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Orderings and Functions

1.1 Basic Notation

Definition 1.1.1.

- (1) The natural numbers are defined as $\mathbf{N} = \{1, 2, 3, \dots\}$,
- (2) The positive integers are defined as $\mathbf{N}_0 = \mathbf{Z}^+ = \{0, 1, 2, 3, \dots\}$,
- (3) The integers are defined as $\mathbf{Z} = \{0, \pm 1, \pm 2, \pm 3, \dots\}$,
- (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 $a \leq_R b$. If A is an ordered set we write it as the ordered pair (A, \leq_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 \leq_a is defined as follows: $m \leq_a n$ 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 $m \leq_d n$ 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 $A \leq_{\mathcal{P}(S)} B$ 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 $\frac{a}{b} \leq_a \frac{c}{d}$ if and only if $ad \leq_a bc$ (in \mathbf{Z}).

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

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

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

- (1) A is called bounded above if there exists an element $u \in X$ with $a \leq u$ 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 $v \leq a$ 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 $\mathcal{L}_A = \{v \in X \mid v \text{ is a lowerbound of } A\}$. If g is the greatest element of \mathcal{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 $a \geq m$, then $a = m$ (not necessarily unique).
- (8) A minimal element of A is an element $n \in A$ such that if $a \leq n$, then $a = n$ (not necessarily unique).
- (9) If (A, \leq) is a total ordering, then A is called a chain.

Proposition 1.2.1. Let (X, \leq) 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 $u \leq u'$ and $u' \leq u$. 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, $\mathcal{L}_A \subseteq X$. By definition the greatest element of \mathcal{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). \square

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 (\mathbb{N}, \leq_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 $\text{lcm}(4, 7, 12, 28, 35)$.
- 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, \leq) 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, \leq) be an ordered set. Then (X, \leq) 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 $\text{im}(f)$).
- (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 $\text{Graph}(f) = \{(x, f(x)) \mid x \in X\} \subseteq X \times Y$.

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

Example 1.3.1. Let X be a set.

- (1) The *identity map* $\text{id}_X : X \rightarrow X$ is defined by $\text{id}_X(x) = x$.
- (2) If $X \subseteq Y$, the *inclusion map* $\iota : X \rightarrow Y$ is defined by $\iota(x) = x$.
- (3) If $A \subseteq X$ is a set, the *characteristic function* (or *step function*) $\mathbf{1}_A : X \rightarrow \mathbf{R}$ is defined by

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

Definition 1.3.2. Given $f, g : X \rightarrow \mathbf{R}$ 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 $f : X \rightarrow Y$ and $g : Y \rightarrow Z$ be maps between sets. The composition of f and g is denoted $g \circ f : X \rightarrow Z$.

$$\begin{array}{ccccc} X & \xrightarrow{f} & Y & \xrightarrow{g} & Z \\ & \searrow & & \nearrow & \\ & & g \circ f & & \end{array}$$

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

- (1) f is left-invertible if there exists a map $g : Y \rightarrow X$ with $g \circ f = \text{id}_X$.
- (2) f is right-invertible if there exists a map $h : Y \rightarrow X$ with $f \circ h = \text{id}_Y$.
- (3) f is invertible if there exists a map $k : Y \rightarrow X$ with $k \circ f = \text{id}_X$ and $f \circ k = \text{id}_Y$.

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

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

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

Suppose that s has a right inverse, that is, there exists a function $h : \mathbf{N} \rightarrow \mathbf{N}$ such that $s \circ h = \text{id}_{\mathbf{N}}$. 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 $f : X \rightarrow Y$ 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 $h, g : Y \rightarrow X$ 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. □

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

- (1) f is injective if $f(x_1) = f(x_2)$ implies $x_1 = x_2$,
- (2) f is surjective if $\text{im}(f) = Y$, and
- (3) f is bijjective if it is injective and surjective.

Proposition 1.3.2. *Let $f : X \rightarrow Y$ 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 $f : X \rightarrow Y$ is injective. Define $g : Y \rightarrow X$ 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 $f : X \rightarrow Y$ is onto. Note that the preimage of f is nonempty, so we can define $h : Y \rightarrow X$ by $h(y) = x_y$, where $x_y \in f^{-1}(y)$. By our construction $(f \circ h)(y) = f(x_y) = y$ for all $y \in Y$.

