x} + 1 \notin S_{-x}$, hence $n_{-x} < -x \leqslant n_{-x} + 1$. This establishes $-n_{-x} - 1 \leqslant x < -n_{-x}$. ◻

Definition 4.1.1. Let I be an open interval. A subset $D \subseteq \mathbf{R}$ is <u>dense</u> if $I \cap D \neq \emptyset$.

**Theorem 4.1.8.** $\mathbf{Q} \subseteq \mathbf{R}$ *is dense.*

Proof. Let I be an open interval. Then there exists $a, b \in \mathbf{R}$ with $(a, b) \subseteq I$. We have that $b - a > 0$. By Archimedean Property 2 there exists $n \in \mathbf{N}$ with $\frac{1}{n} < b - a$. So $1 + na < nb$. By Corollary 4.1.7, there exists $m \in \mathbf{Z}$ with $m - 1 \leqslant na < m$. Equivalently, we have that $a < \frac{m}{n}$. We also have that $m \leqslant na + 1 < nb$, which yields $\frac{m}{n} < b$. Thus $\frac{m}{n} \in (a, b) \cap \mathbf{Q}$.   □

Corollary 4.1.9. $\mathbf{R} \setminus \mathbf{Q} \subseteq \mathbf{R}$ *is dense.*

Proof. Let $a < b$. Consider $a' = a\sqrt{2}$ and $b' = b\sqrt{2}$. Then $a' < b'$. By Theorem 4.1.8, there exists a $q \in \mathbf{Q}$ with $a' < q < b'$. Thus $a < \frac{q}{\sqrt{2}} < b$. Since $\frac{q}{\sqrt{2}} \notin \mathbf{Q}$, the corollary is established.

Alternatively, observe the following picture:
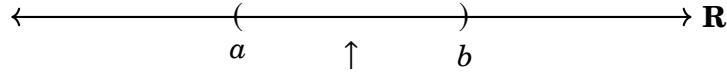
If there is not an irrational number between (a, b), then $(a, b) \subseteq \mathbf{Q}$, which is a contradiction.   □

Theorem 4.1.10. *There exists a unique positive number x with $x^2 = 2$.*

Proof. Consider the set $S = \{t \in \mathbf{R} \mid t > 0, t^2 < 2\}$. Note that $S \neq 0$ because $1 \in S$. If $t \geqslant 2$, then $t^2 \geqslant 2t > 4$, meaning it would not be an element of S. So S is bounded above by 2. Hence there exists $u := \sup(S)$.

———— / /————

Scratchwork: Assume $u^2 < 2$. Find a sufficiently small n so that $(u + \frac{1}{n})^2 \in S$; i.e., $(u + \frac{1}{n})^2 < 2$. Solving for n yields:

$$u^2 + \frac{2u}{n} + \frac{1}{n^2} < 2$$

$$\Longleftrightarrow$$

$$\frac{2u}{n} + \frac{1}{n^2} < 2 - u^2$$

$$\Longleftrightarrow$$

$$\frac{1}{n}\left(2u + \frac{1}{n}\right) < 2 - u^2$$

$$\Longleftrightarrow$$

$$\frac{1}{n}(2u + 1) < 2 - u^2$$

$$\Longleftrightarrow$$

$$\frac{1}{n} < \frac{2 - u^2}{2u + 1} \in \mathbf{R}^+ \setminus \{0\}$$

———— / /————

If $u^2 < 2$, then $\frac{2-u^2}{2u+1} > 0$. By Archimedean Property 2, there exists an $n \in \mathbf{N}$ with $\frac{1}{n} < \frac{2-u^2}{2u+1}$. Simplifying yields $(u + \frac{1}{n})^2 < 2$, or equivalently $u + \frac{1}{n} \in S$, which is a contradiction. It must be the case that $u^2 \geqslant 2$; i.e., $u^2 - 2 \geqslant 0$. Now since $u = \sup(S)$, for all $m \in \mathbf{N}$, there exists $t_m \in S$ with $u - \frac{1}{m} < t_m$. We have that $(u - \frac{1}{m})^2 < t_m^2 < 2$. This simplifies to $u^2 - 2 < \frac{2u}{m} - \frac{1}{m^2} < \frac{2u}{m}$, or equivalently $\frac{u^2-2}{2u} < \frac{1}{m}$. But if $\frac{u^2-2}{2u} < \frac{1}{m}$ for all $m \in \mathbf{N}$, it must be that $\frac{u^2-2}{2u} = 0$, hence $u^2 = 2$.

Lastly we show that u^2 is unique. Suppose $u^2 = 2 = v^2$. Since $u, v \geqslant 0$, $(u^2 - v^2) = 0$. Then $(u - v)(u + v) = 0$. If $u + v = 0$, then $u = 0$ and $v = 0$, which is a contradiction. So $u - v = 0$ implies $u = v$. $\qquad \square$

Remark. Picking 2 was completely arbitrary, we could have showed $x^2 = a$ for any $a \geqslant 0$.

