M 361K: Real Analysis

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1.1 Algebraic Axioms

$\forall a, b, c \in \mathbb{R}$

- (A1) $a + b = b + a$.
- (A2) $(a + b) + c = a + (b + c)$.
- (A3) $\exists$ an element $o \in \mathbb{R}$ such that $a + o = o + a = a$.
- (A4) For each element $a \in \mathbb{R}$, $\exists$ an element $(-a) \in \mathbb{R}$ such that $a + (-a) = 0$.
- (M1) $ab = ba$.
- (M2) $(ab)c = a(bc)$.
- (M3) $\exists$ an element $1 \in \mathbb{R}$ such that $a * 1 = 1 * a = a$.
- (M4) For each element $a \in \mathbb{R} \setminus 0$, $\exists$ an element $\frac{1}{a} \in \mathbb{R}$ such that $a * \frac{1}{a} = \frac{1}{a} * a = 1$.
- (D) $a * (b + c) = a * b + a * c$.

Remark (Equality property of $\mathbb{R}$). If $a = b$ and $c = d$, then $a + c = b + d$ and $a * c = b * d$.

$\forall x, y, z \in \mathbb{R}$:

Theorem 1.1. If $x + z = y + z$ then $x = y$.

Proof.

$$\begin{aligned} x + z &= y + z \quad (A4) \\ (x + z) + (-z) &= (y + z) + (-z) \quad (A2) \\ x + (z + (-z)) &= y + (z + (-z)) \quad (A4) \\ x + 0 &= y + 0 \quad (A3) \\ x &= y \end{aligned}$$

□

Theorem 1.2. For any $x \in \mathbb{R}$, $x * 0 = 0$.

Proof.

$$\begin{aligned} x * 0 &= x * (0 + 0) \\ x * 0 &= x * 0 + x * 0 \\ x * 0 + (-x * 0) &= (x * 0 + x * 0) + (-x * 0) \\ 0 &= x * 0 + (x * 0 + (-x * 0)) \\ &= x * 0 + 0 \\ &= x * 0 \end{aligned}$$

□

Theorem 1.3. $-1 * x = -x$ i.e. $x + (-1) * x = 0$.

Proof.

$$\begin{aligned} x + (-1) * x &= x + x * (-1) \\ &= x * 1 + x * (-1) \\ &= x * (1 + (-1)) \\ &= x * 0 \\ &= 0 \end{aligned}$$

□

Theorem 1.4 (Zero-product property)**.** $\forall x, y \in \mathbb{R}$, $x * y = 0 \iff x = 0 \vee y = 0$.

Proof. Let $x, y \in \mathbb{R}$, if $x = 0$ or $y = 0$, then $x * y = 0$. Suppose $x \neq 0$, then we must show $y = 0$. Since $x \neq 0$, $\frac{1}{x}$ exists. Thus, if:

$$\begin{aligned} xy &= 0 \\ \frac{1}{x} * (xy) &= \frac{1}{x} * 0 \\ (\frac{1}{x} * (xy)) * y &= 0 \\ 1 * y &= 0 \\ y &= 0 \end{aligned}$$

□

1.2 Order Axioms

$\forall x, y \in \mathbb{R}$:

- (O1) One of $x < y$, $x > y$ or $x = y$ is true.
- (O2) If $x < y$ and $y < z$, then $x < z$.
- (O3) If $x < y$ then $x + z < y + z$.
- (O4) If $x < y$ and $z > 0$ then $xz < yz$.

Theorem 1.5. If $x < y$ then $-y < -x$.

Proof.

$$\begin{gathered} x < y \\ x + (-x + -y) < y + (-x + -y) \\ (x + -x) + -y < (y + -y) + -x \\ 0 + -y < 0 + -x \\ -y < -x \end{gathered}$$

□

Theorem 1.6. If $x < y$ and $z > 0$ then $xz > yz$.

Proof. If $x < y$ and $z > 0$ then $-z > 0$. Thus, $x(-z) < y(-z)$. But,

$$\begin{aligned} x(-z) &= x(-1 * z) \\ &= (x * -1) * z \\ &= (-1 * x) * z \\ &= -1(x * z) \\ &= -x * z \end{aligned}$$

Similarly, $y(-z) = -y * z$. Thus, $-x * z < -y * z$, so $xz > yz$. $\square$

Remark (Completeness of $\mathbb{R}$). $\mathbb{R}$ is an ordered field. $\mathbb{R}$ is complete, while $\mathbb{Q}$ is not complete.