(3) **Do this yourself its easy!** □

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

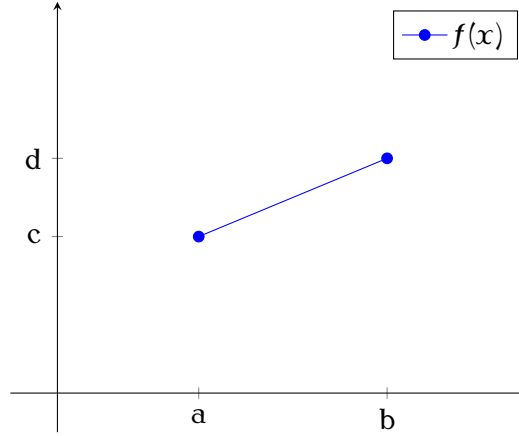
Proof. If $f : A \rightarrow B$ is injective, then f is left invertible, that is, there exists a function $g : B \rightarrow A$ with $g \circ f = \text{id}_A$. But this means g is right invertible, so g is onto. The other direction follows identically. □

1.4 Cardinality

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

Example 1.4.1.

- (1) Define $f : \mathbb{N}_0 \rightarrow \mathbb{N}$ by $f(n) = n + 1$. This is a bijection, hence $\text{card}(\mathbb{N}_0) = \text{card}(\mathbb{N})$.
- (2) Let $[a, b]$ and $[c, d]$ be intervals with $a < b$ and $c < d$. Define $f : [a, b] \rightarrow [c, d]$ by $f(x) = \left(\frac{d-c}{b-a}\right)(x - a) + c$.



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 $\tan : (-\frac{\pi}{2}, \frac{\pi}{2}) \rightarrow \mathbb{R}$ is a bijection. Consider the maps $(0, 1) \xrightarrow{g} (-\frac{\pi}{2}, \frac{\pi}{2}) \xrightarrow{\tan} \mathbb{R}$. Since g and \tan are bijective, $\tan \circ g$ is bijective, hence $\text{card}((0, 1)) = \text{card}(\mathbb{R})$.

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

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

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

Proposition 1.4.2. \mathbb{N} is infinite.

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

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

Proof. Let $\pi : \mathbf{N} \rightarrow A$ 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 $\mathbf{N} \hookrightarrow A$. \square

Example 1.4.2.

- (1) Define $k : \mathbf{Z} \rightarrow \mathbf{N}$ by $k(n) = (-1)^{n-1} \lfloor \frac{n}{2} \rfloor$. This is a bijection, hence $\text{card}(\mathbf{Z}) = \text{card}(\mathbf{N})$.
- (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 $2^X = \{f \mid f : X \rightarrow \{0, 1\}\}$. Let $A \subseteq X$. Define $\varphi : \mathcal{P}(X) \rightarrow 2^X$ by $\varphi(A) = \mathbf{1}_A$, where $\mathbf{1}_A$ is the *characteristic 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 $\text{card}(\mathcal{P}(X)) = \text{card}(2^X)$.

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

Proof. **do this** \square

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

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

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

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

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

$$\begin{aligned} r(1) &= 0.\sigma_1(1)\sigma_2(1)\sigma_3(1)\sigma_4(1)\dots \\ r(2) &= 0.\sigma_1(2)\sigma_2(2)\sigma_3(2)\sigma_4(2)\dots \\ r(3) &= 0.\sigma_1(3)\sigma_2(3)\sigma_3(3)\sigma_4(3)\dots \\ r(4) &= 0.\sigma_1(4)\sigma_2(4)\sigma_3(4)\sigma_4(4)\dots \\ &\vdots \\ r(n) &= 0.\sigma_1(n)\sigma_2(n)\sigma_3(n)\sigma_4(n) \dots \sigma_n(n). \end{aligned}$$

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

$$\begin{aligned} r(m) &= 0.\sigma_1(m)\sigma_2(m)\sigma_3(m)\dots\sigma_m(m)\dots \\ &= 0.\tau(1)\tau(2)\tau(3)\dots\tau(m)\dots \end{aligned}$$

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 $\mathbf{N} \xrightarrow{r} (0, 1)$. \square

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

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

Definition 1.4.3. Let A and B be sets.

- (1) We write $\text{card}(A) \leq \text{card}(B)$ if there exists an injection $A \hookrightarrow B$.
- (2) We write $\text{card}(A) < \text{card}(B)$ if $\text{card}(A) \leq \text{card}(B)$ and $\text{card}(A) \neq \text{card}(B)$

Example 1.4.3.

- (1) If $A \subseteq B$, then the inclusion map $\iota : A \rightarrow B$ gives $\text{card}(A) \leq \text{card}(B)$.
- (2) If $m > n$, then $\text{card}\{1, \dots, n\} < \text{card}\{1, \dots, m\}$

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

Proof. Define $f : A \rightarrow \mathcal{P}(A)$ by $a \mapsto \{a\}$. This is clearly an injective map. Now suppose towards contradiction that there exists a surjection $g : A \rightarrow \mathcal{P}(A)$ 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 $x \in g(x)$. 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 $A \rightarrow \mathcal{P}(A)$. Hence $\text{card}(A) < \text{card}(\mathcal{P}(A))$. \square

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

- (1) $\text{card}(A) \leq \text{card}(B)$;
- (2) there exists an injection $A \hookrightarrow B$;
- (3) there exists a surjection $B \twoheadrightarrow A$.

