Analysis Notes

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Chapter 1

The Real Numbers

1.1 Discussion: the Irrationality of $\sqrt{2}$

THEOREM 1.1.1. *There is no rational number whose square is 2.*

Proof. A rational number can be written in the form $\frac{p}{q}$ where p and q are integers. We will use an indirect proof. First, assume there is a rational so that its square is 2. It can be written that

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

We can assume p and q have no common factors since they would cancel anyways and give us a new p and q. Now we can written

$$p^2 = 2q^2$$

which implies that p^2 is an even number, which implies p is an even number. So we can let $p = 2r$. Plugging this in

$$2r^2 = q^2$$

With the same logic as for with p, q is also even. So p and q share a common factor of 2 which contradicts the assumption made in the beginning that they share no common factors. $\square$

Important number systems as sets

Natural Numbers

$$\mathbf{N} = \{1, 2, 3, 4, 5, \dots\}$$

Addition works well he, but there is no additive identity or inverse.

Integers

$$\mathbf{Z} = \{\dots, -2, -1, 0, 1, 2, \dots\}$$

This includes the additive identity (0) and the additive inverses, which define subtraction. The multiplicative identity is 1, but for multiplicative inverses we need to extend to ...

Rational Numbers

$$\mathbf{Q} = \{\text{all fractions } \frac{p}{q} \text{ where } p \text{ and } q \text{ are integers and } q \neq 0\}$$

The multiplicative inverses define division. All of these properties of $\mathbf{Q}$ make it into a *field*. A field is any set where addition and multiplication are well-defined operations that are commutative, associative, and obey the distributive property: $a(b + c) = ab + bc$. There must be an additive and multiplicative identity, and each element must have an additive and multiplicative inverse.

The set $\mathbf{Q}$ has a natural *order*. Given two rational numbers r and s, one of the following is true:

$$r < s, \ r = s, \text{ or } r > s$$

This ordering is transitive: if $r < s$ and $s < t$, then $r < t$. Also, between any two rational numbers, r and s, there is a rational number between them: $\frac{r+s}{2}$, which implies that rational numbers are densely packed.

$\mathbf{Q}$ is has holes in the spots of irrationals, such as $\sqrt{2}$ and $\sqrt{3}$. To fill these we add ...

Real Numbers

$$\mathbf{R} = \{\text{all real numbers}\}$$

Just like $\mathbf{Q}$, $\mathbf{R}$ is a field. $\mathbf{R}$ is added as a superset of $\mathbf{Q}$. $\mathbf{N} \subseteq \mathbf{Z} \subseteq \mathbf{Q} \subseteq \mathbf{R}$.

1.2 Some Preliminaries

Sets

A *set* is a collection of object, usually real numbers. The objects that make up the set are *elements*.

Notation

- $x \in A$ means x is in A
- $A \cup B$ (union of A and B) is defined by: if $x \in A \cup B$ then $x \in A$ or $x \in B$ (or both)
- $A \cap B$ (intersection of A and B) is defined by: if $x \in A \cap B$ then $x \in A$ and $x \in B$
- $\emptyset$ is an *empty set*, or a set without any elements in it
- if $A \cap B = \emptyset$, then A and B are *disjoint*
- $A \supseteq B$ or $B \subseteq A$ every element of B is in A so for each $x \in B$, $x \in A$. So B is a *subset* of A, or A *contains* B
- $A = B$ means each element of $A \subseteq B$ and $B \subseteq B$. So the sets are the same.

- $\bigcup_{n=1}^{\infty} A_n$ or $\bigcup_{n\in\mathbf{N}} A$ means $A_1 \cup A_2 \cup \cdots \cup A_\infty$
- $\bigcap_{n=1}^{\infty} A_n$ or $\bigcap_{n\in\mathbf{N}} A$ means $A_1 \cap A_2 \cap \cdots \cap A_\infty$
- $A^c = \{x \in \mathbf{R} : x \notin A\}$

You can define a set by listing items ($N = \{1, 2, 3, \dots\}$), with words (let E be all even natural numbers), or with a rule or algorithm ($S = \{r \in \mathbf{Q} : r^2 < 2\}$).

De Morgan's Laws
$(A \cap B)^c = A^c \cup B^c$ and $(A \cup B)^c = A^c \cap B^c$

Functions

Given two sets A and B, a *function* from A to B is a rule or mapping that takes each element $x \in A$ to a single element in B. We can write $f\colon A \to B$. Given $x \in A$, $f(x)$ represents an element of B associated with x by f. A is the domain of f. The range is a subset of B.
Triangle Inequality
Absolute Value Function:

$$|x| = \begin{cases} x & \text{if } x \geq 0 \\ -x & \text{if } x < 0 \end{cases}$$

The Absolute Value Function satisfies:

$$|ab| = |a||b|$$

$$|a + b| \leq |a| + |b|$$

Logic and Proofs

A type of indirect proof previously used is *proof by contradiction*,which starts by negating what we are proving and then finding a contradiction. Most proofs are direct, which means it starts from a true statement and then gets to the theorems conclusion.