Remark. Using the same argument, we have that for all $a > 0$, there exists a unique $b > 0$ with $b^2 = a$. So we have a map:

$$\mathbf{R}^+ \xrightarrow{\sqrt{}} \mathbf{R}^+,$$

where $\sqrt{x}$ is the unique positive number with $(\sqrt{x})^2 = x$.

Remark. We could have similarly defined S as:

$$S' = \{t \in \mathbf{Q} \mid t > 0, t^2 < 2\},$$

and the proof would not have changed. However, $\sup(S') = \sqrt{2} \notin \mathbf{Q}$, meaning $\mathbf{Q}$ is *not* complete.

4.2 Nested Intervals

> **Axiom 4.** *Given any interval I, if $x, y \in I$ with $x < y$, then $[x, y] \in I$.*

Theorem 4.2.1. *Let $S \subseteq \mathbf{R}$ be any subset containing at least two points. If S satisfies Axiom 4, then S is an interval.*

Proof. We proceed with cases. Case 1: S is bounded. Write $a = \inf(S)$ and $b = \sup(S)$. Therefore $S \subseteq [a, b]$. If we show $(a, b) \subseteq S$, then it follows that $S = (a, b]$, or $[a, b)$, or (a, b) or $[a, b]$. We must use that S satisfies Axiom 4 and $a = \inf(S)$ and $b = \sup(S)$. Let $x \in (a, b)$. Since $x > a$, there exists and $s_1 \in S$ with $s_1 < x$. Since $x < b$, there exists an $s_2 \in S$ with $x < s_2$. Thus $s_1, s_2 \in S$ and $s_1 < s_2$. By Axiom 4 $[s_1, s_2] \subseteq S$. But $x \in [s_1, s_2]$ implies $x \in S$. Thus $(a, b) \subseteq S$.

Case 2: S is bounded above do this.

Case 3: S is bounded below need to do. $\qquad \square$

Definition 4.2.1. A sequence of intervals $(I_n)_{n \geqslant 1}$ is said to be <u>nested</u> if $I_1 \supseteq I_2 \supseteq I_3 \supseteq \dots$.

Proposition 4.2.2. $\bigcap_{n \geqslant 1} \left[0, \frac{1}{n}\right) = \{0\}$.

Proof. Note that $0 \in \left[0, \frac{1}{n}\right)$ for all $n \geqslant 1$. So $0 \in \bigcap_{n \geqslant 1} \left[0, \frac{1}{n}\right)$. Let $a \in \bigcap_{n \geqslant 1} \left[0, \frac{1}{n}\right)$. Then $0 \leqslant a < \frac{1}{n}$ for all $n \geqslant 1$. Hence $a = 0$. $\qquad \square$

Proposition 4.2.3. $\bigcap_{n \geqslant 1} [n, \infty) = \emptyset$.

Proof. Suppose towards contradiction there exists a $t \in \bigcap_{n \geqslant 1} [n, \infty) = \emptyset$. Then $t \in [n, \infty)$ for all $n \geqslant 1$. So $t \geqslant n$ for all $n \geqslant 1$. Hence $\mathbf{N}$ is bounded above, which is a contradiction. $\qquad \square$

Theorem 4.2.4 (Nested Intervals). *Let $(I_n)_{n \geqslant 1}$ be a sequence of closed and bounded nested intervals. Then $\bigcap_{n \geqslant 1} I_n \neq \emptyset$. Furthermore, if $\inf \{length(I_n) \mid n \geqslant 1\} = 0$, then $\bigcap_{n \geqslant 1} I_n = \{\xi\}$.*

Proof. Let $I_n = [a_n, b_n]$. Note that:

$$a_1 \leqslant a_2 \leqslant a_3 \leqslant \dots$$
$$b_1 \geqslant b_2 \geqslant b_3 \geqslant \dots$$

We have that $a_1 \leqslant a_n \leqslant b_n \leqslant b_1$ for all $n \geqslant 1$. So the set $\{a_n \mid n \geqslant 1\}$ is bounded above, and similarly $\{b_n \mid n \geqslant 1\}$ is bounded below. Let

$$\xi = \sup_{n \geqslant 1} \{a_n\}$$
$$\eta = \inf_{n \geqslant 1} \{b_n\}.$$

Claim: $\xi \leqslant b_n$ for all $n \geqslant 1$. Assume towards contradiction $\xi > b_m$ for some $m \geqslant 1$. Since $\xi = \sup_{n \geqslant 1} \{a_n\}$, there exists an a_k with $b_m < a_k \leqslant \xi$. If $k \geqslant m$, then $b_m < a_k \leqslant b_k \leqslant b_m$, which is a contradiction. If $k < m$, then $a_k \leqslant a_m \leqslant b_m < a_k$, which is a contradiction.