Example 1.4.4.

- (1) Define $\mathbf{N} \times \mathbf{Z} \rightarrow \mathbf{Q}$ by $(n, m) \mapsto \frac{m}{n}$. This is surjective, so $\text{card}(\mathbf{Q}) \leq \text{card}(\mathbf{N} \times \mathbf{Z})$.
- (2) Define $\mathbf{N} \times \mathbf{N} \rightarrow \mathbf{N}$ by $(m, n) \mapsto 2^m \cdot 3^n$. Then g is injective by the fundamental theorem of arithmetic. So $\text{card}(\mathbf{N} \times \mathbf{N}) \leq \text{card}(\mathbf{N})$.
- (3) Recall from Example 1.4.2 that $k : \mathbf{N} \rightarrow \mathbf{Z}$ defined by $k(n) = (-1)^{n-1} \lfloor \frac{n}{2} \rfloor$ is a bijection. Define $K : \mathbf{Z} \times \mathbf{N} \rightarrow \mathbf{N} \times \mathbf{N}$ by $(m, n) \mapsto (k^{-1}(m), n)$. This is a bijection, so $\text{card}(\mathbf{Z} \times \mathbf{N}) = \text{card}(\mathbf{N} \times \mathbf{N})$.
- (4) From the previous examples, we've established that:

$$\text{card}(\mathbf{N}) \leq \text{card}(\mathbf{Q}) \leq \text{card}(\mathbf{Z} \times \mathbf{N}) = \text{card}(\mathbf{N} \times \mathbf{N}) \leq \text{card}(\mathbf{N})$$

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

- (1) $\text{card}(A) \leq \text{card}(A)$ (reflexive).
- (2) If $\text{card}(A) \leq \text{card}(B) \leq \text{card}(C)$, then $\text{card}(A) \leq \text{card}(C)$ (transitive).
- (3) If $\text{card}(A) \leq \text{card}(B)$ and $\text{card}(B) \leq \text{card}(A)$, then $\text{card}(A) = \text{card}(B)$ (antisymmetric).
- (4) Either $\text{card}(A) \leq \text{card}(B)$ or $\text{card}(B) \leq \text{card}(A)$ (total).

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

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

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

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

(4) Let $A \rightarrow B$ 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: $(D, f) \leq_{\mathcal{F}} (E, g)$ 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:

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

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

Corollary 1.4.8. $\text{card}(\mathbb{Q}) = \text{card}(\mathbb{N})$.

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

Definition 1.4.4. A set A is countable if $\text{card}(A) \leq \text{card}(\mathbb{N})$. Equivalently, there exists an injection $A \hookrightarrow \mathbb{N}$ and a surjection $\mathbb{N} \twoheadrightarrow A$. 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, $\text{card}(\mathbf{N}) \leq \text{card}(A)$, and by definition (since A is countable), $\text{card}(A) \leq \text{card}(\mathbf{N})$. So by Theorem 1.4.7, $\text{card}(A) = \text{card}(\mathbf{N}) = \aleph_0$. \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 $\pi_i : \mathbf{N} \rightarrow A_i$. Define $\pi : \mathbf{N} \times \mathbf{N} \rightarrow \bigcup_{i=1}^{\infty} A_i$ 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 $\text{card}(\bigcup_{i=1}^{\infty} A_i) \leq \text{card}(\mathbf{N} \times \mathbf{N}) = \text{card}(\mathbf{N})$. \square

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

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 $\varphi : 2^{\mathbf{N}} \rightarrow [0, 1]$ defined by $\varphi(f) = \sum_{k=1}^{\infty} \frac{f(k)}{2^k}$. Letting $f(k) = \sigma_k$ gives φ is surjective. \square

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

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

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

Proof. Consider the map $\lambda : 2^{\mathbf{N}} \rightarrow [0, 1]$ 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:

$$\begin{aligned} f(1) &= g(1) \\ f(2) &= g(2) \\ &\vdots \\ f(k_0 - 1) &= g(k_0 - 1) \\ f(k_0) &\neq g(k_0). \end{aligned}$$

Let:

$$\begin{aligned}
 t_1 &= \sum_{k > k_0} \frac{f(k)}{3^k} && \text{sum past } k_0 \\
 t_2 &= \sum_{k > k_0} \frac{g(k)}{3^k} && \text{sum past } k_0 \\
 s_1 &= \sum_{k=1}^{k_0-1} \frac{f(k)}{3^k} && \text{sum before } k_0 \\
 s_2 &= \sum_{k=1}^{k_0-1} \frac{g(k)}{3^k} && \text{sum before } k_0
 \end{aligned}$$