THEOREM 1.2.1. *Two real numbers a and b are equal if and only if for every real number $\epsilon > 0$ it follows that $|a - b| < \epsilon$*

Proof. Must prove both:
$\Rightarrow$ If $a = b$, then for every real number ϵ it follows that $|a - b| < \epsilon$.
If $a = b$, then $|a - b| = 0$, and $|a - b| < \epsilon$ for any $\epsilon > 0$.

$\Leftarrow$ If for every real number $\epsilon > 0$ if follows that $|a - b| < \epsilon$, then we must have $a = b$.
Assume $a \neq b$,

let $\epsilon_0 = |a - b| > 0$ since $a \neq b$
But $|a - b| = \epsilon_0$ contradicts $|a - b| < \epsilon_0$, which was given. So $a \neq b$ is unacceptable, and a must equal b. ☐

Induction

The fundamental principle behind induction is that if S is a subset of $\mathbf{N}$ so that S contains 1 and if S contains n, then S contains $n+1$, then by induction $S = \mathbf{N}$.

1.3 The Axiom of Completeness

Axiom of Completeness. *Every nonempty set of real numbers that is bounded above has a least upper bound*

Least Upper Bounds and Greatest Lower Bounds

Definition A set $A \in \mathbf{R}$ is *bounded above* if there exists a number $b \in \mathbf{R}$ such that $a \leq b$ fro all $a \in A$. The number b is an *upper bound* for A.

The set A is *bounded below* if there exists a *lower bound* $l \in \mathbf{R}$ so that $l \leq a$ for all $a \in A$.
Definition A real number s is the *least upper bound* for a set $A \in \mathbf{R}$ if it meets two criteria:

(i) s is an upper bound for A;

(ii) if b is any upper bound for A, then $s \leq b$;

The least upper bound is also called the *supremum* of A. So, $s = \text{lub } A = \sup A$.

The *greatest lower bound* or *infimum* for A is defined similarly and is denoted by $\inf A$.

A set can have many upper bounds, but only one least upper bound. If s_1 and s_2 are both least upper bounds, then by property (ii) we can assert $s_1 \leq s_2$ and $s_2 \leq s_1$, and that $s_1 = s_2$.

A real number a_0 is a *maximum* of set A if a_0 is an element of A and $a_0 \geq a$ for each $a \in A$. Similarly, a number a_1 is a *minimum* of A if $a_1 \in A$ and $a_1 \leq a$ for each $a \in A$.

An upper bounded set is guaranteed to have a least upper bound by *The Axiom of Completeness*, but it is not guaranteed to have a maximum. A supremum can exist and not be a maximum (if the supremum does not exist in the set), but when a maximum exists it is also the supremum. **Lemma** *Assume $s \in \boldsymbol{R}$ is an upper bound for a set $A \in \boldsymbol{R}$. Then, $s = sup\ A$ if and only if, for every choice of $\epsilon > 0$, there exists an element $a \in A$ satisfying $s - \epsilon < a$*

Proof. Given that s is an upper bound, s is the leastupper bound if and only if any number smaller than s is not an upper bound.

$\Rightarrow$ Assume $s = \sup A$ and consider $s - \epsilon$, where $\epsilon > 0$ has been chosen. Since $s - \epsilon < s$, $s - \epsilon$ is not an upper bound for A. So there must be an $a \in A$ such that $s - \epsilon < a$.

$\Leftarrow$ Assume s is an upper bound so that for every $\epsilon > 0$, $s - \epsilon$ is no longer an upper bound for A. $s = \sup A$ since s is an upper bound, and any real number $b < s$ is not an upper bound. This is apparent by setting $\epsilon = s - b$. □

1.4 Consequences of Completeness

THEOREM 1.4.1 (Nested Interval Property)**.** *For each $n \in \boldsymbol{N}$, assume we are given a closed interval $I_n = [a_n, b_n] = \{x \in \boldsymbol{R} : a_n \leq x \leq b_n\}$. Assume also that each I_n contains I_{n+1}. Then, the resulting nested sequence of closed intervals*

$$I_1 \supseteq I_2 \supseteq I_3 \supseteq I_4 \supseteq \ldots$$

has a nonempty intersection; that is, $\bigcap_{n=1}^{\infty} I_n \neq \emptyset$.

Proof. In order to show $\bigcap_{n=1}^{\infty} I_n$ is not empty, we are going to use the Axiom of Completeness to produce a single real number x satisfying $x \in I_n$ for every $n \in \mathbf{N}$. Consider the set

$$A = \{a_n : n \in \mathbf{N}\}$$

of left-hand endpoints of the intervals. Since the intervals are nested, every b_n is an upper bound for A. let $x = \sup A$. Consider a particular $I_n = [a_n, b_n]$. Since x is an upper bound for A, $a_n \leq x$. Since x is the least upper bound and each b_n are upper bounds, $x \leq b_n$. So $a_n \leq x \leq b_n$ for any n. So $x \in I_n$ for any $n \in \mathbf{N}$. Hence, $x \in \bigcap_{n=1}^{\infty} I_n \neq \emptyset$. □

The Density of Q in R

THEOREM 1.4.2 (Archimedean Property)**.** *(i) Given any number $x \in \boldsymbol{R}$, there exists an $n \in \boldsymbol{N}$ satisfying $n > x$.*

(ii) Given any real number $y > 0$, there exists an $n \in \boldsymbol{N}$ satisfying $1/n < y$.