Claim: $a_n \leqslant \xi$ for all $n \geqslant 1$. Then $\xi \leqslant \eta$ since $\sup_{n \geqslant 1} \{a_n\} = \xi$. We have $[\xi, \eta] \subseteq [a_n, b_n]$ for all $n \in \mathbf{N}$. Let $x \in [\xi, \eta]$. Then:

$$a_n \leqslant \xi \leqslant x \leqslant \eta \leqslant b_n,$$

hence $x \in [a_n, b_n]$; i.e., $[\xi, \eta] \subseteq [a_n, b_n]$ for all $n \geqslant 1$. Thus $[[\xi, \eta] \subseteq \bigcap_{n \geqslant 1}[a_n, b_n]]$. Conversely, let $t \in [a_n, b_n]$ for all $n \geqslant 1$. Then $a_n \leqslant t \leqslant b_n$. This implies t is both an upper bound for $\{a_n\}_{n \geqslant 1}$ and a lower bound for $\{a_b\}_{n \geqslant 1}$. Hence $\xi \leqslant t \leqslant eta$, implying $t \in [\xi, \eta]$. This establishes $[\xi, \eta] = \bigcap_{n \geqslant 1}[a_n, b_n]$.

Now suppose $\inf \{\text{length}(I_n) \mid n \geqslant 1\} = 0$. Then:

$$0 = \inf_{n \geqslant 1}(b_n - a_n)$$
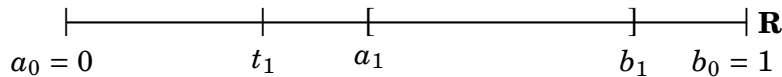$$= \inf_{n \geqslant 1} b_n - \inf_{n \geqslant 1} a_n$$
$$= \eta - \xi.$$

Hence $\xi = \eta$, which establishes the theorem.

Alternatively, had we assumed $\xi \neq \eta$, then $\eta - \xi > 0$. So there exists an m such that $b_m - a_m < \eta - \xi$, which is a contradiction since $[\xi, \eta] \subseteq [a_m, b_m]$. $\square$

Corollary 4.2.5. $[0, 1]$ *is uncountable.*

Proof. By way of contradiction, suppose $[0, 1] = \{t_1, t_2, t_3, \dots\}$. Consider the following picture:

Find $[a_1, b_1] \subseteq [0, 1]$ with $t_1 \notin [a_1, b_1]$. Find $[a_2, b_2] \subseteq [a_1, b_1]$ with $t_2 \notin [a_2, b_2]$. Inductively, find $[a_n, b_n] \subseteq [a_{n-1}, b_{n-1}]$ with $t_n \notin [a_n, b_n]$. Thus $[a_n, b_n]$ is nested. Now let $\xi \in \bigcap_{n \geqslant 1}[a_n, b_n]$. Then $\xi \in [0, 1]$. But $\xi \neq t_n$ for all n, which is a contradiction. $\square$

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Sequences

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5.1   Basic Definitions and Examples

Definition 5.1.1. A *sequence* in a metric space X is a map $x : \mathbf{N} \to X$. We often write $x = (x_n)_{n \geqslant 1} = (x_1, x_2, x_3, \ldots)$, where $x_n = x(n)$. If $X = \mathbf{R}$, we call x a *real sequence*.

Example 5.1.1 (Sequences Defined Explictly).

(1) A constant sequence: $x_n = t$, $(x_n)_{n \geqslant 1} = (t, t, t, t, \ldots)$.

(2) Sequences defined by a function: $d_n = (1 + \frac{1}{n})^n$.

(3) Geometric sequences[1]: fix $b \in \mathbf{R}$, $x_n = b^n$. Then $(x_n)_{n \geqslant 1} = (1, b, b^2, b^3, \ldots)$.

Example 5.1.2 (Sequences Defined Recursively).

(1) Let $a_1 = 1$, $a_{n+1} = 2a_n + 1$. Then $(a_n)_{n \geqslant 1} = (1, 3, 7, 15, \ldots)$.

(2) Let $f_1 = 1$, $f_2 = 1$, $f_{n+1} = f_n + f_{n-1}$. Then $(f_n)_{n=1}^{\infty} = (1, 1, 2, 3, 5, 8, \ldots)$. This is the *Fibonacci sequence*.

(3) Let X be a metric space and $f : X \to X$ be an endomorphism. Fix $x_0 \in X$. Then define:

$$x_1 = f(x_0)$$
$$x_2 = f(x_1)$$
$$\vdots$$
$$x_n = f(x_{n-1}).$$

Example 5.1.3 (New Sequences from Old).

(1) Let $(a_n)_{n \geqslant 1}$ and $(b_n)_{n \geqslant 1}$ be sequences. Then define:

$$(a_n)_{n \geqslant 1} \pm (b_n)_{n \geqslant 1} = (a_n + b_n)_{n \geqslant 1},$$
$$t(a_n)_{n \geqslant 1} = (ta_n)_{n \geqslant 1},$$
$$(a_n)_{n \geqslant 1} \cdot (b_n)_{n \geqslant 1} = (a_n \cdot b_n)_{n \geqslant 1}.$$

If $(b_n)_{n \geqslant 1} \neq 0$ for all n, then:

$$\frac{(a_n)_{n \geqslant 1}}{(b_n)_{n \geqslant 1}} = \left(\frac{a_b}{b_n} \right)_{n \geqslant 1}.$$

---

[1]These are called geometric because the ratio between each x_n is constant: $x_{n+1}/x_n = b^{n+1}/b^n = b$.