We have that:

$$\begin{aligned}
 \lambda(f) &= s_1 + \frac{f(k_0)}{3^{k_0}} + t_1 \\
 \lambda(g) &= s_2 + \frac{g(k_0)}{3^{k_0}} + t_2
 \end{aligned}$$

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:

$$\begin{aligned}
 |t_2 - t_1| &= \left| \sum_{k > k_0} \frac{g(k) - f(k)}{3^k} \right| \\
 &\leq \sum_{k > k_0} \frac{|g(k) - f(k)|}{3^k} && \text{By triangle inequality} \\
 &\leq \sum_{k > k_0} \frac{1}{3^k} && \text{By comparison test} \\
 &= \frac{1}{3^{k_0+1}} \sum_{k \geq 0} \frac{1}{3^k} \\
 &= \frac{1}{3^{k_0+1}} \cdot \frac{1}{1 - \frac{1}{3}} \\
 &= \frac{3}{2 \cdot 3^{k_0+1}} \\
 &= \frac{1}{2 \cdot 3^{k_0}} \\
 &< \frac{1}{3^{k_0}}.
 \end{aligned}$$

Since $|t_2 - t_1| < \frac{1}{3^{k_0}}$, $\lambda(g) - \lambda(f) \neq 0$, establishing λ as an injection. Thus $\text{card}(2^{\mathbb{N}}) \leq \text{card}([0, 1])$. \square

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

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 $\mathbf{Z}^+ = \{n \in \mathbf{Z} \mid n \geq_a 0\}$, where \geq_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 \leq_a).

- (1) $m \leq_a n$ if and only if $n - m \in \mathbf{Z}^+$.
- (2) If $m \leq_a n$ and $p \leq_a q$, then $m + p \leq_a n + q$.
- (3) If $m \leq_a n$ and $p \in \mathbf{Z}^+$, then $pm \leq_a pn$.
- (4) If $m \leq_a n$ then $-n \leq_a -m$.
- (5) (\mathbf{Z}, \leq_a) forms a total ordering.
- (6) If $m >_a 0$ and $mn >_a 0$, then $n >_a 0$.
- (7) If $m >_a 0$ and $mn \geq_a mp$, then $n \geq_a p$.

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) $n \leq_a m$ or $m \leq_a n$. Thus (\mathbf{Z}, \leq_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 $n \in \mathbf{Z}^+$. \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 \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*

$$\begin{aligned} + : \mathbb{Q} \times \mathbb{Q} &\rightarrow \mathbb{Q} \text{ defined by } [(a, b)] + [(c, d)] = [(ad + bc, bd)] \\ \cdot : \mathbb{Q} \times \mathbb{Q} &\rightarrow \mathbb{Q} \text{ defined by } [(a, b)] \cdot [(c, d)] = [(ac, bd)] \end{aligned}$$

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

Proof. I dont wana □

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

$$\begin{aligned} j(n + m) &= j(n) + j(m) \\ j(nm) &= j(n)j(m). \end{aligned}$$

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

Proof. i REALLY dont □

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

- (1) If $q_1, q_2 \in \mathbb{Q}^+$, then $q_1 + q_2 \in \mathbb{Q}^+$ and $q_1 q_2 \in \mathbb{Q}^+$.
- (2) For all $q \in \mathbb{Q}$, $q \in \mathbb{Q}^+$ or $-q \in \mathbb{Q}^+$.
- (3) If $q \in \mathbb{Q}^+$ and $-q \in \mathbb{Q}^+$, then $q = 0$.
- (4) $q_1 \leq_Q q_2$ if and only if $q_2 - q_1 \in \mathbb{Q}^+$.

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

- (1) *If $r \leq_Q s$ and $t \leq_Q u$, then $r + t \leq_Q s + u$.*
- (2) *If $r \leq_Q s$ and $t \geq_Q 0$, then $tr \leq_Q ts$.*

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

$$\begin{aligned} (r + si) + (t + ui) &:= (r + t) + (s + u)i \\ (r + si)(t + ui) &:= (rt - su) + (ru + st)i \end{aligned}$$

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 \leq_F such that:

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

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

We similarly define $F^+ = \{x \in F \mid x \geq_F 0\}$ as the cone of positive elements.

Proposition 2.3.1. *Let (F, \leq_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) \mathbf{Q} is an ordered field.
- (2) Is $\mathbf{C}_{\mathbf{Q}}$ an ordered field?