Proof. Part (i) states that $\mathbf{N}$ is not bounded above. Assume, for contradiction, that $\mathbf{N}$ is bounded above. By AoC, $\mathbf{N}$ has a least upper bound. Let $\alpha = \sup N$. $\alpha - 1$ is not an upper bound, so there is an $n \in \mathbf{N}$, such that $\alpha - 1 < n$, which is the same as saying $\alpha < n + 1$. $n + 1 \in \mathbf{N}$, we have a contradiction to the fact α is an upper bound.

Part (ii) follows from (i) by letting $x = 1/y$. □

THEOREM 1.4.3 (Density of Q in R)**.** *For every two real numbers a and b with $a < b$, there exists a rational number r satisfying $a < r < b$.*

Proof. To simplify matters, let's assume $0 \leq a < b$. A rational number is a quotient of integers, so we must product m, $n \in \mathbf{N}$ so that

$$a < \frac{m}{n} < b$$

First, we must choose a large enough n so that an increment of size $1/n$ is small enough so it doesn't step over the interval (a, b). Basically, we need an $n \in \mathbf{N}$ such that

$$\frac{1}{n} < b - a$$

By the first inequality, we can get $na < m < nb$. With n chosen, we need to choose an m to be the smallest natural number greater than na. So,

$$m - 1 \leq na < m$$

which yields $a < m/n$. And $a < b - 1/n$ from the second inequality. So

$$m \leq na + 1 < n(b - \frac{1}{n}) + 1 = nb$$

Because $m < nb$ so $m/n < b$. Now we have $a < m/n < b$. □

Collary *Given any two real numbers $a < b$, there exists an irrational number t satisfying $a < t < b$*

The Existence of Square Roots

THEOREM 1.4.4. *There exists a real numbers $\alpha \in \boldsymbol{R}$ satisfying $\alpha^2 = 2$.*

Proof. Consider the set

$$T = \{t \in \mathbf{R} : t^2 < 2\}$$

and set $\alpha = \sup T$. If $\alpha^2 < 2$. NEED TO FINISH THIS PROOF. □

Countable and Uncountable Sets

Cardinality

Cardinality refers to the size of a set. The cardinalities of finite sets can be compared by attaching a natural number to each set. By using comparisons rather than just length, this idea extends to infinite sets.

Definition A function $f : A \to B$ is one-to-one (1-1) if $a_1 \neq a_2$ in A implies that $f(a_1) \neq f(a_2)$ in B. The function f is *onto* if given any $b \in B$, it is possible to find the element $a \in A$ such that $f(a) = b$. **Definition** Two sets A and B havethe same cardinality if there exists $f : A \to B$ that is 1-1 and onto. In this case, we write $A \sim B$.

Countable Sets

Definition A set A is *countable* if $N \sim A$. AN infinite set that is countable is called an *uncountable* set.

THEOREM 1.4.5. *(i) The set $\boldsymbol{Q}$ is countable*
(ii) The set $\boldsymbol{R}$ is uncountable

Proof. (i) For each $n \in \mathbf{N}$, let

$$A_n = \{\pm\frac{p}{q} : \text{where } p, q \in \mathbf{N} \text{ are in lowest terms with } p + q = n\}$$

so

$$A_1 = \{\frac{0}{1}\}, \qquad A_2 = \{\frac{1}{1}, \frac{-1}{1}\}, \qquad A_3 = \{\frac{1}{2}, \frac{-1}{2}, \frac{2}{1}, \frac{-2}{1}\}$$

Our one to one correspondence from $\mathbf{N}$ to $\mathbf{Q}$ is by listing the elements from $\bigcup_{n=1}^{\infty} A_n$. So, $f(n) = (\bigcup_{n=1}^{\infty} A_n)[n]$. For any fraction, like 22/7, it will be in $\bigcup_{n=1}^{\infty} A_n$ exactly once ($22/7 \in A_2 9$). This makes $\bigcup_{n=1}^{\infty}\bigcup_{m=1}^{\infty} A_n \cap A_m = \emptyset$. So, $\mathbf{N} \sim \mathbf{Q}$ and $\mathbf{Q}$ is countable.

(ii) Proof by contradiction. Assume there exists a 1-1 from $\mathbf{N}$ to $\mathbf{R}$. If we let $x_n = f(n)$ for each $n \in \mathbf{N}$, we can write

$$\mathbf{R} = \{x_1, x_2, x_3, \dots\}$$

Let I_1 be a closed interval that does not contain x_1. Then create infinite intervals based on the following rules. Given an I_n, construct I_{n+1} to satisfy

(i) $I_{n+1} \subseteq I_n$ and

(ii) $x_{n+1} \notin I_{n+1}$.