(2) Given $(x_n)_{n \geqslant 1}$ and $k \in \mathbf{N}$, consider $(x_{n+k})_{n=0}^{\infty} = (x_k, x_{k+1}, x_{k+1}, \ldots)$. This is called a *shift* or the kth *tail* of $(x_n)_{n \geqslant 1}$.

(3) If $(a_n)_{n \geqslant 1}$ is a sequence, $a_n \neq 0$ for all n, consider:

$$r_n = \frac{a_{n+1}}{a_n}.$$

So $(r_n)_{n \geqslant 1} = \left(\frac{a_2}{a_1}, \frac{a_3}{a_2}, \frac{a_4}{a_3}, \ldots \right)$. These are called sequences of *ratios*.

(4) Given a real sequence $(x_k)_{k=1}^{\infty}$, consider the sequence $(s_n)_{n=1}^{\infty}$ where:

$$s_1 = x_1$$
$$s_2 = x_1 + x_2 = s_1 + x_2$$
$$s_3 = x_1 + x_2 + x_3 = s_2 + x_3$$
$$\vdots$$
$$s_n = \sum_{k=1}^{n} x_k = s_{n-1} + x_k.$$

We call these n^{th} *partial sums*. An example of these are geometric sequences and telescoping sequences.

5.2   Convergence

Definition 5.2.1. Let $(x_n)_{n \geqslant 1}$ be a sequence.

(1) x_n is *increasing* if $x_1 \leqslant x_2 \leqslant x_3 \leqslant \ldots$

(2) x_n is *decreasing* if $x_1 \geqslant x_2 \geqslant x_3 \geqslant \ldots$

(3) x_n is *strictly increasing* if $x_1 < x_2 < x_3 < \ldots$

(4) x_n is *strictly decreasing* if $x_1 > x_2 > x_3 > \ldots$

Note 1. A sequence is said to *eventually* have a certain property, if it does not have the said property across all its ordered instances, but will after some instances have passed.

Note 2. x_n is *monotone* if it is either increasing or decreasing, strictly increasing, or strictly decreasing.

Definition 5.2.2. A sequence $(x_n)_n$ in a metric space X *converges* to $x \in X$ if:

$$(\forall \epsilon > 0)(\exists N_\epsilon \in \mathbf{N}) \text{ s.t. } n \geqslant N_\epsilon \implies d(x_n, x) < \epsilon.\text{[2]}$$

If no such x exists, the sequence is *divergent*. If $(x_n)_n$ converges to x, we write $(x_n)_n \xrightarrow{n \to \infty} x$ or $\lim_{n \to \infty} x_n = x$.

---

[2]I try not to use first-order logic symbols but this will be one of the few exceptions.

Example 5.2.1. Let $X = \mathbf{R}$. Then from the above definition, write $d(x_n, x) = |x_n - x|$. Recall that this is equivalent to $x_n \in V_\epsilon(x)$. We can visually represent convergence as follows:
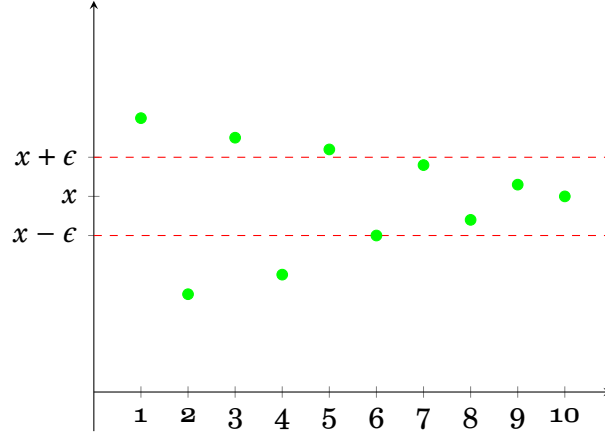
If the sequence is convergent it will eventually be contained between the two dashed lines.

Example 5.2.2. Prove $\left(\frac{1}{n}\right)_{n \geqslant 1} \to 0$.

Solution. Let $\epsilon > 0$ be given. Find N_ϵ large so $\frac{1}{N_\epsilon} < \epsilon$ (Archimedean Property 2). So if $n \geqslant N_\epsilon$, then $\frac{1}{n} \leqslant \frac{1}{N_\epsilon}$, implying that:

$$\left|\frac{1}{n} - 0\right| = \frac{1}{n} \leqslant \frac{1}{N_\epsilon} < \epsilon.$$

Example 5.2.3. Prove $\left(\frac{5n-1}{3-n}\right)_{n=4}^{\infty} \to -5$.