Proposition 2.3.2. *Let (F, \leq) 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 $n \cdot 1_F := \underbrace{1_F + 1_F + \dots + 1_F}_{n \text{ times}}$, 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 $0 < x \leq y$, then $y^{-1} \leq x^{-1}$.*
- (7) *If $x \leq y$, then $-y \leq -x$.*
- (8) *If $x \geq 1_F$, then $x^2 \geq x$.*
- (9) *If $x \leq 1_F$, then $x^2 \leq x$.*

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 $n \cdot 1 = 1 + 1 + \dots + 1 \in F^+$.

(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) $y \geq x > 0$ implies $x, y \in F^+$. So $x^{-1}, y^{-1} \in F^+$. Then $y^{-1}xx^{-1} \leq y^{-1}yx^{-1}$, and simplifying yields $y^{-1} \leq x^{-1}$. *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 \mathbb{Q} with the following properties:

- (1) $D \neq \mathbb{Q}$;
- (2) If $b \in D$, then $a \in D$ for all $a \in \mathbb{Q}$ with $a < b$;
- (3) D does not contain a largest element.

Example 3.1.1. The following examples are Dedekind cuts:

- (1) $\{a \in \mathbb{Q} \mid a < 3\}$ (the set of all rational numbers less than 3).
- (2) $\{a \in \mathbb{Q} \mid a < 0 \text{ or } a^2 < 2\}$ (the set of all rational numbers less than $\sqrt{2}$).
- (3) $\{a \in \mathbb{Q} \mid a < 1 + \frac{1}{1!} + \frac{1}{2!} + \dots + \frac{1}{n!} \text{ for some } n \in \mathbb{Z}^+\}$ (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. \mathbb{R} is an ordered field.

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

Proof. If $x \in \mathbb{Q}^+$, then $x = \frac{p}{q}$ with $p \in \mathbb{Z}^+$ and $q \in \mathbb{N}$. Write $p = \underbrace{1 + 1 + \dots + 1}_{p \text{ times}}$, then $p \in \mathbb{R}^+$. Similarly, write $q = \underbrace{1 + 1 + \dots + 1}_{q \text{ times}}$. Then $q \in \mathbb{R}^+$, which implies that $q^{-1} \in \mathbb{R}^+$. Hence $\frac{p}{q} \in \mathbb{R}^+$, establishing $\mathbb{Q}^+ \subseteq \mathbb{R}^+$. □

Proposition 3.2.2. The maps $\mathbb{Z} \xrightarrow{j} \mathbb{Q} \xrightarrow{i} \mathbb{R}$ are order embeddings (defined in Lemma 2.2.3 and Theorem 2.2.4).

Proof. Suppose $i(q_1) \leq_{\mathbb{Q}} i(q_2)$. Then $q_1 \leq_{\mathbb{R}} q_2$, hence $q_2 - q_1 \in \mathbb{R}^+$. Now If $q_2 - q_2 \in \mathbb{Q}^+$, then $q_2 - q_1 \in \mathbb{R}^+$. Hence $q_1 \leq_{\mathbb{R}} q_2$. wtf is this saying? □

Proposition 3.2.3. Let $a, b \in \mathbb{R}$. If $a \leq b$ (or $a < b$), then $a \leq \frac{1}{2}(a + b) \leq b$ (or $a < \frac{1}{2}(a + b) < b$).

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

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

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

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

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

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

Proposition 3.2.7 (Bernoulli's Inequality). If $x > -1$, then $(1 + x)^n \geq 1 + nx$ 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 $n = k + 1$:

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

\square

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

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

¹Because order is preserved under multiplication by positive elements.

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

$$\begin{aligned} \sum_{j=1}^n (a_j - b_j t)^2 &= \sum_{j=1}^n (a_j^2 - 2a_j b_j t + b_j^2 t^2) \\ &= \sum_{j=1}^n a_j^2 - \sum_{j=1}^n 2a_j b_j t + \sum_{j=1}^n b_j^2 t^2. \end{aligned}$$

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

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

Simplifying gives:

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

Pulling 2 out from the left-hand side, dividing both sides by 4, and then square-rooting gives the desired result. \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 $a_1, \dots, a_n, b_1, \dots, b_n \in \mathbb{R}^n$. Then:*

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

Proof. Observe that:

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

Squaring both sides gives the desired result. \square

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

Definition 3.3.1. The absolute value is a function $|\cdot| : \mathbf{R} \rightarrow \mathbf{R}$ 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) $-|a| \leq a \leq |a|$.
- (6) $|a| \leq \delta$ if and only if $-\delta \leq a \leq \delta$.
- (7) $|a + b| \leq |a| + |b|$.
- (8) $|a - b| \leq |a| + |b|$.
- (9) $||a| - |b|| \leq |a - b|$.

