21-355: Real Analysis 1

Carnegie Mellon University

Professor Ian Tice - Fall 2013

Project LaTeX'd by Ivan Wang

Contents

1 Section 1 - The Number Systems **2**

1.1 The Natural Numbers . . . 2

1.1.1 Positivity . . . 3

1.1.2 Order . . . 3

1.1.3 Multiplication . . . 4

1.2 The Integers . . . 4

1.2.1 Properties of Integers . . . 5

1.2.2 Algebraic Properties . . . 5

1.3 The Rationals and Ordered Fields . . . 6

1.3.1 Fields and Orders . . . 6

1.4 Problems with $\mathbb{Q}$ . . . 7

1.4.1 Bounds (Infimum and Supremum) . . . 7

1.5 The Real Numbers . . . 8

1.5.1 Defining the Real Numbers: Dedekind Cuts . . . 8

1.5.2 Defining the Real Numbers: The Least Upper Bound Property . . . 9

1.5.3 Defining the Real Numbers: Addition . . . 9

1.5.4 Defining the Real Numbers: Multiplication . . . 10

1.5.5 Defining the Real Numbers: Distributivity . . . 10

1.5.6 Defining the Real Numbers: Archimedean . . . 11

1.6 Properties of $\mathbb{R}$ . . . 11

1.6.1 Absolute Value . . . 12

2 Sequences **12**

2.1 Convergence and Bounds . . . 12

2.1.1 Squeeze Lemma . . . 13

2.2 Monotonicity and limsup, liminf . . . 14

2.3 Subsequences . . . 14

2.3.1 Limsup Theorem . . . 15

1 Section 1 - The Number Systems

1.1 The Natural Numbers

Theorem (existence of $\mathbb{N}$): There exists a set $\mathbb{N}$ satisfying the following properties, known as the Peano Axioms:

PA1 $0 \in \mathbb{N}$

PA2 There exists a function $S : \mathbb{N} \to \mathbb{N}$ called the successor function. In particular, $S(n) \in \mathbb{N}$.

PA3 $\forall n \in \mathbb{N}.\ S(n) \neq 0$

PA4 $S(n) = S(m) \implies n = m$ (S is injective, one-to-one)

PA5 [Axiom of Induction] Let $P(n)$ be a property associated to each $n \in \mathbb{N}$.
If $P(0)$ is true, and $P(n) \implies P(S(n))$, then $P(n)$ is true $\forall n \in \mathbb{N}$.

Definition: **PA1** $\implies 0 \in \mathbb{N}$. **PA2** $\implies S(0) \in \mathbb{N}$.

Define $1 = S(0), 2 = S(1), 3 = S(2)$, etc.

PA2 guarantees that $\{0, 1, 2, \cdots\} \subseteq \mathbb{N}$.

PA3 prevents "wraparound": no successor can map to a "negative" number.

PA4 prevents "stagnation": the cycle does not terminate.

Theorem: $\mathbb{N} = \{0, 1, 2, \cdots\}$

Proof: We know that $\{0, 1, 2, \cdots\} \subseteq \mathbb{N}$, so it suffices to prove that $\mathbb{N} \subseteq \{0, 1, 2, \cdots\}$.

Let $P(n)$ denote the proposition that $n \in \{0, 1, 2, \cdots\}$. Clearly $P(0)$ is true.

Suppose $P(n)$ is true; then $n \in \{0, 1, 2, \cdots\} \implies S(n) \in \{0, 1, 2, \cdots\}$ by construction. Hence, $P(S(n))$ is true. By induction, **PA5** guarantees that $P(n)$ is true $\forall n \in \mathbb{N}$.

It follows that $\mathbb{N} \subseteq \{0, 1, 2, \cdots\}$.

Definition: For any $m \in \mathbb{N}$, we define $0 + m = m$.
Then if $n + m$ is defined for $n \in \mathbb{N}$, we set $S(n) + m = S(n + m)$.

Proposition (Properties of Addition):

1. $\forall n \in \mathbb{N}.\ n + 0 = n$ (0 is the additive identity)
2. $\forall m, n \in \mathbb{N}.\ n + S(m) = S(n + m)$
3. $\forall m, n \in \mathbb{N}.\ m + n = n + m$ (commutativity)
4. $\forall k, m, n \in \mathbb{N}.\ k + (m + n) = (k + m) + n$ (associativity)
5. $\forall k, m, n \in \mathbb{N}.\ n + k = n + m \implies k = m$ (cancelation)

Proof:

1. Let $P(n)$ be $n + 0 = n$.
   $P(0)$ is true because $0 + 0 = 0$ by definition.
   Note $P(n) \implies S(n) + 0 = S(n + 0) = S(n)$, so $P(S(n))$ is true. By induction, (1) is true.