Solution. Note that:

$$
\begin{aligned}
|x_n - x| &= \left|\frac{5n - 1}{3 - n} - (-5)\right| \\
&= \frac{14}{|3 - n|} \\
&= \frac{14}{n - 3}.
\end{aligned}
$$

So given $\epsilon > 0$, we want $\frac{14}{n-3} < \epsilon$, provided n is big enough. This means $\frac{14}{\epsilon} + 3 < n$. We can now start the proof.

Given $\epsilon > 0$, find N_ϵ such that $N_\epsilon > \frac{14}{\epsilon} + 3$ (Arcimedean Property 1). Now, if $n \geqslant N_\epsilon$, then $n > \frac{14}{\epsilon} + 3$ implies $n - 3 > \frac{14}{\epsilon}$. Hence:

$$\frac{14}{n - 3} = |x_n - x| < \epsilon.$$

Lemma 5.2.1. *Let (X, d) be a metric space. Then $(x_n)_n \to x$ if and only if $(d(x_n, x))_n \to 0$.*

Proof. Suppose $(x_n)_n \to x$. Let $\epsilon > 0$. Find $N_\epsilon \in \mathbf{N}$ such that $n \geqslant N_\epsilon$ implies $d(x_n, x) \leqslant \epsilon$. This is equivalent to $|d(x_n, x) - 0| \leqslant \epsilon$. The converse follows identically. $\square$

Lemma 5.2.2. *If $(t_n)_n$ is a real sequence, then $(t_n)_n \to 0$ if and only if $(|t_n|)_n \to 0$.*

Proof. need to do $\square$

Lemma 5.2.3. *Let (X, d) be a metric space and $(x_n)_n$ a sequence in (X, d). If $d(x_n, x) \leqslant c\epsilon_n$, where c is a constant and $(\epsilon_n)_n \to 0$ with $\epsilon_n > 0$ for all n, then $(x_n)_n \to x$.*

Proof. need to do $\square$

Example 5.2.4. Prove $\left(\frac{\sin(n^2-1)}{n^2+3} \right)_n \to 0$.

Solution. Note that:

$$\left| \frac{\sin(n^2-1)}{n^2+3} - 0 \right| = \frac{|\sin(n^2-1)|}{n^2+3} \leqslant \frac{1}{n^2+3} \leqslant \frac{1}{n^2} \leqslant \frac{1}{n}.$$

By Lemma 5.2.3, take $c = 1$ and $\epsilon_n = \frac{1}{n}$.

Example 5.2.5. Prove $\left(\frac{1}{2^n} \right)_n \to 0$.

Solution. Note that:

$$\left| \frac{1}{2^n} \right| = \frac{1}{2^n} \leqslant \frac{1}{n}.$$

Example 5.2.6. Prove $\left(\frac{1}{n} - \frac{1}{n+1} \right)_n \to 0$.

Solution. Note that:

$$\left| \frac{1}{n} - \frac{1}{n+1} \right| = \frac{1}{n} - \frac{1}{n+1} \leqslant \frac{1}{n}.$$

Lemma 5.2.4. *Let $k \geqslant 1$ be fixed. Given a sequence $(x_n)_n$ in a metric space (X, d), $(x_n)_n \to x$ if and only if $(x_{k+n})_n \to x$.*

Proof. Let $(x_n)_n \to x$. Let $\epsilon > 0$. We know there exists $N_\epsilon \in \mathbf{N}$ with $n \geqslant N_\epsilon$ implying $d(x_n, x) < \epsilon$. But if $n \geqslant N_\epsilon$, then $n + k \geqslant N_\epsilon$. Hence $d(x_{n+k}, x) < \epsilon$.

Conversely, assume that $(x_{n+k})_n \to 0$. Let $\epsilon > 0$. We know there exists $N_\epsilon \in \mathbf{N}$ such that $n \geqslant N_\epsilon$ implies $d(x_{n+k}, x) < \epsilon$. Consider $M = N_\epsilon + k$. Then $n \geqslant M$ implies $n \geqslant N_\epsilon + k$; i.e., $n - k \geqslant N_\epsilon$. Hence $d(x_{(n-k)+k}, x) = d(x_n, x) < \epsilon$. $\square$

Proposition 5.2.5. *Suppose $(x_n)_n$ is a real sequence with $\left(\left| \frac{x_{n+1}}{x_n} \right| \right)_n \to L < 1$. Then $(x_n)_n \to 0$.*

Proof. Since $L < 1$, let ρ be any number satisfying $L < \rho < 1$. Set $\epsilon = \rho - L$. Since $\left(\left| \frac{x_{n+1}}{x_n} \right| \right)_n \to L$, we know there exists $N_\epsilon \in \mathbf{N}$ such that $n \geqslant N_\epsilon$ implies $\left| \frac{x_{n+1}}{x_n} \right| < \rho$, or equivalently $|x_{n+1}| < \rho|x_n|$. Now observe that:

$$|x_{N+1}| < \rho|x_N|$$
$$|x_{N+2}| < \rho|x_{N+1}| < \rho \cdot \rho|x_N| = \rho^2|x_N|$$
$$\vdots$$