Proof. **do later** □

Lemma 3.3.2. $\pm x \leq \delta$ if and only if $|x| \leq \delta$.

Proof. **do later** □

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 $l \leq a \leq u$ for all $a \in A$. We have that:

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

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

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

Definition 3.3.2. A function $f : D \rightarrow \mathbf{R}$ is bounded if $\text{im}(f) \subseteq \mathbf{R}$ 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 $f : [3, 7] \rightarrow \mathbf{R}$ defined by $f(x) = \frac{x^2+2x+1}{x-1}$. Since $3 \leq x \leq 7$, observe that:

$$\begin{aligned} |x^2 + 2x + 1| &\leq |x^2| + |2x| + 1 \\ &= |x|^2 + 2|x| + 1 \quad \text{Evaluate at 7} \\ &= 64 \end{aligned}$$

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

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

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 $d : X \times X \rightarrow \mathbf{R}^+$. We say (X, d) is a semi-metric if for all $x, y, z \in X$,

- (1) $d(x, y) = d(y, x)$,
- (2) $d(x, z) \leq d(x, y) + d(y, z)$, 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) $(\mathbf{R}^n, d_1(\vec{x}, \vec{y}) = \sum_{j=1}^n |y_j - x_j|)$ is a metric space.
- (3) $(\mathbf{R}^n, d_\infty(\vec{x}, \vec{y}) = \max_{j=1}^n \{|y_j - x_j|\})$ is a metric space.
- (4) $(\mathbf{R}^n, d_2(\vec{x}, \vec{y}) = \left(\sum_{j=1}^n |y_j - x_j|^2 \right)^{\frac{1}{2}})$ is a metric space.
- (5) $(\mathbf{R}^n, d_p(\vec{x}, \vec{y}) = \left(\sum_{j=1}^n |y_j - x_j|^p \right)^{\frac{1}{p}})$ 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, $d(s, r) = |s - r| = |s - t + t - r| \leq |s - t| + |t - r| = d(s, t) + d(t, r)$. 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:

$$\begin{aligned}
 d_2(\vec{x}, \vec{z}) &= \left(\sum_{j=1}^n |z_j - x_j|^2 \right)^{\frac{1}{2}} \\
 &= \left(\sum_{j=1}^n |z_j - y_j + y_j - x_j|^2 \right)^{\frac{1}{2}} \\
 &= \left(\sum_{j=1}^n (z_j - y_j + y_j - x_j)^2 \right)^{\frac{1}{2}} \\
 &\leq \left(\sum_{j=1}^n (z_j - y_j)^2 \right)^{\frac{1}{2}} + \left(\sum_{j=1}^n (y_j - x_j)^2 \right)^{\frac{1}{2}} \\
 &= \left(\sum_{j=1}^n |z_j - y_j|^2 \right)^{\frac{1}{2}} + \left(\sum_{j=1}^n |y_j - x_j|^2 \right)^{\frac{1}{2}} \\
 &= d_2(\vec{x}, \vec{y}) + d_2(\vec{y}, \vec{z}).
 \end{aligned}$$

Thus (\mathbb{R}^n, d_2) is a metric space. □

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 $B(x_0, \delta) = \{y \in X \mid d(y, x_0) \leq \delta\}$.
- (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 $X = \mathbb{R}$ and $d(s, t) = |s - t|$. Observe that:

$$\begin{aligned}
 U(t, \delta) &= \{s \in \mathbb{R} \mid d(s, t) < \delta\} \\
 &= \{s \in \mathbb{R} \mid |s - t| < \delta\} \\
 &= \{s \in \mathbb{R} \mid -\delta < s - t < \delta\} \\
 &= \{s \in \mathbb{R} \mid -\delta + t < s < \delta + t\} \\
 &= (t - \delta, t + \delta).
 \end{aligned}$$

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** □

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 $a \leq t$ 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 $a \leq b$ for all $a \in A$ and $b \in B$. Then $\sup(A) \leq \inf(B)$.

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

Axiom 2 (Completeness of \mathbf{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 $a \in A$, $-a \leq u$. Hence $-u$ is a lower bound for A . Suppose v is another lower bound for A . Then $v \leq a$ for all $a \in A$. So $-v \geq -a$ for all $a \in A$. Thus $-v$ is an upper bound of $-A$. Therefore, since u is the least upper bound, $-v \geq u$; i.e., $-u \geq v$. Thus $-u = \inf(A)$. \square

Axiom 3 (Well-Ordering Principle). *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 $n \leq x$ for all $n \in \mathbf{N}$. Then x is an upper bound for \mathbf{N} . Thus $\sup(\mathbf{N}) := u$ 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. \square

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 $x = \frac{1}{t}$. \square

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 $\text{card}(\{1, 2, \dots, n\}) < \text{card}(\mathcal{P}(\{1, 2, \dots, n\}))$. Then Exercise 1.4.2 gives:

$$n = \text{card}(\{1, 2, \dots, n\}) < \text{card}(\mathcal{P}(\{1, 2, \dots, n\})) = 2^n.$$

Alternatively, **Bernoulli's Inequality** gives $(1 + 1)^n \geq 1 + n$. Hence $2^n > n$. \square

Example 4.1.2.