Given I_n, it is clear that I_{n+1} exists since I_n certainly contains two smaller disjoint closed intervals and x_{n+1} can only be in one of them. Since $x_{n_0} \notin I_{n_0}$,

$$x_{n_0} \notin \bigcap_{n=1}^{\infty} I_n$$

This is true for every natural number n_0, and hence every real number x_{n_0}, so

$$\bigcap_{n=1}^{\infty} I_n = \emptyset$$

which contradicts the Nested Interval Property, which asserts that $\bigcap_{n=1}^{\infty} I_n \neq \emptyset$. Due to this contradiction, $\mathbf{R}$ cannot be countable, and is uncountable. □

Since $\mathbf{R} = \mathbf{Q} \cup \mathbf{I}$, where $\mathbf{I}$ is all irrational numbers, $\mathbf{I}$ cannot be countable because otherwise $\mathbf{R}$ would be.

THEOREM 1.4.6. *If $A \subseteq B$ and B is countable, then A is either countable, finite, or empty.*

THEOREM 1.4.7. *(i) If A_1, A_2, $\dots A_m$ are each countable sets, then the union $\bigcup_{n=1}^{m} A_n$ is countable.*
(ii) If A_n is a countable set for each $n \in \boldsymbol{N}$, then $\bigcup_{n=1}^{\infty} A_n$ is countable.

1.5 Cantor's Theorem

Cantor's Diagonalization Method

Cantor initially published his discovery that $\mathbf{R}$ is uncountable in 1874, but in 1891 he offered another simpler proof that relies on decimal representations for real numbers.

THEOREM 1.5.1. *The open interval* $(0,1) = \{x \in \boldsymbol{R} : 0 < x < 1\}$ *is uncountable.*

Power Sets and Cantor's Theorem

Given a set A, the *power set* $P(A)$ refers to the collection of all subsets of A.
Example:

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

THEOREM 1.5.2 (Cantor's Theorem)**.** *Given any set A, there does not exist a function $f : A \to P(A)$ that is onto.*

Proof. For contradiction, assume that $f : A \to P(A)$ is onto. So for each element $a \in A$, $f(a)$ is a particular subset of A. Since f is onto, eery subset of A appears as $f(a)$ for some $a \in A$. Now, let B be a subset of A ($B \subseteq A$) following

$$B = \{a \in A : a \notin f(a)\}$$

Since f is onto $B = f(a')$ for some $a' \in A$.

If a' is in B ($a' \in B$), $a' \notin f(a')$ since this is a requirement to be in B. Since $a' \notin f(a')$ and $f(a') = B$ implies $a' \notin B$ and we assumed that $a' \in B$, we have a contradiction.

If a' is not in B ($a' \notin B$), $a' \in f(a')$ since it would otherwise be in B. Since $a' \in f(a')$ and $f(a') = B$ implies $a' \in B$ and we assumed that $a' \notin B$, we have a contradiction. $\square$

Chapter 2

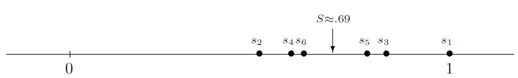
Sequences and Series

2.1 Discussion: Rearrangements of Infinite Series

Consider the infinite series

$$\sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} = 1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \frac{1}{5} - \frac{1}{6} + \dots$$

If we just add from left to right, we get a series of *partial sums*: $s_1 = 1$, $s_2 = 1/2$, $s_3 = 5/6$, and so on. We also see that the sums oscillate such that $s_1 > s_3 > s_5 > \dots$ and $s_2 < s_4 < s_6 < \dots$.



$$s_2 < s_4 < s_6 < \dots < S < \dots < s_5 < s_3 < s_1$$

It is reasonable to say that this series converges to a number $S = 0.69$ (by experimentation with s_N where N is a large number). It is tempting to think that the sum of all those numbers "add" up to S, but for that we must redefine addition for infinite sums. Treating this series algebraically, lets multiply through by 1/2 and add it back.

$$\begin{array}{rcl}
\frac{1}{2}S = & & \frac{1}{2} \quad - \frac{1}{4} \quad + \frac{1}{6} \quad - \frac{1}{8} \quad + \frac{1}{10} \quad - \frac{1}{12} \quad + \cdots \\
+ \; S = & 1 & - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \frac{1}{5} - \frac{1}{6} + \frac{1}{7} - \frac{1}{8} + \frac{1}{9} - \frac{1}{10} + \frac{1}{11} - \frac{1}{12} + \frac{1}{13} - \cdots \\
\hline
\frac{3}{2}S = & 1 & + \frac{1}{3} - \frac{1}{2} + \frac{1}{5} \quad + \frac{1}{7} - \frac{1}{4} + \frac{1}{9} \quad + \frac{1}{11} - \frac{1}{6} + \frac{1}{13} \quad \cdots
\end{array}$$

The resulting series has the same terms as the original series except in a different order. It has two positive terms and then the negative term instead of switching each time. But $\frac{3}{2}S \neq S$. This is also seen by experimentation with large Ns. Addition, in this infinite setting, is not commutative.

Let us look at another series

$$\sum_{n=0}^{\infty}(-1/2)^n$$

Using $\sum_{n=0}^{\infty} r^n = \frac{1}{1-r}$ for geometric series, we get

$$1 - \frac{1}{2} + \frac{1}{4} - \frac{1}{8} + \frac{1}{16} - \frac{1}{32} + \cdots = \frac{1}{1-1/2} = \frac{2}{3}$$

If we rearrange this into two positive and then a negative, you get the same result. Hence addition in an infinite setting is sometimes commutative.