Inductively, $|x_{N+n}| < \rho^n |x_N|$ for $n \in \mathbf{N}$. But note that $|x_{N+n}| = |x_{N+n} - 0|$ is a tail of $(x_n)_n$. So by taking $\epsilon_n = \rho^n$ and $c = |x_N|$, Lemma 5.2.3 gives $(x_n)_n \to 0$. $\qquad\square$

Note 3. The negation of Definition 5.2.2 is:

$$(\exists \epsilon_0 > 0)(\forall N_\epsilon \in \mathbf{N}) \text{ s.t. } \exists n \geqslant N_\epsilon \implies d(x_n, x) \geqslant \epsilon_0.$$

Example 5.2.7. Prove $((-1)^n)_n$ is divergent.

Solution. Suppose $((-1)^n)_n \to x$. Let $\epsilon_0 = \max\{|x-1|, |x+1|\} > 0$. Let $N \in \mathbf{N}$. Set $n = 2N$. Then:

$$(-1)^{2N} = 1$$
$$(-1)^{2N+1} = -1$$

Hence $d((-1)^{2N}, x) = |x - 1| \geqslant \epsilon_0$ or $d((-1)^{2N+1}, x) = |x + 1| \geqslant \epsilon_0$.

Exercise 5.2.1. *Prove $(\sin(n))_n$ is divergent.*

Proposition 5.2.6. *Let (X, d) be a metric space. A sequence $(x_n)_n$ can have at most one limit.*

Proof. Suppose $(x_n)_n \to L_1$ and $(x_n)_n \to L_2$ with $L_1 \neq L_2$. Set $\delta = \frac{|L_1 - L_2|}{2}$. Then $V_\delta(L_1) \cap V_\delta(L_2) = \emptyset$. Since $(x_n)_n \to L_1$, there exists $N_1 \in \mathbf{N}$ such that $n \geqslant N_1$ implies $x_n \in V_\delta(L_1)$. Similarly, since $(x_n)_n \to L_2$, there exists $N_2 \in \mathbf{N}$ such that $n \geqslant N_2$ implies $x_n \in V_\delta(L_2)$. Pick $N = \max\{N_1, N_2\}$. Then $x_N \in V_\delta(L_1) \cap V_\delta(L_2)$, which is a contradiction. $\qquad\square$

Lemma 5.2.7. *If $(x_n)_n \to x$, then $(|x_n|)_n \to |x|$.*

Proof. Note that $(|x_n|)_n$ if and only if $(|x_n - x|)_n \to 0$. Since $||x_n| - |x|| \leqslant |x_n - x|$, taking $\epsilon_n = |x_n - x|$ and $c = 0$, applying Lemma 5.2.3 yields the desired result. $\qquad\square$

Question. Does the converse hold in general?

Answer. No. Consider $(x_n)_n = ((-1)^n)_n$. Then $(|x_n|)_n \to 1$, but $((-1)^n)_n$ diverges.

Lemma 5.2.8. $(a_n)_n \to 0$ *if and only if* $(|a_n|)_n \to 0$.

Proof. The forward direction follows directly from Lemma 5.2.8. If $(|a_n|)_n \to 0$, we have then that $||a_n| - 0| \leqslant |a_n - 0|$. Taking $\epsilon_n = |a_n - 0|$ and $c = 1$, applying Lemma 5.2.3 establishes the proof. $\qquad\square$

Definition 5.2.3.

(1) A sequence $(x_n)_n$ *diverges properly* to $+\infty$ if:

$$(\forall M > 0)(\exists N_M \in \mathbf{N}) \text{ s.t. } n \geqslant N_M \implies x_n \geqslant M.$$

We write $(x_n)_n \to +\infty$.

(2) A sequence $(x_n)_n$ _diverges properly_ to $-\infty$ if:

$$(\forall M < 0)(\exists N_M \in \mathbf{N}) \text{ s.t. } n \geqslant N_M \implies x_n \leqslant M.$$

We write $(x_n)_n \to -\infty$.

Example 5.2.8. Prove $(n - \sqrt{n})_n \to +\infty$.

Solution. Write $(n - \sqrt{n})_n = \left(n \left(1 - \frac{1}{\sqrt{n}} \right) \right)_n$ help.