- (1) Claim: $\inf \left\{ \frac{1}{n} \mid n \in \mathbf{N} \right\} = 0$. 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 $t \leq 0$, 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 $\frac{1}{n_t} \in \inf \left\{ \frac{1}{n} \mid n \in \mathbf{N} \right\}$). Thus $\inf \left\{ \frac{1}{n} \mid n \in \mathbf{N} \right\} = 0$.
- (2) Claim: $\inf \left\{ \frac{1}{2^m} \mid m \in \mathbf{N} \right\} = 0$. 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 $n_x - 1 \leq x < n_x$.*

Proof. Case 1: $x \geq 0$. Let $S_x = \{n \in \mathbf{N} \mid x < n\}$. By **Arcimedean Property 1** $S_x \neq \emptyset$. By the **Well-Ordering Principle**, 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 $n_x - 1 \leq x$.

Case 2: $x < 0$. Define $S_{-x} = \{n \in \mathbf{N} \mid n < -x\}$. As a consequence of the **Well-Ordering Principle**, 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 $n_{-x} < -x \leq n_{-x} + 1$. This establishes $-n_{-x} - 1 \leq x < -n_{-x}$. \square

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

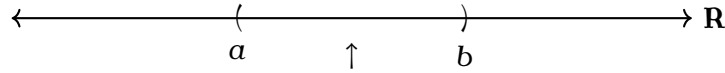
Theorem 4.1.8. $\mathbf{Q} \subseteq \mathbf{R}$ is dense.

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 $m - 1 \leq na < m$. Equivalently, we have that $a < \frac{m}{n}$. We also have that $m \leq na + 1 < nb$, which yields $\frac{m}{n} < b$. Thus $\frac{m}{n} \in (a, b) \cap \mathbf{Q}$. \square

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. \square

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 $S \neq \emptyset$ because $1 \in S$. If $t \geq 2$, then $t^2 \geq 2t > 4$, 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:

$$\begin{aligned}
 & \text{—————/—————} \\
 & u^2 + \frac{2u}{n} + \frac{1}{n^2} < 2 \\
 & \iff \\
 & \frac{2u}{n} + \frac{1}{n^2} < 2 - u^2 \\
 & \iff \\
 & \frac{1}{n} \left(2u + \frac{1}{n} \right) < 2 - u^2 \\
 & \iff \\
 & \frac{1}{n} (2u + 1) < 2 - u^2 \\
 & \iff \\
 & \frac{1}{n} < \frac{2 - u^2}{2u + 1} \in \mathbf{R}^+ \setminus \{0\} \\
 & \text{—————/—————}
 \end{aligned}$$

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 $u^2 \geq 2$; i.e., $u^2 - 2 \geq 0$. 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 $u, v \geq 0$, $(u^2 - v^2) = 0$. 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 $u = v$. \square

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

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:

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

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 $s_1 \in S$ 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**. □

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

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

Proof. Note that $0 \in [0, \frac{1}{n})$ for all $n \geq 1$. So $0 \in \bigcap_{n \geq 1} [0, \frac{1}{n})$. Let $a \in \bigcap_{n \geq 1} [0, \frac{1}{n})$. Then $0 \leq a < \frac{1}{n}$ for all $n \geq 1$. Hence $a = 0$. □

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

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

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

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

$$\begin{aligned} a_1 &\leq a_2 \leq a_3 \leq \dots \\ b_1 &\geq b_2 \geq b_3 \geq \dots \end{aligned}$$

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

$$\xi = \sup_{n \geq 1} \{a_n\}$$

$$\eta = \inf_{n \geq 1} \{b_n\}.$$

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

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

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

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

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

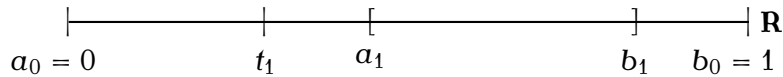
$$\begin{aligned} 0 &= \inf_{n \geq 1} (b_n - a_n) \\ &= \inf_{n \geq 1} b_n - \inf_{n \geq 1} a_n \\ &= \eta - \xi. \end{aligned}$$

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 $\xi \in \bigcap_{n \geq 1} [a_n, b_n]$. Then $\xi \in [0, 1]$. But $\xi \neq t_n$ for all n , which is a contradiction. \square

5

Sequences

5.1 Basic Definitions and Examples

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

Example 5.1.1 (Sequences Defined Explicitly).