This is applied to the double summation of numbers in a *grid*. For example, $a_{ij} : i, j \in \mathbf{N}$, where $a_{ij} 1/2^{j-i}$ if $j > i$, $a_{ij} = -1$ if $j = i$, and $a_{ij} = 0$ if $j < i$.

$$\begin{bmatrix} -1 & \frac{1}{2} & \frac{1}{4} & \frac{1}{8} & \frac{1}{16} & \dots \\ 0 & -1 & \frac{1}{2} & \frac{1}{4} & \frac{1}{8} & \dots \\ 0 & 0 & -1 & \frac{1}{2} & \frac{1}{4} & \dots \end{bmatrix}$$

We are trying to give

$$\sum_{i,j=1}^{\infty} a_{ij}$$

mathematical meaning. If we sum over all of the j while holding i for each row we get

$$\sum_{i,j=1}^{\infty} a_{ij} = \sum_{i=1}^{\infty}(\sum_{j=1}^{\infty} a_{ij}) = \sum_{i=1}^{\infty} 0 = 0$$

since the sum of each row is zero. If we hold j constant and iterate over i first we get

$$\sum_{i,j=1}^{\infty} a_{ij} = \sum_{j=1}^{\infty}(\sum_{i=1}^{\infty} a_{ij}) = \sum_{j=1}^{\infty}(\frac{-1}{2^{j-1}}) = -2$$

The order in which we add causes us to get different results. This double summation occurs when we are multiplying two series:

$$\sum a_i \sum b_j = \sum_{i,j} a_i b_j$$

Now consider the associative property of addition. Consider $\sum_{n=1}^{\infty}(-1)^n$.

$$sum_{n=1}^{\infty}(-1)^n = (-1+1) + (-1+1) + (-1+1) + (-1+1) + (-1+1) + \cdots = 0$$

$$sum_{n=1}^{\infty}(-1)^n = -1 + (1-1) + (1-1) + (1-1) + (1-1) + (1-1) + \cdots = -1$$

Different associations cause use to get different results. Manipulations that are legitimate in finite settings do not always extend to infinite settings.

2.2 The Limit of a Sequence

Definition 2.2.1. A *sequence* is a function whose domain is $\mathbf{N}$.
Each of the following are common ways to describe a sequence.

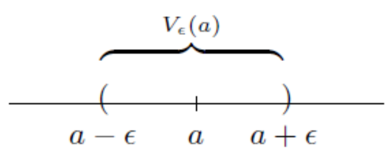
1. $(1, \frac{1}{2}, \frac{1}{3}, \dots)$
2. $(\frac{1}{n})_{n=1}^{\infty}$
3. (a_n), where $a_n = 1/n$ for each $n \in \mathbf{N}$
4. (x_n), where $x_1 = 2$ and $x_{n+1} = \frac{x_n+1}{2}$

We do not need to start the sequence at $n = 1$, we can start it at $n = 0$ or $n = n_0$ where $n_0 \in \mathbf{N}$.
Definition 2.2.3 (Convergence of a Sequence). A sequence (a_n) *converges* to a real number a if, for every positive number ϵ, there exists an $N \in \mathbf{N}$ such that whenever $n \geq N$ it follows that $|a_n - a| < \epsilon$.

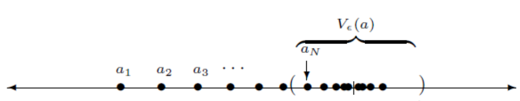
To indicate that (a_n) converges to a, we write either $\lim_{n\to\infty} a_n = \lim a_n = a$ or $(a_n) \to a$.
Definition 2.24. Given a real number $a \in \mathbf{R}$ and a positive number $\epsilon > 0$, the set

$$V_\epsilon(a) = x \in \mathbf{R} : |x - a| < \epsilon$$

is called the *ϵ-neighborhood of a.*



Definition 2.2.3B (Convergence of a Sequence: Topological Version). A sequence (a_n) converges to a if, given any ϵ-neighborhood $V_\epsilon(a)$ of a, there exists a point in the sequence after which all of the terms are in $V_\epsilon(a)$. In other words, every ϵ-neighborhood contains all but a finite number of the terms of (a_n).



Quantifiers

TEMPLATE FOR A PROOF THAT $(x_n) \to x$:

- "Let $\epsilon > 0$ be arbitrary."
- Demonstrate a choice for $N \in \mathbf{N}$. This step usually requires the most work, almost all of which is done prior to actually writing the formal proof.
- Now, show that N actually works.
- "Assume $n \geq N$."
- With N well chosen, it should be possible to derive the inequality $|x_n - x| < \epsilon$.

Divergence

Definition 2.2.8. A sequence that does not converge is said to *diverge*.

2.3 The Algebraic and Order Limit Theorems

Definition 2.3.1. A sequence (x_n) is *bounded* if there exists a number $M > 0$ such that $|x_n| \leq M$ for all $n \in \mathbf{N}$.