Example 5.2.9. Prove:

$$(b^n)_{n=0}^{\infty} \to \begin{cases} 0, & |b| < 1 \\ 1, & b = 1 \\ +\infty, & b > 1 \\ \text{DNE}, & b \leqslant -1 \end{cases}$$

Solution. We have proven cases $b = 0$, 1, and -1 previously.
  Case 1: $0 < b < 1$. Then $b < 1$ implies $\frac{1}{b} > 1$. Then $\frac{1}{b} = 1 + a$ for some $a > 0$. We have:

$$\left(\frac{1}{b} \right)^n = (1 + a)^n \geqslant 1 + na. \qquad \text{\color{green}(Bernoulli's Inequality)}$$

Hence:

$$|b^n - 0| \leqslant \frac{1}{1 + na} \leqslant \frac{1}{na} = \frac{1}{a} \left(\frac{1}{n} \right).$$

Take $\epsilon_n = \frac{1}{n}$ and $c = \frac{1}{a}$, then Lemma 5.2.3 establishes our claim.
  Case 2: $-1 < b < 0$. Since $(|b^n|)_n = (|b|^n)_n \to 0$ by above, Lemma 5.2.8 gives that $(b^n)_n \to 0$.
  Case 3: $b > 1$. Then $b = 1 + a$ for some $a > 0$. Then:

$$b^n = (a + 1)^n \geqslant 1 + na \geqslant na. \qquad \text{\color{green}(Bernoulli's Inequality)}$$

Given $M > 0$, let $N_M = \frac{[M]}{a}$. This implies that $N_M \geqslant \frac{M}{a}$. Now if $n \geqslant N_M$, then $n \geqslant \frac{M}{a}$, which is equivalent to $na \geqslant M$. Hence $b^n \geqslant M$, establishing $(b^n)_n \to +\infty$.
  Case 4: $b < 1$. If $(b^n)_n \to L$ for some $L \in \mathbf{R}$, then $(|b^n|)_n \to |L|$. So $(|b|^n)_n \to |L|$, which contradicts the $b > 1$ case. Now if $(b^n)_n \to +\infty$, then there exists $N_1 \in \mathbf{N}$ such that $n \geqslant N_1$ implies $b^n \geqslant 1$. However, for n odd, $b^n < 0$, which is a contradiction. Assuming $(b^n)_n \to -\infty$ leads to a similar contradiction.

Example 5.2.10. Prove that if $c > 0$, then $(c^{\frac{1}{n}})_n \to 1$.

Solution. If $c = 1$ then idk. Let $c > 1$. Then $c^{\frac{1}{n}} > 1$. Write $c^{\frac{1}{n}} = 1 + a_n$ where $a_n > 0$ for all $n \in \mathbf{N}$. So:

$$c = (c^{\frac{1}{n}})^n = (1 + a_n)^n \geqslant 1 + na_n > na_n. \qquad \text{\color{green}(Bernoulli's Inequality)}$$

Thus $0 < a_n < \frac{c}{n}$. We have:

$$\left| c^{\frac{1}{n}} - 1 \right| = a_n < \frac{c}{n}.$$

Take $\epsilon_n = \frac{1}{n}$. Since c is constant, Lemma 5.2.3 gives $(c^{\frac{1}{n}})_n \to 1$.

Now let $0 < c < 1$ dont know!.

Lemma 5.2.9. *If $(x_n)_n \to x \in \mathbf{R}$ with $x_n \geq 0$, then $x \geq 0$ and $(\sqrt{x_n})_n \to \sqrt{x}$.*

Proof. If $x < 0$, set $\epsilon = \frac{-x}{2} > 0$. For n sufficiently large, $x_n \in V_\epsilon(x) \subseteq (-\infty, 0)$, which is contradiction. Hence $x \geq 0$. Now observe that:

$$|\sqrt{x_n} - \sqrt{x}| \leq |\sqrt{x_n} - \sqrt{x}||\sqrt{x_n} + \sqrt{x}| = |x_n - x| < \epsilon.$$

$\square$

Example 5.2.11. Prove $(n^{\frac{1}{n}})_n \to 1$.

Solution. Recall that:

$$(x + y)^n = \sum_{k=0}^{n} \binom{n}{k} x^{n-k} y^k.$$

Note that $n^{\frac{1}{n}} > 1$ for all $n > 1$. Write $n^{\frac{1}{n}} = 1 + a_n$. Then:

$$n = (1 + a_n)^n = \sum_{k=0}^{n} \binom{n}{k} a_n^k \geq \binom{n}{0} + \binom{n}{2} a_n^2 = 1 + \frac{n(n-1)}{2} a_n^2.$$

We have:

$$n - 1 \geq \frac{n(n-1)}{2} a_n^2,$$

which simplifies to:

$$\frac{2}{n} \geq a_n^2.$$

Hence $a_n \leq \sqrt{2} \, \frac{1}{n}$, thus by our lemma $(a_n)_n^{\infty} \to 0$. Therefore:

$$|n^{\frac{1}{n}} - 1| = d_n,$$

establishing that $(n^{\frac{1}{n}})_n \to 1$.