2. Fix $m \in \mathbb{N}$. Let $P(n)$ denote $n + S(m) = S(n + m)$.
   $P(0)$ is true because $0 + S(m) = S(m) = S(0 + m)$.
   $P(n) \implies S(n)+S(m) = S(n+S(m)) = S(S(n+m)) = S(S(n)+m)$, so $P(S(n))$ is true. By induction, since $m \in \mathbb{N}$ was arbitrary, (2) is true.
3. Let m be fixed and $P(n)$ denote $n + m = m + n$.
   $P(0)$ is true since $0 + m = m$ by definition, and $m + 0 = m$ by 1, so $0 + m = m = m + 0$.
   Suppose $P(n)$; then $S(n) + m = S(n + m) = S(m + n) = m + S(n)$, so $P(S(n))$ is true. By induction and arbitrary choice of m, (3) is true.
4. Fix $k, m \in \mathbb{N}$ and let $P(n)$ denote $k + (m + n) = (k + m) + n$.
   $P(0)$ is true as $k + (m + 0) = k + m = (k + m) + 0$.
   Suppose $P(n)$; then $k+(m+S(n)) = k+S(m+n) = S(k+(m+n)) = S(k+m)+n = (k + m) + S(n)$ by (2). By induction and arbitrary choice, (4) is true.
5. Fix $m, n \in \mathbb{N}$ and let $P(k)$ denote proposition 5.
   $P(0)$ is true because $n + 0 = n = n + m \implies m = 0 \implies k = m$.
   Suppose $P(k)$; also, suppose $m + S(k) = n + S(k)$. Then $S(m + k) = m + S(k) = n + S(k) = S(n + k) \implies m + k = n + k \implies m = n$ (by 4). By the axiom of induction, (5) is true.

1.1.1 Positivity

Definition: We say that $n \in \mathbb{N}$ is *positive* if $n \neq 0$.

Proposition (Properties of Positivity):

1. $\forall n, m \in \mathbb{N}$, if m is positive, then $m + n$ is positive.
2. $\forall n, m \in \mathbb{N}$, if $m + n = 0$, then $m = n = 0$.
3. $\forall n \in \mathbb{N}$, if n is positive, then there exists a unique $m \in \mathbb{N}$ such that $n = S(m)$.

1.1.2 Order

Definition: For all $m, n \in \mathbb{N}$, $m \leq n$ or $n \geq m$ iff $n = m + p$ for some $p \in \mathbb{N}$.
$m < n$ or $n > m$ iff $m \leq n \wedge m \neq n$. The relation $\leq$ provides what is called an *order* on $\mathbb{N}$.

Proposition (Properties of Order):

Let $j, k, m, n \in \mathbb{N}$. Then:

1. $n \geq n$ (reflexitivity)
2. $m \leq n \wedge k \leq m \implies k \leq n$ (transitivity)
3. $m \geq n \wedge m \leq n \implies m = n$ (anti-symmetry)
4. $j \leq k \wedge m \leq n \implies j + m \leq k + n$ (order preservation)
5. $m < n \iff S(m) \leq n$
6. $m < n \iff n = m + p$ for some positive $p \in \mathbb{N}$.
7. $n \geq m \iff S(n) > m$
8. $n = 0 \oplus 0 < n$

Theorem (Trichotomy of Order): Let $m, n \in \mathbb{N}$. Then exactly one of the following is true:

$$m < n \quad \oplus \quad m = n \quad \oplus \quad m > n$$

Proof: Show that no two can be true simultaneously (by definition of $<$ and $>$), and then at least one must be true (by induction on n).

1.1.3 Multiplication

Definition: Fix $m \in \mathbb{N}$. Define $0 \cdot m = 0$. Now, if $n \cdot m$ is defined for some $n \in \mathbb{N}$, we define $S(n) \cdot m = n \cdot m + m$.

Proposition (Properties of Multiplication):

Fix $k, m, n \in \mathbb{N}$. Then:

1. $m \cdot n = n \cdot m$ (commutativity)
2. m, n are positive $\implies mn$ is positive
3. $m \cdot n = 0 \iff m = 0 \vee n = 0$ (no zero divisors)
4. $k \cdot (m \cdot n) = (k \cdot m) \cdot n$ (associativity)
5. $k \cdot m = k \cdot n \wedge k$ is positive $\implies m = n$ (cancelation)
6. $k \cdot (m + n) = (m + n) \cdot k = k \cdot m + k \cdot n$ (distributivity)
7. $m < n \wedge k \leq l \wedge k, l$ are positive $\implies m \cdot k < n \cdot l$

1.2 The Integers

Consider the following relation on the set $\mathbb{N} \times \mathbb{N}$:

$$(m, n) \simeq (m', n') \iff m + n' = m' + n$$

Lemma: $\simeq$ is an equivalence relation.