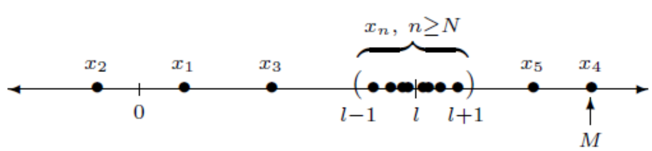
This means $[-M, M]$ contains every term in (x_n)

THEOREM 2.3.2. *Every convergent sequence is bounded.*

Proof. Assume (x_n) converges to a limit l. So for any value of ϵ, there exists an $N \in \mathbf{N}$ such that if $n \geq N$, then x_n is in the interval $(l - \epsilon, l + \epsilon)$, or

$$|x_n| < |l| + \epsilon$$

for all $n \geq N$, for any value of ϵ.



Since there are only a finite number of terms before N, we let

$$M = max\{|x_1|, |x_2|, |x_3|, \ldots, |x_{N-1}|, |l| + \epsilon\}$$

Then it follows that $|x_n| \leq M$ for all $n \in \mathbf{N}$ as desired. $\square$

THEOREM 2.3.3 (Algebraic Limit Theorem)**.** *Let* $\lim a_n = a$*, and* $\lim b_n = b$*. Then,*
(i) $\lim(ca_n) = ca$*, for all* $c \in \boldsymbol{R}$*;*
(ii) $\lim(a_n + b_n) = a + b$*;*
(iii) $\lim(a_n b_n) = ab$*;*
(iv) $\lim(a_n/b_n) = a/b$*, provided* $b \neq 0$*;*

Proof. (i) Consider if $c \neq 0$. Let ϵ be some arbitrary positive number. We want to show that after some point in the sequence (ca_n),

$$|ca_n - ca| < \epsilon$$

Now,

$$|ca_n - ca| = |c||a_n - a|$$

Since $(a_n) \to a$, we can make $|a_n - a|$ as small as we want. So we choose an N so

$$|a_n - a| < \frac{\epsilon}{|c|}$$

whenever $n \geq N$. Then,

$$|ca_n - ca| = |c||a_n - a| < |c|\frac{\epsilon}{|c|} = \epsilon$$

The case $c = 0$ reduces to showing the constant sequence $(0, 0, 0, \dots)$ converges to 0. Let $\epsilon > 0$ be arbitrary. Then for any $N \in \mathbf{N}$, $|ca_n - ca| < \epsilon$ for all $n \geq \mathbf{N}$ since $|0 - 0| = 0 < \epsilon$.

(ii) Now, we are proving

$$|(a_n + b_n) - (a + b)|$$

can be made less than an arbitrary ϵ. First, use the triangle inequality to say

$$|(a_n + b_n) - (a + b)| = |(a_n - a) + (b_n - b)| \leq |a_n - a| + |b_n - b|$$

Since $(a_n) \to a$ and $(b_n) \to b$, we know there exists an N_1 and N_2 such that

$$|a_n - a| < \frac{\epsilon}{2} \text{ whenever } n \geq N_1$$

and

$$|b_n - b| < \frac{\epsilon}{2} \text{ whenever } n \geq N_2$$

Now, let $N = max\{N_1, N_2\}$ so that when $n \geq N$, then $n \geq N_1$ and $n \geq N_2$. So,

$$\begin{aligned} |(a_n + b_n) - (a + b)| = |(a_n - a) + (b_n - b)| &\leq |a_n - a| + |b_n - b| \\ &< \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon \end{aligned}$$

for all $n \geq N$, as desired.

(iii) To begin,

$$\begin{aligned}|a_n b_n - ab| &= |a_n b_n - ab_n + ab_n - ab| \\ &\leq |a_n b_n - ab_n| + |ab_n - ab| \\ &= |b_n||a_n - a| + |a||b_n - b|\end{aligned}$$

Let $\epsilon > 0$ be arbitrary. For $|a||b_n - b|$, we can choose N_1 so that

$$n \geq N_1 \text{ implies } |b_n - b| < \frac{1}{|a|}\frac{\epsilon}{2}$$

as long as $a \neq 0$. This causes the right side to be less than $\frac{\epsilon}{2}$ Now for $|b_n||a_n - a|$, we know $|b_n| \leq M$ for some M since it is bounded. So,

$$|b_n||a_n - a| \leq M|a_n - a|$$

So we choose an N_2 so that

$$|a_n - a| < \frac{1}{M}\frac{\epsilon}{2} \text{ whenever } n \geq N_2$$

Now, pick $N = max\{N_1, N_2\}$, and observe that if $n \geq N$, then

$$\begin{aligned}|a_n b_n - ab| &= |a_n b_n - ab_n + ab_n - ab| \\ &\leq |a_n b_n - ab_n| + |ab_n - ab| \\ &= |b_n||a_n - a| + |a||b_n - b| \\ &\leq M|a_n - a| + |a||b_n - b| \\ &< M(\frac{\epsilon}{M2}) + |a|(\frac{\epsilon}{|a|2}) = \epsilon\end{aligned}$$

(iv) This is proven by (iii) if we can prove that

$$(b_n) \to b \text{ implies } (\frac{1}{b_n}) \to \frac{1}{b}$$

whenever $b \neq 0$.

$$|\frac{1}{b_n} - \frac{1}{b}| = \frac{|b - b_n|}{|b||b_n|}$$

We can make $|b - b_n|$ as small as we want. To find a worst case estimate of $|b||b_n|$, we must find a lower bound greater than 0. Consider $\epsilon_0 = |b|/2$. Since $(b_n) \to b$, there exists an N_1 such that $|b_n - b| < |b|/2$ for all $n \geq N_1$. This implies $|b_n| > |b|/2 > 0$.