Proposition 5.2.10. *A convergent sequence is bounded.*

Proof. Suppose $(x_n)_n \to x$. Since $(x_n)_n$ is convergent, we know for all $\epsilon > 0$ that $|x_n - x| < \epsilon$. Pick $\epsilon = 1$ and consider the following diagram:

Eventually the entire sequence will be contained in $V_1(x)$. More formally, there exists $N_1 \in \mathbf{N}$ such that $n \geqslant N_1$ implies $x_n \in V_1(x)$. Define:

$$c = \max \left\{ |x_1|, |x_n|, ..., |x_{N_1}|, |x - 1|, |x + 1| \right\}.$$

If $n \leqslant N_1$, then $|x_n| \leqslant c$. If $n \geqslant N_1$, then $x - 1 \leqslant x_n \leqslant x + 1$; i.e., $|x_n| \leqslant c$. Thus $|x_n| \leqslant c$ for all n, establishing this sequence as bounded.   □

Theorem 5.2.11. *Let x_n, y_n, z_n be convergent sequences with $(x_n)_n \to x$, $(y_n)_n \to y$, and $(z_n)_n \to z$ and $t \in \mathbf{R}$. Moreover, let $z_n \neq 0$ for all n and $z \neq 0$. We have:*

(1) $(x_n \pm y_n)_n \to x \pm y$.

(2) $(tx_n)_n \to tx$.

(3) $(x_n y_n)_n \to xy$.

(4) $\left(\frac{1}{z_n} \right)_n \to \frac{1}{z}$.

(5) $\left(\frac{x_n}{z_n} \right)_n \to \frac{x}{z}$.

Proof. (3) We have:

$$
\begin{aligned}
|x_n y_n - xy| &= |x_n y_n - xy_n + xy_n - xy| \\
&= |(x_n - x)y_n + x(y_n - y)| \\
&\leqslant |(x_n - x)y_n| + |x(y_n - y)| \\
&= |x_n - x||y_n| + |x||y_n - y|.
\end{aligned}
$$

Since y_n is convergent, it is bounded. So there exists a $c > 0$ with $|y_n| \leqslant c$ for all $n \geqslant 1$. Hence:

$$|x_n - x||y_n| + |x||y_n - y| \leqslant \underset{\to 0}{\underbrace{|x_n - x|}}\, c + |x|\, \underset{\to 0}{\underbrace{|y_n - y|}}.$$

Thus $(|x_n y_n - xy|)_n \to 0$, which implies $(x_n y_n)_n \to xy$.
   (4) We have:

$$\left| \frac{1}{z_n} - \frac{1}{z} \right| = \frac{|z - z_n|}{|z||z_n|}.$$

Since $z \neq 0$, it won't be "near" zero. We have the following picture:

Let $\delta = \frac{|z|}{2} > 0$. There exists $N \in \mathbf{N}$ such that $n \geqslant N$ implies $z_n \in V_\delta(z)$. We have:

$$z - \delta < z_n < z + \delta$$
$$\implies z - \frac{|z|}{2} < z_n$$
$$\implies \frac{|z|}{2} < |z_n|.$$

Since $|z_n| \geqslant \frac{|z|}{2}$, we have $\frac{1}{|z_n|} < \frac{2}{|z|}$. So for $n \geqslant N$,

$$\left| \frac{1}{z_n} - \frac{1}{z} \right| = \frac{|z - z_n|}{|z||z_n|} \leqslant \frac{2}{|z|^2} |z - z_n|.$$

By Lemma 5.2.3, $\left(\frac{1}{z_n} \right)_n \to \frac{1}{z}$. $\qquad\square$

Theorem 5.2.12. *Suppose* $(x_n) \to x$ *and* $(y_n)_n \to y$ *with* $x_n \leqslant y_n$ *for all n. Then* $x \leqslant y$.

Proof. We have that $(y_n - x_n)_n \to y - x$, and $y_n - x_n \geqslant 0$ for all n. Thus $y - x \geqslant 0$. $\qquad\square$

Corollary 5.2.13. *If* $(x_n)_n \to x$ *and* $a \leqslant x_n \leqslant b$, *then* $a \leqslant x \leqslant b$.

Proof. From Theorem 5.2.12, taking $(y_n)_n = (a, a, a, \ldots)$ and $(y_n)_n = (b, b, b, \ldots)$ gives the desired result. $\qquad\square$

Theorem 5.2.14 (Squeeze Theorem)**.** *Let* $(x_n)_n$, $(y_n)_n$, *and* $(z_n)_n$ *be sequences with* $(x_n)_n \leqslant (y_n)_n \leqslant (z_n)_n$ *for all* $n \geqslant 1$. *If* $\lim x_n = \lim z_n = L$, *then* $(y_n)_n \to L$.

Proof. Let $\epsilon > 0$. There exists $N_1 \in \mathbf{N}$ such that $n \geqslant N_1$ implies $x_n \in V_\epsilon(L)$. Likewise, there exists $N_2 \in \mathbf{N}$ such that $n \geqslant N_2$ implies $z_n \in V_\epsilon(L)$. So for $n \geqslant \max\{N_1, N_2\} := N$, both $x_n, z_n \in V_\epsilon(L)$. We have:

$$L - \epsilon < x_n \leqslant y_n < z_n \leqslant L + \epsilon.$$

Thus $y_n \in V_\epsilon(L)$ for $n \geqslant N$. $\qquad\square$