Proof:

Reflexivity: $m + n = m + n \implies (m, n) \simeq (m, n)$

Symmetry: $(m, n) \simeq (m', n') \implies m + n' = m' + n \implies m' + n = m + n' \implies (m', n') \simeq (m, n)$

Transitivity: Suppose $(m, n) \simeq (m', n') \wedge (m', n') \simeq (m'', n'')$. Then:

$$\begin{aligned} & m + n' = m' + n \wedge m' + n'' = m'' + n' \\ \implies & m + n'' = m'' + n \\ \implies & (m, n) \simeq (m'', n'') \end{aligned}$$

Definition: Write the *equivalence class* of (m, n) as $[(m, n)] = \{(p, q) \mid (p, q) \simeq (m, n)\}$.
Define the *integers* $\mathbb{Z} = \{[(m, n)]\}$.

Lemma: Suppose $(m, n) \simeq (m', n'), (p, q) \simeq (p', q')$. Then:

1. $(m + p, n + q) \simeq (m' + p', n' + q')$

2. $(mp + nq, mq + np) \simeq (m'p' + n'q', m'q' + n'p')$

Proof: Consider equalities $(a) : m + n' = m' + n$ and $(b) : p + q' = p' + q$ (by definition of $\simeq$).

Using linear combinations of (a) and (b), we derive the two rules of the lemma:

1. $(a) + (b)$
2. $(a)(p' + q') + (b)(m + n)$

Definition: Let $[(m, n)], [(p, q)] \in \mathbb{Z}$. Then:

1. $[(m, n)] + [(p, q)] = [(m + p, n + q)]$ (addition of integers)
2. $[(m, n)] \cdot [(p, q)] = [(mp + nq, mq + np)]$ (multiplication of integers)

By the lemma, these are well-defined operations.

Note that for all $m, n \in \mathbb{N}$:

$$[(m, 0)] = [(n, 0)] \iff m + 0 = n + 0 \iff m = n$$
$$[(m, 0)] + [(n, 0)] = [(m + n, 0)]$$
$$[(m, 0)] \cdot [(n, 0)] = [(mn, 0)]$$

As such, the set $\{[(n, 0)] \mid n \in \mathbb{N}\} \subseteq \mathbb{Z}$ behaves exactly like a copy of $\mathbb{N}$.

Definition: For $n \in \mathbb{N}$ we set $n \in \mathbb{Z}$ to be $n := [(n, 0)]$.

For $x = [(m, n)] \in \mathbb{Z}$ we define $-x = [(n, m)]$.

1.2.1 Properties of Integers

(We can see that every integer $x \in \mathbb{Z}$ can be represented as $x := m - n$ where $x = [(m, n)]$.)

Theorem: Every $x \in \mathbb{Z}$ satisfies exactly one of the following:

1. $x = n$ for some $n \in \mathbb{N}\backslash\{0\}$
2. $x = 0$
3. $x = -n$ for some $n \in \mathbb{N}\backslash\{0\}$

Proof: Write $x = [(p, q)]$ for some $p, q \in \mathbb{N}$. By trichotomy of order on $\mathbb{N}$ we know that $p < q$ or $p = q$ or $p > q$. Each of these correlates to one of the three properties.

Corollary: $\mathbb{Z} = \{0, 1, 2, \ldots\} \cup \{-1, -2, -3, \ldots\}$

1.2.2 Algebraic Properties

Proposition: Let $x, y, z \in \mathbb{Z}$. Then the following hold:

1. $x + y = y + x$
2. $x + (y + z) = (x + y) + z$
3. $x + 0 = 0 + x = x$
4. $x + (-x) = (-x) + x = 0$
5. $xy = yx$

6. $(xy)z = x(yz)$
7. $x \cdot 1 = 1 \cdot x = x$
8. $x(y+z) = xy + xz$

Definition: Define $x - y = x + (-y)$. The usual properties hold.

Definition: For $x, y \in \mathbb{Z}$, we say $x \leq y$ or $y \geq x$ if $y - x = n$ for some $n \in \mathbb{N}$.
We say $x < y$ if $x \leq y \wedge x \neq y$.

1.3 The Rationals and Ordered Fields

Let a relation on $\mathbb{Z} \times (\mathbb{Z} \backslash \{0\})$ be given by $(m, n) \simeq (m', n') \iff mn' = m'n$.

Lemma: $\simeq$ is an equivalence relation. Proof follows from properties of $\mathbb{Z}$.