2 August 30

Theorem 2.1. $\sqrt{2}$ is irrational.

Proof. Suppose not. Suppose that $\sqrt{2}$ is rational. Then $\exists m, n \in \mathbb{Z}$ such that $\sqrt{2} = \frac{m}{n}, n \neq 0$ and m and n share no common factors. Then,

$$\begin{aligned} 2 &= \frac{m^2}{n^2} \\ 2n^2 &= m^2 \end{aligned}$$

Thus, m^2 is even and m is even. Then, $m = 2k$ for some $k \in \mathbb{Z}$. But, by substituting $m = 2k$ into the above equation, we get

$$\begin{aligned} 2n^2 &= (2k)^2 \\ 2n^2 &= 4k^2 \\ n^2 &= 2k^2 \end{aligned}$$

Thus, n^2 is even, so n is even. So, n is a perfect square, which is a contradiction. Thus, $\sqrt{2}$ is irrational. $\square$

2.1 Upper and Lower Bounds

Theorem: Let S be a subset of $\mathbb{R}$. If there exists a real number m such that $m \geq s \forall s \in S$, m is called an **upper bound** for S. If $m \leq s \forall s \in S$, m is called a **lower bound** for S. **Minimums** and **maximums** must exist in the set to be valid.

$$T = \{q \in \mathbb{Q} \mid 0 \leq q \leq \sqrt{2}\}$$

- Lower bound: -420, -1
- Upper bound: 100, 5, 2

- Minimum: 0
- Maximum: No max

Because rationals are not complete, there is no upper bound for T.

Definition 2.1 (Supremum)**.** The least upper bound of a set is called the supremum of the set.

Definition 2.2 (Infimum)**.** The greatest lower bound of a set is called the infimum of the set.

2.2 Completeness Axiom

Definition 2.3 (Completeness axiom)**.** Every nonempty subset of $\mathbb{R}$ that is bounded above has a least upper bound. That is, $\sup S$ exists and is a real number.

Theorem 2.2. The set of natural numbers $\mathbb{N}$ is unbounded above.

Proof. Suppose not. Suppose that $\mathbb{N}$ is bounded above. If $\mathbb{N}$ were bounded above, it must have a supremum m. Since $\sup \mathbb{N} = m$, $m - 1$ is not an upper bound. Thus, $\exists n_0 \in \mathbb{N}$ such that $n_0 > m - 1$. But then, $n_0 + 1 > m$. This is a contradiction since $n_0 + 1 \in N$. Thus, N is unbounded above. $\square$

Theorem 2.3. If A and B are nonempty subsets of $\mathbb{R}$, let $C = \{x + y \mid x \in A, y \in B\}$. If $\sup A$ and $\sup B$ exist, then $\sup C = \sup A + \sup B$.

Proof. Let $\sup A = a$ and $\sup B = b$. Then if $z \in C, z = x + y$ for some $x \in A, y \in B$. Then,

$$z = x + y \leq a + b = \sup A + \sup B$$

By the completeness axiom, $\exists$ a least upper bound of $C, c = \sup C$. It must be that $c \leq a+b$, so we must show $c \geq a + b$. Let $\epsilon > 0$. Since $a = \sup A$, $a - \epsilon$ is not an upper bound for A. $\exists x \in A$ such that $a - \epsilon < x$. Likewise, $\exists y \in B$ such that $b - \epsilon < y$. Then,

$$(a - \epsilon) + (b - \epsilon) = a + b - 2 * \epsilon < x + y \leq c$$

Thus, $a + b < c + 2 * \epsilon \forall \epsilon > 0$. So, $a + b \leq c \therefore c = a + b$. $\square$

3 September 6

3.1 Cardinality

Definition 3.1 (Cardinality)**.** The cardinality of a set A is the number of elements in A. We denote this as $|A|$. We say that two sets A and B have the same cardinality if and only if $\exists$ a bijection $f : A \to B$, or $|A| = |B|$.

Remark. This bijection holds true because cardinality is reflexive (via the identity function), symmetric (via the inverse function), and transitive (via composition).