- (1) A constant sequence: $x_n = t$, $(x_n)_{n \geq 1} = (t, t, t, \dots)$.
- (2) Sequences defined by a function: $d_n = (1 + \frac{1}{n})^n$.
- (3) Geometric sequences¹: fix $b \in \mathbb{R}$, $x_n = b^n$. Then $(x_n)_{n \geq 1} = (1, b, b^2, b^3, \dots)$.

Example 5.1.2 (Sequences Defined Recursively).

- (1) Let $a_1 = 1$, $a_{n+1} = 2a_n + 1$. Then $(a_n)_{n \geq 1} = (1, 3, 7, 15, \dots)$.
- (2) Let $f_1 = 1$, $f_2 = 1$, $f_{n+1} = f_n + f_{n-1}$. Then $(f_n)_{n=1}^\infty = (1, 1, 2, 3, 5, 8, \dots)$. This is the *Fibonacci sequence*.
- (3) Let X be a metric space and $f : X \rightarrow X$ be an endomorphism. Fix $x_0 \in X$. Then define:

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

Example 5.1.3 (New Sequences from Old).

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

$$\begin{aligned} (a_n)_{n \geq 1} \pm (b_n)_{n \geq 1} &= (a_n \pm b_n)_{n \geq 1}, \\ t(a_n)_{n \geq 1} &= (ta_n)_{n \geq 1}, \\ (a_n)_{n \geq 1} \cdot (b_n)_{n \geq 1} &= (a_n \cdot b_n)_{n \geq 1}. \end{aligned}$$

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

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

¹These 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 $(x_n)_{n \geq 1}$ and $k \in \mathbf{N}$, consider $(x_{n+k})_{n=0}^\infty = (x_k, x_{k+1}, x_{k+1}, \dots)$. This is called a *shift* or the k^{th} *tail* of $(x_n)_{n \geq 1}$.

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

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

So $(r_n)_{n \geq 1} = \left(\frac{a_2}{a_1}, \frac{a_3}{a_2}, \frac{a_4}{a_3}, \dots \right)$. 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:

$$s_1 = x_1$$

$$s_2 = x_1 + x_2 = s_1 + x_2$$

$$s_3 = x_1 + x_2 + x_3 = s_2 + x_3$$

$$\vdots$$

$$s_n = \sum_{k=1}^n x_k = s_{n-1} + x_n.$$

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 $(x_n)_{n \geq 1}$ be a sequence.

- (1) x_n is increasing if $x_1 \leq x_2 \leq x_3 \leq \dots$
- (2) x_n is decreasing if $x_1 \geq x_2 \geq x_3 \geq \dots$
- (3) x_n is strictly increasing if $x_1 < x_2 < x_3 < \dots$
- (4) x_n is strictly decreasing if $x_1 > x_2 > x_3 > \dots$

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.

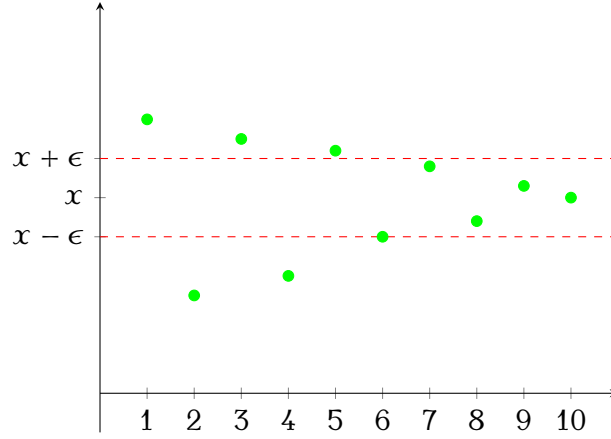
Definition 5.2.2. A sequence $(x_n)_n$ in a metric space X converges to $x \in X$ if:

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

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

²I 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 $(\frac{1}{n})_{n \geq 1} \rightarrow 0$.

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

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

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

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 $N_\epsilon > \frac{14}{\epsilon} + 3$ ([Archimedean Property 1](#)). Now, if $n \geq N_\epsilon$, 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 $(x_n)_n \rightarrow x$ if and only if $(d(x_n, x))_n \rightarrow 0$.

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

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

Proof. need to do □

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

Proof. need to do □

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

Solution. Note that:

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

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

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

Solution. Note that:

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

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

Solution. Note that:

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

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

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

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

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

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

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

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 $(x_n)_n \rightarrow 0$. \square

Note 3. The negation of Definition 5.2.2 is:

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

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

Solution.