Definition: $\mathbb{Q} = \{[(m, n)]\}$

1. $[(m, n)] + [(p, q)] = [(mq + np, nq)]$ (addition)
2. $[(m, n)] \cdot [(p, q)] = [(mp, nq)]$ (multiplication)
3. $-[(m, n)] = [(-m, n)]$ (negation)
4. If $m \neq 0$ we set $[(m, n)]^{-1} = [(n, m)]$

Remark: the heuristic here is that $\frac{m}{n} = [(m, n)]$.

Definition: If $m \in \mathbb{Z}$, we write $m = [(m, 1)] \in \mathbb{Q}$; and thus $\mathbb{N} \subset \mathbb{Z} \subset \mathbb{Q}$.

1. For $x, y \in \mathbb{Q}$, we define $x - y = x + (-y) \in \mathbb{Q}$
2. For $x, y \in \mathbb{Q}, y \neq 0$ we define $\frac{x}{y} = x(y)^{-1}$. This is well defined because $y = 0 \iff y = [(0, n)]$.

Proposition: $\mathbb{Q} = \{\frac{m}{n} \mid m, n \in \mathbb{Z}, n \neq 0\}$.

We define and propose the trichotomy of order on $\mathbb{Q}$, as per the integers.

1.3.1 Fields and Orders

Definition: A field is a set $\mathbb{F}$ endowed with two binary operations, $+, \cdot$, satisfying the following axioms:

(A1, M1) $\forall x, y \in \mathbb{F}.\ x + y \in \mathbb{F}, xy \in \mathbb{F}$ (closure)

(A2, M2) $\forall x, y \in \mathbb{F}.\ x + y = y + x,\ xy = yx$ (commutativity)

(A3, M3) $\forall x, y, z \in \mathbb{F}.\ x + (y + z) = (x + y) + z,\ x(yz) = (xy)z$ (associativity)

(A4, M4) $\exists (0, 1) \in \mathbb{F}.\ \forall x \in \mathbb{F}.\ 0 + x = x + 0 = x,\ 1 \cdot x = x \cdot 1 = x$ (identity)

(A5, M5) $\forall x \in \mathbb{F}.\ \exists (-x).\ x + (-x) = 0;\ \exists x^{-1} \in \mathbb{F}.\ xx^{-1} = x^{-1}x = 1$ (inverse)

(D1) $\forall x, y, z \in \mathbb{F}.\ x(y + z) = xy + xz$ (distributivity)

Remark: Field must have at least 2 elements (0, 1) by (A/M4). To prove field, must prove 5 properties of addition and multiplication (closure, symmetry, associativity, identity, inverse) as well as distributivity.

Definition: Let E be a set; an *order* on E is a relation $<$ satisfying the following:

1. $\forall x, y \in E$ exactly one of the following is true: $x < y$ or $x = y$ or $y < x$ (trichotomy)
2. $\forall x, y, z \in E$, $x < y \wedge y < z \implies x < z$ (transitivity)

Definition: Let $\mathbb{F}$ be a field. Then we define $x - y = x + (-y)$ and $\frac{x}{y} = xy^{-1}$ (for $y \neq 0$).

Theorem: $\mathbb{Q}$ is an ordered field with order $<$.

Proof: Follows from definitions and properties of $\mathbb{Z}$.

1.4 Problems with $\mathbb{Q}$

Theorem: There does not exist a $q \in \mathbb{Q}$ such that $q^2 = 2$.

Proof: Suppose not; i.e. there does exist such a $q \in \mathbb{Q}$.

Consider the set $S(q) = \{n \in \mathbb{N}^+ \mid q = \frac{m}{n} \text{ for some } m \in \mathbb{Z}\}$. Cleary $|S(q)| > 0$. Then the well-ordering principle implies that $\exists! n \in S(q).\ n = \min S(q)$.

Since $n \in S(q)$, we know that $q = \frac{m}{n}$ for some $m \in \mathbb{Z}$. Then $q^2 = (\frac{m}{n})^2 = \frac{m^2}{n^2} \implies m^2 = 2n^2 \implies m^2$ is even. We claim that m is also even (proof is exercise to reader).

Then $\exists l \in \mathbb{Z}.\ m = 2l$. Then $4l^2 = (2l)^2 = m^2 = 2n^2 \implies n^2 = 2l^2 \implies n^2$ is even $\implies n$ is even $\implies n = 2p$ for some $p \in \mathbb{N}^+$.

Hence $q = \frac{m}{n} = \frac{2l}{2p} = \frac{l}{p} \implies p \in S(q)$. But clearly $p < n$, which contradicts the fact that n is the minimal element. By contradiction, the theorem must be true.

1.4.1 Bounds (Infimum and Supremum)

Informally, $\mathbb{Q}$ has "holes":

Definition: Let E be an ordered set with order $<$.