Remark. The following examples demonstrate how to prove whether two sets have the same cardinality.

- $|\text{even integers}| = |\text{odd integers}|$: $f(2n) = 2n + 1$.
- $|\mathbb{Z}| = |\mathbb{Z}^+|$: $f(0) = 1$, $f(1) = 2$, $f(-1) = 3$, $f(2) = 4$, $\ldots$
- $|\mathbb{Q}^+| = |\mathbb{Z}^+|$: We can create a diagonal mapping by taking $\frac{n}{m}$ for counting numbers on the rows and columns.
- $|\mathbb{Q}| = |\mathbb{Z}^+|$: $\mathbb{Q} = \mathbb{Q}^+ \cup \mathbb{Q}^- \cup \{0\}$, so we can repeat the diagonal mapping for $\mathbb{Q}^-$. This is because any subset of a countable set is countable.
- $|\mathbb{Q}| \neq |\mathbb{R}|$: For the real numbers, Cantor's Diagonal Argument proves the sets have different cardinality since no possible surjection exists.

In essence, if we show that there exists some one-to-one mapping between the two sets we can claim that $|A| = |B|$.

3.2 Countability

Definition 3.2 (Countable)**.** If a set is finite or has the same cardinality as $\mathbb{N}$ (i.e. $\mathbb{Z}^+$), we say that the set is countable.

Theorem 3.1. Any subset of a countable set is countable.

Theorem 3.2. Any set that contains an uncountable set is uncountable.

Theorem 3.3. If $[a_n, b_n] \forall n \in \mathbb{N}$ is a nested sequence of closed bounded intervals, $\exists \delta \in \mathbb{R}$ such that $\delta \in I_n \forall n \in \mathbb{N}$.

Proof. $I_n \subseteq I_1 \forall n \in \mathbb{N}$. Thus, $a_n \subseteq b_1 \forall n \in \mathbb{N}$. So, b_n is an upper bound for $\{a_n \mid n \in \mathbb{N}\}$. Let δ be the supremum of $\{a_n \mid n \in \mathbb{N}\}$. Thus, $a_n \leq \delta \forall n \in \mathbb{N}$.

We have now shown that $a_n \leq \delta \forall n \in \mathbb{N}$, and we need to show that $\delta \leq b_n \forall n \in \mathbb{N}$. This is left as an exercise for the reader. □

Remark. A nested sequence means that successive subsets contain the previous subset. For example, $[0, 1] \subseteq [0, 2] \subseteq [0, 3] \subseteq \ldots$ is a nested sequence.

Theorem 3.4. $[0, 1]$ is uncountable.

Proof. Assume $[0, 1]$ is countable. That is, $[0, 1] = I = \{x_1, x_2, x_3, \ldots\}$. Select a closed interval $I_1 \subseteq I$ such that $x_1 \notin I_1$. Next, select a closed interval $I_2 \subseteq I_1$ such that $x_2 \notin I_2$, and so on. Then, we have

$$I_n \subseteq \ldots \subseteq I_2 \subseteq I_1 \subseteq I$$

and $x_n \notin I_n \forall n \in \mathbb{N}$. By **Theorem 3.3**, $\exists \delta \in I$ such that $\delta \in I_n \forall n \in \mathbb{N}$. This implies that $\delta \neq x_n \forall n \in \mathbb{N}$. Thus, $\delta \notin I$, which is a contradiction. Therefore, $[0, 1]$ is uncountable. □

4 September 8

4.1 Limits of Sequences

Definition 4.1 (Limit of a sequence)**.** A sequence a_n is said to converge to a real number s, if for any $\epsilon > 0$, $\exists$ a real number k such that for all $n \geq k$, the terms a_n satisfy $|a_n - s| < \epsilon$.

Theorem 4.1. $\lim_{n\to\infty} \frac{1}{\sqrt{n}} = 0$.