Next, choose N_2 so that $n \geq N$ implies

$$|b_n - b| < \frac{\epsilon|b|^2}{2}$$

Finally, set $N = max\{N_1, N_2\}$, then $n \geq N$ implies

$$|\frac{1}{b_n} - \frac{1}{b}| = |b - b_n|\frac{1}{|b||b_n|} < \frac{\epsilon|b|^2}{2}\frac{1}{|b|\frac{|b|}{2}} = \epsilon$$

□

Limits and Order

THEOREM 2.3.4 (Order Limit Theorem)**.** *Assume* $\lim a_n = a$ *and* $\lim b_n = b$
(i) if $a_n \geq 0$ *for all* $n \in \boldsymbol{N}$*, then* $a \geq 0$*.*
(ii) if $a_n \geq b_n$ *for all* $n \in \boldsymbol{N}$*, then* $a \geq b$*.*
(iii) If there exists $c \in \boldsymbol{R}$ *for which* $c \leq b_n$ *for all* $n \in \boldsymbol{N}$*, then* $c \leq b$*. And same for* a_n *and* a*.*

Proof. (i) We prove this by contradiction. Assume $a < 0$. Then, consider a value of $\epsilon_0 = |a|$. The definition of convergence guarantees that we can find an N such that $|a_n - a| < |a|$ for all $n \geq N$. This means that $|a_N - a| < |a|$, which implies $a_N < 0$, which contradicts that $a_N \geq 0$. We therefore conslude that $a \geq 0$.
(ii) The Algebraic Limit Theorem ensures that the sequence $(b_n - a_n)$ converges to $b - a$. Because $b_n - a_n \geq 0$, we can apply part (i) to get that $b - a \geq 0$.
(iii) Take $a_n = c$ (or $b_n = c$) for all $n \in \mathbf{N}$, and apply (ii). □

In this theorem, we assumed things for all $n \in \mathbf{N}$, but these properties hold true if these assumptions are true for all $n \geq N$, where N is a finite natural number. If a property is of this form it is said to be *eventually* true. Theorem 2.3.4, part (i), could be restated, "Convergent sequences that are eventually nonnegative converge to nonnegative limits."

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

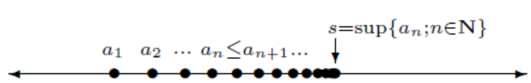
Definition 2.4.1. A sequence (a_n) is *increasing* if $a_n \leq a_{n+1}$ for all $n \in \mathbf{N}$ and *decreasing* if $a_n \geq a_{n+1}$ for all $n \in \mathbf{N}$. A sequence is *monotone* if it is either increasing or decreasing.

THEOREM 2.4.2 (Monotone Convergence Theorem)**.** *If a sequence is monotone and bounded, then it convergences*

Proof. Let (a_n) be monotone and bounded. Let's assume (a_n) is increasing (the decreasing case is handled similarly), and consider the *set* of points $\{a_n : n \in \mathbf{N}\}$. Since the series is bounded, this set it also bounded, so using the Axiom of Completeness, we can let

$$s = \sup\{a_n : n \in \mathbf{N}\}$$

It seems reasonable for $\lim(a_n) = s$



Let $\epsilon > 0$ be arbitrary. Since s is the least upper bound, $s-\epsilon$ is not an upper bound, so there exists a point in the sequence a_N such that $s-\epsilon < a_N$. Now, since (a_n) is increasing, $a_N \leq a_n$ for all $n \geq N$. Hence,

$$s-\epsilon < a_N \leq a_n \leq s \leq s+\epsilon$$

which implies $|a_n - s| < \epsilon$, as desired. □

The Monotone Convergence Theorem is useful for infinite series, since it asserts convergealignnces without any mention of the actual limit. **Definition 2.4.3.** Let (b_n) be a sequence. An *infinite series* is a formal expression of the form

$$\sum_{n=1}^{\infty} b_n = b_1 + b_2 + b_3 + \dots$$

We define the corresponding *sequence of partial sums* (s_m) by

$$s_m = \sum_{n=1}^{m} b_n = b_1 + b_2 + b_3 + \cdots + b_m$$

and say the the series $\sum_{n=1}^{\infty} b_n$ *converges to* B if the sequence (s_m) converges to B. In this case, we write $\sum_{n=1}^{\infty} b_n = B$.

THEOREM 2.4.7 (Cauchy Condensation Test)**.** *Suppose* (b_n) *is decreasing and satisfies* $b_n \geq 0$ *for all* $n \in \boldsymbol{N}$*. Then, the series* $\sum_{n=1}^{\infty} b_n$ *converges if and only if the series*

$$\sum_{n=0}^{\infty} 2^n b_{2^n}$$

converges.