1. We say $A \subseteq E$ is bounded above iff $\exists x \in E.\ \forall a \in A.\ a \leq x$. We say x is an upper bound of A.
2. We say $A \subseteq E$ is bounded below iff $\exists x \in E.\ \forall a \in A.\ x \leq a$. We say x is a lower bound of A.
3. We say $A \subseteq E$ is bounded iff it's bounded above and below.
4. We say x is a minimum of A iff $x \in A$ and x is a lower bound of A.
5. We say x is a maximum of A iff $x \in A$ and x is an upper bound of A.

Remark: If a min or max exists, then it is unique.

Definition: Let E be an ordered set and $A \subseteq E$.

1. We say $x \in E$ is the least upper bound (*supremum*) of A, written $x = \sup A$, iff x is an upper bound of A and $y \in E$ is an upper bound of $A \implies x \leq y$.
2. We say $x \in E$ is the greatest lower bound (*infimum*) of A, written $x = \inf A$, iff x is a lower bound of A and $y \in E$ is a lower bound of $A \implies y \leq x$.

Remark: If $x = \min(A)$, then $x = \inf(A)$. If $x = \max(A)$, then $x = \sup(A)$. But the converse is false; some sets have a supremum but no maximum, others a infimum but no minimum.

Definition: Let $\mathbb{F}$ be an ordered field. We say that $\mathbb{F}$ has the *least upper bound property* iff every $\varnothing \neq A \subseteq \mathbb{F}$ that is bounded above has a least upper bound.

Theorem: $\mathbb{Q}$ does not satisfy the least upper bound property.

Proof: Consider the set $A = \{x \in \mathbb{Q} \mid x > 0, x^2 \leq 2\}$.

Note that $0 < 1 = 1^2 \leq 2 \implies 1 \in A$, so A is non-empty. Also, $2 \leq 4 = 2^2$ implies $(x \in A \implies 0 < x^2 < 2 < 2^2) \implies x < 2$. Then 2 is an upper bound of A.

Assume for sake of contradiction that $\mathbb{Q}$ has the least upper bound property. Then A has a supremum. Let $x = \sup A \in \mathbb{Q}$ and write $x = \frac{p}{q}$ for $p, q \in \mathbb{Z}$.

By trichotomy, $x^2 < 2$ or $x^2 = 2$ or $x^2 > 2$. We know $x^2 \neq 2$.

Case 1: Suppose $x^2 < 2$. Then for any $n \in \mathbb{N}^+$ we have $(\frac{p}{q} + \frac{1}{n})^2 = \frac{p^2}{q^2} + \frac{2p}{qn} + \frac{1}{n^2} \leq \frac{p^2}{q^2} + \frac{1}{n}(\frac{2p+q}{q})$. From algebra, we derive $(\frac{p}{q} + \frac{1}{n})^2 < 2$ for some $n \in \mathbb{N}^+$.

Cleary $x > 0$ since otherwise $x \leq 0 < 1 \in A$. Hence $0 < x = \frac{p}{q} < \frac{p}{q} + \frac{1}{n} \in A$. But then x is not an upper bound $\implies$ contradiction.

Case 2: Suppose $x^2 > 2$. Considering $(\frac{p}{q} - \frac{1}{n})^2 > 2$ and using the same logic as before, we can choose n large enough such that $\frac{p}{q} - \frac{1}{n}$ is an upper bound of A. But $\frac{p}{q} - \frac{1}{n} < \frac{p}{q} = x$, which contradicts the fact that $x = \sup A$.

As all cases are false, we contradict trichotomy, and hence $\mathbb{Q}$ cannot have the least upper bound property.

1.5 The Real Numbers

We now construct an ordered field satisfying the least upper bound property using $\mathbb{Q}$.

Definition: We say $\mathbb{Q}$ is Archimedean iff $\forall(x \in \mathbb{Q}).\ x > 0 \implies \exists(n \in \mathbb{N}).\ x < n$.

Lemma: If $\mathbb{Q}$ is Archimedean, then $\forall(p < q \in \mathbb{Q}).\ \exists(r \in \mathbb{Q}).\ p < r < q$.
(Proofs in HW 2.)

1.5.1 Defining the Real Numbers: Dedekind Cuts

Definition: We say that $\mathcal{C} \in \mathcal{P}(\mathbb{Q})$ is a *cut* (Dedekind cut) iff the following hold:

(C1) $\varnothing \neq \mathcal{C}, \mathcal{C} \neq \mathbb{Q}$

(C2) If $p \in \mathcal{C}$ and $q \in \mathbb{Q}$ with $q < p$, then $q \in \mathcal{C}$.

(C3) If $p \in \mathcal{C}$, $\exists(r \in \mathbb{Q}).\ p < r \land r \in \mathcal{C}$.