Proof. We need to find some N such that $n > N \forall \epsilon > 0$.

$$\begin{aligned} |\frac{1}{\sqrt{n}} - 0| &< \epsilon \\ \frac{1}{\sqrt{n}} &< \epsilon \\ \frac{1}{n} &< \epsilon^2 \\ n &> \frac{1}{\epsilon^2} \end{aligned}$$

Let $\epsilon > 0$ and $N = \frac{1}{\epsilon^2}$. Then, if $n > N$, we have that

$$\begin{aligned} |\frac{1}{\sqrt{n}} - 0| &= \frac{1}{\sqrt{n}} \\ &< \frac{1}{\sqrt{\frac{1}{\epsilon^2}}} \\ &= \epsilon \end{aligned}$$

Thus, $\lim_{n\to\infty} \frac{1}{\sqrt{n}} = 0$. □

Theorem 4.2. $\lim_{n\to\infty} 1 + \frac{1}{2^n} = 1$.

Proof. Let $\epsilon > 0$ and $N = \frac{1}{\epsilon}$. Then, we have

$$\begin{aligned} |1 + \frac{1}{2^n} - 1| &< \epsilon \\ |\frac{1}{2^n}| = \frac{1}{2^n} < \frac{1}{n} &< \frac{1}{\frac{1}{\epsilon}} < \epsilon \\ n &> \frac{1}{\epsilon} \end{aligned}$$

Thus, $\lim_{n\to\infty} 1 + \frac{1}{2^n} = 1$. □

Theorem 4.3. Every convergent sequence is bounded.

Proof. Let S_n be a convergent sequence with a limit s and $\epsilon = 1$. Then, there exists some N such that $|S_n - s| < 1$. That is, $|S_n| < |s| + 1$.

Let $M = \max\{S_1, S_2, \ldots, S_n, |s| + 1\}$. Then, $|S_n| \leq M$, so S_n is bounded. □

Theorem 4.4. If a sequence converges, its limit is unique.

Proof. Suppose a sequence S_n converges to s and t. Let $\epsilon > 0$. Then, $\exists N_1$ such that $|S_n - s| < \frac{t}{2}$. For $n > N_1$, $\exists N_2$ such that $|S_n - t| < \frac{t}{2}$. For $n > N_2$, let $N = m + \{N_1, N_2\}$. Then, for $n > N$, we have

$$\begin{aligned} |s-t| &= |s + S_n - S_n - t| \\ &= |s - S_n + S_n - t| \\ &\leq |s - S_n| + |S_n - t| \\ &< \frac{\epsilon}{2} + \frac{\epsilon}{2} \\ |s-t| &= \epsilon \end{aligned}$$

Thus, the limit is unique. □

5 September 13

5.1 Monotone Sequences

Definition 5.1 (Monotone sequence)**.** A sequence S_n of real numbers is said to be increasing $\iff S_n \leq S_{n+1} \; \forall \; n \in \mathbb{N}$ and decreasing $\iff S_n \geq S_{n+1} \; \forall \; n \in \mathbb{N}$.

The Fibonacci sequence is an example of an increasing sequence.

Definition 5.2 (Monotone convergence theorem)**.** A monotone sequence is convergent if and only if it is bounded.

Theorem 5.1. An increasing bounded sequence is convergent.

Proof. Suppose S_n is a bounded increasing sequence. Let S be the set $\{S_n \mid n \in \mathbb{N}\}$. By the completeness axiom, $\sup S$ exists. Let $s = \sup S$. We claim $\lim_{n\to\infty} S_n = s$. Given $\epsilon > 0, s - \epsilon$ is not an upper bound for S.
Thus, $\exists \; N \in \mathbb{N}$ such that $S_N > s - \epsilon$. Furthermore, since S_n is increasing and s is an upper bound for S, we have $s - \epsilon < S_N \leq S_n \leq s \; \forall \; n \geq N$. □

Remark. This is an elementary proof because it only uses axioms to make the conclusion.

Ex. $S_{n+1} = \sqrt{1 + S_n}, S_1 = 1$.

Theorem 5.2. If S_n is an unbounded increasing sequence, then $\lim_{n\to\infty} S_n = \infty$.

Proof. Let S_n be an increasing unbounded sequence. Then, $\{S_n \mid n \in \mathbb{N}\}$ is not bounded above, but S is bounded below by S_1. Thus, given $M \in \mathbb{R}, \exists N \in \mathbb{N}$ such that $S_N > M$. But since S_n is increasing, $S_n > M \; \forall \; n > N$. Thus, $\lim_{n\to\infty} S_n = \infty$. □

6 September 15

6.1 Cauchy Sequences

Definition 6.1 (Cauchy sequence)**.** A sequence of real numbers S_n is called a Cauchy sequence if and only if for each $\epsilon > 0$, $\exists N$ such that $m, n > N \implies |S_m - S_n| < \epsilon$.