Proof. First, assume that $\sum_{n=0}^{\infty} 2^n b_{2^n}$ converges. Then the partial sums

$$t_k = b_1 + 2b_2 + 4b_4 + \cdots + 2^k b_{2^k}$$

are bounded. There exists an $M > 0$ such that $t_k \leq M$ for all $k \in \mathbf{N}$. Since $b_n \geq -$, we now that the partial sums are increasing, so we only need to show that

$$s_m = b_1 + b_2 + \cdots + b_m$$

is bounded.

Fix m and let k be large enough to ensure $m \leq 2^{k+1}-1$. Then, $s_m \leq s_{2^{k+1}-1}$ and

$$s_{2^{k+1}-1} = b_1 + (b_2+b_3) + (b_4+b_5+b_6+b_7) + \cdots + (b_{2^k} + \cdots + b_{2^{k+1}-1})$$
$$\leq b_1 + (b_2+b_2) + (b_4+b_4+b_4+b_4) + \cdots + (b_{2^k} + \cdots + b_{2^k}) = b_1 + 2b_2 + 4b_4 + \cdots + 2^k b_{2^k} = t_k$$

Thus, $s_m \leq t_k \leq M$, and the sequence (s_m) is bounded. By the Monotone Convergence Theorem, we can conclude that $\sum_{n=1}^{\infty} b_n$ converges.

Now, if $\sum_{n=0}^{\infty} 2^n b_{2^n}$ diverges. Fix m and let k be big enough to ensure $m \leq 2^k$. Then,

$$\begin{aligned} s_{2^k} &= b_1 + b_2 + (b_3 + b_4) + (b_5 + b_6 + b_7 + b_8) + \cdots + (b_{2^{k-1}+1} + \dots b_{2^k}) \\ &\geq b_1 + b_2 + (b_4 + b_4) + (b_8 + b_8 + b_8 + b_8) + \cdots + (b_{2^k} + b_{2^k} + \cdots + b_{2^k}) \\ &= b_1 + b_2 + 2b_4 + 4b_8 + \cdots + k(b_k) \\ &= b_1 + (t_k - b_1)/2 = (b_1 + t_k)/2 \end{aligned}$$

So, $s_m > (b_1 + t_k)/2$, which diverges since t_k diverges so s_m diverges. □

Corollary 2.4.7 *The series $\sum_{n=1}^{\infty} 1/n^p$ converges if and only if $p > 1$*

2.5 Subsequence and the Bolzano-Weierstrass Theorem

Definition 2.5.1. Let (a_n) be a sequence of real numbers, and let $n_1 < n_2 < n_3 < n_4 < \dots$ be an increasing sequence of natural numbers. Then the sequence

$$a_{n_1}, a_{n_2}, a_{n_3}, a_{n_4}, a_{n_5}, a_{n_6}, \dots$$

is called a *subsequence* of (a_n) and is denoted by (a_{n_j}), where $j \in \mathbf{N}$ indexes the subsequence.

The terms in a subsequence are in the same order as the original sequence, and repetitions are not allowed.

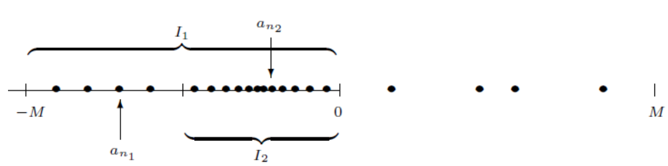
THEOREM 2.5.2. *Subsequences of a convergent sequence converge to the same limit as the original sequence.*

Proof. TODO: Exercise 2.5.1 □

The Bolzano–Weierstrass Theorem

THEOREM 2.5.5 (The Bolzano–Weierstrass Theorem)**.** *Every bounded sequence contains a convergent subsequence.*

Proof. Let (a_n) be a bounded sequence so that there exists $M > 0$ satisfying $|a_n| \leq M$ for all $n \in \mathbf{N}$. Split $[-M, M]$ into $[-M, 0]$ and $[0, M]$. At least one of these intervals contain an infinite number of the points in the sequence (a_n). Select a half for which this is the case and label that interval as I_1. Then, let a_{n_1} be some point in the sequence (a_n) satisfying $a_{n_1} \in I_1$.



Next, we bisect I_1 into closed intervals of equal length, and let I_2 be a half that again contains an infinite number of points of the original sequence. Then choose an a_{n_2} such that $n_2 > n_1$ and $a_{n_2} \in I_2$. In general, we construct the closed interval I_k by taking a half of I_{k-1} containing an infinite number of points of (a_n) and then select $n_k > n_{k-1} > \cdots > n_2 > n_1$ so that $a_{n_k + \in I_k}$. The sets

$$I_1 \subseteq I_2 \subseteq I_3 \subseteq \ldots$$

form a nested sequence of closed intervals, so by the Nested Interval Property there exists at least one point $x \in \mathbf{R}$ contained in every I_k. Now, we will show that $(a_{n_k} \to x)$.

Let $\epsilon > 0$. By construct, the length of I_k is $M(1/2)^{k-1}$ which converges to zero. Choose N so that $k \geq N$ implies that the length of I_k is less than ϵ. Since x and a_{n_k} are both in I_k, it follows that $|a_{n_k} - x| < \epsilon$. $\square$