Lemma: Suppose $\mathcal{C}$ is a cut. Then:

1. $p \in \mathcal{C}, q \notin \mathcal{C} \implies p < q$
2. $r \notin \mathcal{C}, r < s \implies s \notin \mathcal{C}$
3. $\mathcal{C}$ is bounded above

Lemma: Let $q \in \mathbb{Q}$. Then $\{p \in \mathbb{Q} \mid p < q\}$ is a cut.

Proof: Call the set $\mathcal{C}$. We prove the 3 properties of a cut:

(C1) $q - 1 \in \mathcal{C} \implies \mathcal{C} \neq \varnothing$; $q + 1 \notin \mathcal{C} \implies \mathcal{C} \neq \mathbb{Q}$.

(C2) If $p \in \mathcal{C}$ and $r \in \mathbb{Q}$ such that $r < p$, then $r < p < q \implies r < q \implies r \in \mathcal{C}$.

(C3) Let $p \in \mathcal{C}$ where $p < q$. Since $\mathbb{Q}$ is Archimedean, $\exists(r \in \mathbb{Q}).\ p < r < q \implies r \in \mathcal{C}$.

Definition: Given $q \in \mathbb{Q}$ we write $\mathcal{C}_q = \{p \in \mathbb{Q} \mid p < q\}$. By the above lemma, $\mathcal{C}_q$ is a cut.

Definition: We write $\mathbb{R} = \{\mathcal{C} \in \mathcal{P}(\mathbb{Q}) \mid \mathcal{C} \text{ is a cut}\} \neq \varnothing$.

Lemma: The following hold:

1. $\forall \mathcal{A}, \mathcal{B} \in \mathbb{R}$, exactly one of the following holds: $\mathcal{A} \subset \mathcal{B}, \mathcal{A} = \mathcal{B}, \mathcal{B} \subsetneq \mathcal{A}$.
2. $\forall \mathcal{A}, \mathcal{B}, \mathcal{C} \in \mathbb{R}$, $\mathcal{A} \subset \mathcal{B} \wedge \mathcal{B} \subseteq \mathcal{C} \implies \mathcal{A} \subset \mathcal{C}$.

Definition: If $\mathcal{A}, \mathcal{B} \in \mathbb{R}$ we say that $\mathcal{A} < \mathcal{B} \iff \mathcal{A} \subset \mathcal{B}$, and $\mathcal{A} \leq \mathcal{B} \iff \mathcal{A} \subseteq \mathcal{B}$. This defines an order on $\mathbb{R}$ by the above lemma.

1.5.2 Defining the Real Numbers: The Least Upper Bound Property

Lemma: Suppose $\varnothing \neq E \subseteq \mathbb{R}$ is bounded above. Then $\mathcal{B} := \bigcup_{\mathcal{A} \in E} \mathcal{A} \in \mathbb{R}$.

Theorem: $\mathbb{R}$ satisfies the least upper bound property.

Proof: Let $\varnothing \neq E \subseteq \mathbb{R}$ be bounded above and set $\mathcal{B} = \bigcup_{\mathcal{A} \in E} \mathcal{A} \in \mathbb{R}$. We claim $\mathcal{B} = \sup E$.

First, we show that $\mathcal{B}$ is an upper bound of E. Let $\mathcal{A} \in E$. Then $\mathcal{A} \subseteq \mathcal{B} \implies \mathcal{A} \leq \mathcal{B}$ (by definition). This is true for all $\mathcal{A} \in E$, so $\mathcal{B}$ is an upper bound.

We claim that for $\mathcal{C} \in \mathbb{R}$. $\mathcal{C} < \mathcal{B} \implies \mathcal{C}$ is not an upper bound of E. If $\mathcal{C} < \mathcal{B}$, then $\mathcal{C} \subset \mathcal{B}$. This implies $\exists b \in \mathcal{B}.\ b \notin \mathcal{C} \implies \exists (\mathcal{A} \in E).\ b \in \mathcal{A} \wedge b \notin \mathcal{C}$. Then $\mathcal{A} > \mathcal{C}$ since otherwise $\mathcal{A} \subseteq \mathcal{C} \implies b \in \mathcal{C}, b \notin \mathcal{C}$. Hence $\mathcal{C} < \mathcal{A}$ and $\mathcal{C}$ is not an upper bound of E.

By the contrapositive: if $\mathcal{C}$ is an upper bound, $\mathcal{C} \geq \mathcal{B}$. Thus, $\mathcal{B}$ is the least upper bound, and the theorem holds.

1.5.3 Defining the Real Numbers: Addition

Definition: Given $\mathcal{A}, \mathcal{B} \in \mathbb{R}$, set $\mathcal{A} + \mathcal{B} = \{a + b \mid a \in \mathcal{A}, b \in \mathcal{B}\}$.

Lemma: If $\mathcal{A}, \mathcal{B} \in \mathbb{R}$, then $\mathcal{A} + \mathcal{B} \in \mathbb{R}$.