Remark. This means the elements of the sequence get closer to each other as N increases.

Theorem 6.1. Every convergent sequence is Cauchy.

Proof. Let S_n be a convergent sequence. Then $\exists N$ such that $n > N \implies |S_n - s| < \frac{\epsilon}{2}$ for some $s \in \mathbb{R}$. Then, for $n, m > N$, we have

$$\begin{aligned} |S_n - S_m| &= |S_n - s + s - S_m| \\ &\leq |S_n - s| + |s - S_m| \\ &< \frac{\epsilon}{2} + \frac{\epsilon}{2} \\ &= \epsilon \end{aligned}$$

Thus, S_n is Cauchy. □

Theorem 6.2. A sequence of real numbers is Cauchy if and only if it is convergent.

Remark. We cannot prove this yet.

7 September 20

7.1 Empty Set

Theorem 7.1. The empty set is a subset of any set.

Proof. Suppose not. That is, suppose $\exists A$ such that $\emptyset \not\subset A$. Thus, $\exists x \in \emptyset$ such that $x \notin A$. This is a contradiction because the empty set has no elements. Therefore, $\emptyset \subset A$. □

Theorem 7.2. There is only one set with no elements.

Proof. Suppose not. That is, suppose $\exists$ two empty sets E_1, E_2. Then $E_1 \subseteq E_2$ and $E_2 \subseteq E_1$. Thus, $E_1 = E_2$. This is a contradiction because E_1 and E_2 are two different sets. Therefore, there is only one empty set. □

Remark (Closedness of $\emptyset$)*.* The empty set is open and closed (vacuosly true).

7.2 Topology of Real Numbers

Let $S \subseteq \mathbb{R}$ for the following definitions.

7.2.1 Neighborhoods

Definition 7.1 (Neighorhood)**.** A neighorhood of x in S can be thought of an epsilon-sized ball around x, i.e. $N(x, \epsilon) = \{y \in R \mid 0 \leq |x - y| < \epsilon\}$.

Definition 7.2 (Deleted neighborhood)**.** A deleted neighorhood is the same as a neighorhood except that x is not included, i.e. $N^\star(x, \epsilon) = \{y \in R \mid 0 < |x - y| < \epsilon\}$.

Definition 7.3 (Accumulation point)**.** $x \in \mathbb{R}$ is an accumulation point of S if and only if every deleted neighborhood of x contains a point of S.

Remark. $(0, \infty)$ has accumulation points $[0, \infty)$. $(0, 1)$ does not contain all of its accumulation points since 0 and 1 are both accumulation points of the set.

Theorem 7.3. $S \in \mathbb{R}$ is closed if and only if S contains all of its accumulation points.

Proof. Suppose S is closed. Let x be an accumulation point of S. If $x \notin S$, then $x \in S^c$. Thus, $\exists$ a neighborhood N of x such that $N \subseteq S^c$. But $N \cap S = \emptyset$, which contradicts x being an accumulation point of S.

Conversely, suppose S contains all of its accumulation points. Let $x \in S^c$, then x is not an accumulation point of S. Thus, $\exists N^\star(x, \epsilon)$ that misses S. Since $x \notin S$, $N(x, \epsilon)$ misses S. Therefore, S^c is open, which means S is closed. □

Theorem 7.4. If S is a nonempty closed bounded subset of $\mathbb{R}$, then S has a max.

Proof. Let $s = \sup S$. Then, s is an accumulation point of S. Since S is closed, $s \in S$. Thus, s is a max of S. □

7.2.2 Interior and Boundary Points

Definition 7.4 (Interior point)**.** $x \in S$ is an interior point of S if and only if $\exists N(x, t)$ such that $N(x, t) \subset S$.

Definition 7.5 (Boundary point)**.** $x \in S$ is a boundary point of S if and only if every neighborhood N of x has $N \cap S \neq \emptyset$ and $N \cap S^c \neq \emptyset$.