Theorem: Define $-\mathcal{A} = \{q \in \mathbb{Q} \mid \exists (p > q).\ -p \notin \mathcal{A}\}$. Then $\mathbb{R}, +, 0_{\mathbb{R}} = \mathcal{C}_0 = \{p \in \mathbb{Q} \mid p < 0\}$ satisfy the field axioms.

Proof:

(A1) $\mathcal{A} + \mathcal{B} \in \mathbb{R}$ by previous lemma.

(A2) $\mathcal{A} + \mathcal{B} = \{a + b\} = \{b + a\} = \mathcal{B} + \mathcal{A}$.

(A3) $\mathcal{A} + (\mathcal{B} + \mathcal{C}) = \{a + (b + c)\} = \{(a + b) + c\} = (\mathcal{A} + \mathcal{B}) + \mathcal{C}$.

(A4) Show $\forall \mathcal{A} \in \mathbb{R}.\ 0_{\mathbb{R}} + \mathcal{A} = \mathcal{A}$.

(A5) Show that $-\mathcal{A} \in \mathbb{R}$, then $\mathcal{A} + (-\mathcal{A}) = 0_{\mathbb{R}}$ using Archimedean property.

Theorem (Ordered Field): Let $\mathcal{A}, \mathcal{B}, \mathcal{C} \in \mathbb{R}$. If $\mathcal{A} < \mathcal{B}$ then $\mathcal{A} + \mathcal{C} < \mathcal{B} + \mathcal{C}$.

Proof: It's trivial to see that $\mathcal{A} \subseteq \mathcal{B} \implies \mathcal{A} + \mathcal{C} \subseteq \mathcal{B} + \mathcal{C} \implies \mathcal{A} + \mathcal{C} \leq \mathcal{B} + \mathcal{C}$.

If $\mathcal{A} + \mathcal{C} = \mathcal{B} + \mathcal{C}$, we can add $-\mathcal{C}$ to both sides and use the last theorem to see that $\mathcal{A} = \mathcal{B}$, a contradiction. Hence, $\mathcal{A} + \mathcal{C} < \mathcal{B} + \mathcal{C}$.

1.5.4 Defining the Real Numbers: Multiplication

Lemma: Let $\mathcal{A}, \mathcal{B} \in \mathbb{R}$, $\mathcal{A}, \mathcal{B} > 0_{\mathbb{R}}$. Then $\mathcal{C} = \{q \in \mathbb{Q} \mid q \leq 0\} \cup \{a \cdot b \mid a \in \mathcal{A}, b \in \mathcal{B}, a, b > 0\} \in \mathbb{R}$.

Proof:

(C1) $0 \in \mathcal{C} \implies \mathcal{C} \neq \varnothing$. $\mathcal{A}, \mathcal{B}$ are bounded above by, say M_1, M_2, so $M_1 \cdot M_2 + 1 \notin \mathcal{C}$ and $\mathcal{C} \neq \mathbb{Q}$.

(C2) Let $p \in \mathcal{C}$ and $q < p$. If $q \leq 0$ then $q \in \mathcal{C}$ by definition. If $q > 0$ then $0 < q < p$, but then $0 < p \implies p = a \cdot b$ for $a \in \mathcal{A}, b \in \mathcal{B}, a, b > 0$. Then $0 < q < a \cdot b \implies \frac{q}{a} < b \implies 0 < \frac{q}{a} \in \mathcal{B}$. Then $q = a(\frac{q}{a}) \in \mathcal{C}$.

(C3) Let $p \in \mathcal{C}$. If $p \leq 0$ then any $a \cdot b$ with $a \in \mathcal{A}, b \in \mathcal{B}, a, b > 0$ satisfies $p < a \cdot b \in \mathcal{C}$, so $r = a \cdot b$ is the desired element of $\mathcal{C}$. However, if $p > 0$, then $p = a \cdot b$ for $a \in \mathcal{A}, b \in \mathcal{B}, a, b > 0$. Choose $s \in \mathcal{A}$ such that $a < s, t \in \mathcal{B}$ such that $t > b$. Then $p = a \cdot b < s \cdot t \in \mathcal{S}$, so $r = s \cdot t$ proves the claim.

Definition of Multiplication: Let $\mathcal{A}, \mathcal{B} \in \mathbb{R}$.