7.3 Closure

Definition 7.6 (Open set)**.** S is an open set if and only if every point in S is an interior point of S. $\forall x \in S, \exists$ a neighborhood $N(x, \epsilon)$ for some $\epsilon > 0$ such that $N(x, \epsilon) \subseteq S$.

Definition 7.7 (Closed set)**.** S is a closed set if and only S contains at least one of its boundary points. Additionally, S^c must be an open set.

Remark (Closure of $\mathbb{R}$). $\mathbb{R}$ is open because all of its points are interior points. $\mathbb{R}$ is also closed because $\mathbb{R}$ has no boundary points, therefore implying that it contains at least one of its boundary points (vacuously true).

Theorem 7.5. The union of two open sets is open.

Proof. Let A and B be open sets. Let $x \in A \cup B$. Then $x \in A$ or $x \in B$. If $x \in A$, then $\exists$ a neighborhood N_1 of x such that $N_1 \subseteq A$. But then, $N_1 \subseteq A \cup B$. If $x \in B$, then $\exists$ a neighborhood N_2 of x such that $N_2 \subseteq B$. But then, $N_2 \subseteq A \cup B$.

Thus, in either case, $\exists$ a neighborhood N of x such that $N \subseteq A \cup B$. Therefore, $A \cup B$ is open. □

Theorem 7.6. An arbitrary union of open sets is open.

Proof. Let $A_1, A_2, \ldots, A_n$ be open sets. Let $x \in \bigcup_{i=1}^n A_i$. Then $x \in A_i$ for some i. Let N_i be a neighborhood of x such that $N_i \subseteq A_i$. Then $N_i \subseteq A_i \subseteq \bigcup_{i=1}^n A_i$. Therefore, $\bigcup_{i=1}^n N_i \subseteq \bigcup_{i=1}^n A_i$.

Thus, $\bigcup_{i=1}^n N_i$ is a neighborhood of x such that $\bigcup_{i=1}^n N_i \subseteq \bigcup_{i=1}^n A_i$. Therefore, $\bigcup_{i=1}^n A_i$ is open. □

Theorem 7.7. The intersection of two open sets is open.

Proof. Let A and B be open sets. Let $x \in A \cap B$. Then $x \in A$ and $x \in B$. Thus, $\exists$ neighborhoods $N_1(x, \epsilon_1)$ and $N_2(x, \epsilon_2)$. Let $\epsilon = min\{\epsilon_1, \epsilon_2\}$. Then $N_1(x, \epsilon) \subseteq A$ and $N_2(x, \epsilon) \subseteq B$.

Thus, $N(x, \epsilon) \subseteq A \cap B$. Therefore, $A \cap B$ is open. □

Theorem 7.8. A finite intersection of open sets is open.

Proof. Let $A_1, A_2, \ldots, A_n$ be open sets. Let $x \in \bigcap_{i=1}^n A_i$. Then $x \in A_i$ for all i. Let N_i be a neighborhood of x such that $N_i \subseteq A_i$. Then $N_i \subseteq A_i \subseteq \bigcap_{i=1}^n A_i$. Therefore, $\bigcap_{i=1}^n N_i \subseteq \bigcap_{i=1}^n A_i$.

Thus, $\bigcap_{i=1}^n N_i$ is a neighborhood of x such that $\bigcap_{i=1}^n N_i \subseteq \bigcap_{i=1}^n A_i$. Therefore, $\bigcap_{i=1}^n A_i$ is open. □

Theorem 7.9. An arbitrary intersection of open sets is open.

Remark (Counterexample). $\bigcap_{i=1}^{\infty}(-\frac{1}{n}, \frac{1}{n}) = \emptyset$.

7.4 Set Covers

Definition 7.8 (Open cover)**.** An open cover F of some subset $S \in \mathbb{R}$ is a collection of open sets whose union contains S.

Remark. If $E \subseteq F$ and E also covers S, we call E a **subcover**.

Definition 7.9 (Compact)**.** A set S is said to be compact is and only if whenever S is contained in the union of a family F of open sets, then it is contained in a finite number of the sets in F (every open cover has a finite subcover).

Remark. It is hard to show that a set is compact since we have to consider *every* open cover.

Theorem 7.10 (Heine-Borel)**.** A subset S of $\mathbb{R}$ is compact if and only if S is closed and bounded.