1. If $\mathcal{A} > 0, \mathcal{B} > 0$ we set $\mathcal{A} \cdot \mathcal{B} = \{q \in \mathbb{Q} \mid q \leq 0\} \cup \{a \cdot b \mid a \in \mathcal{A}, b \in \mathcal{B}, a, b > 0\} \in \mathbb{R}$.
2. If $\mathcal{A} = 0$ or $\mathcal{B} = 0$, we set $\mathcal{A} \cdot \mathcal{B} = 0_{\mathbb{R}}$.
3. If $\mathcal{A} > 0$ and $\mathcal{B} < 0$, let $\mathcal{A} \cdot \mathcal{B} = -(\mathcal{A} \cdot (-\mathcal{B}))$.
4. If $\mathcal{A} < 0$ and $\mathcal{B} > 0$, let $\mathcal{A} \cdot \mathcal{B} = -((-\mathcal{A}) \cdot \mathcal{B})$.
5. If $\mathcal{A} < 0$ and $\mathcal{B} < 0$, let $\mathcal{A} \cdot \mathcal{B} = (-\mathcal{A}) \cdot (-\mathcal{B})$.

Theorem: $\mathbb{R}, \cdot$ satisfies (M1-M5) with $1_{\mathbb{R}} = \mathcal{C}_1$, and
$\mathcal{A} > 0 \implies \mathcal{A}^{-1} = \{q \in \mathbb{Q} \mid q \leq 0\} \cup \{q \in \mathbb{Q} \mid q > 0, \exists p > q.\ p^{-1} \notin \mathcal{A}\} \in \mathbb{R}$;
$\mathcal{A} < 0 \implies \mathcal{A}^{-1} = -(-\mathcal{A})^{-1}$.

Proof: HW3 (similar to addition).

Theorem: If $\mathcal{A}, \mathcal{B} > 0$, then $\mathcal{A} \cdot \mathcal{B} > 0$.

Proof: By definition $\mathcal{C}_0 \subseteq \mathcal{A} \cdot \mathcal{B} \implies 0 \leq \mathcal{A} \cdot \mathcal{B}$. Equality is impossible since $\mathcal{A}, \mathcal{B} > 0$.

1.5.5 Defining the Real Numbers: Distributivity

Theorem: Let $\mathcal{A}, \mathcal{B}, \mathcal{C} \in \mathbb{R}$. Then $\mathcal{A} \cdot (\mathcal{B} + \mathcal{C}) = \mathcal{A} \cdot \mathcal{B} + \mathcal{A} \cdot \mathcal{C}$.

Proof: We prove the case where all are positive. The other cases are in HW.

Let $p \in \mathcal{A}(\mathcal{B} + \mathcal{C})$. If $p \leq 0$ then $p \in \mathcal{A} \cdot \mathcal{B} + \mathcal{A} \cdot \mathcal{B}$ is trivial (both products contain the interval less than 0).

If $p > 0$, $p = a(b + c)$ for $a \in \mathcal{A}, b \in \mathcal{B}, c \in \mathcal{C}$ for $a > 0, b + c > 0$.

Regardless of sign of b or c, $a \cdot b \in \mathcal{A} \cdot \mathcal{B}, a \cdot c \in \mathcal{A} \cdot \mathcal{C}$. Hence $p = a(b + c) = a \cdot b + a \cdot c \in \mathcal{A} \cdot \mathcal{B} + \mathcal{A} \cdot \mathcal{C}$. So $\mathcal{A}(\mathcal{B} + \mathcal{C}) \subseteq \mathcal{A} \cdot \mathcal{B} + \mathcal{A} \cdot \mathcal{C}$.

Finally, we show the converse is true; let $p \in \mathcal{A} \cdot \mathcal{B} + \mathcal{A} \cdot \mathcal{C} \implies p = r + s$ for $r \in \mathcal{A} \cdot \mathcal{B}, s \in \mathcal{A} \cdot \mathcal{C}$. Case on positivity of p, r, s to show $p \in \mathcal{A}(\mathcal{B} + \mathcal{C})$.

1.5.6 Defining the Real Numbers: Archimedean

Theorem: For $p, q \in \mathbb{Q}$, the following are true:

1. $\mathcal{C}_{p+q} = \mathcal{C}_p + \mathcal{C}_q$
2. $\mathcal{C}_{-p} = -\mathcal{C}_p$
3. $\mathcal{C}_{pq} = \mathcal{C}_p \mathcal{C}_q$
4. If $p \neq 0$ then $\mathcal{C}_{p^{-1}} = (\mathcal{C}_p)^{-1}$
5. $p < q \in \mathbb{Q} \iff \mathcal{C}_p < \mathcal{C}_q \in \mathbb{R}$

Proof: HW.

Definition: For $q \in \mathbb{Q}$ we say $\mathcal{C}_q \in \mathbb{R}$. Then $\mathbb{Q} \subseteq \mathbb{R}$.

Theorem: There exists an ordered field satisfying the least upper bound property; $\mathbb{R}$ is unique (for any ordered field $\mathbb{F}$ satisfying these properties, $\mathbb{F} = \mathbb{R}$ up to isomorphism; and $\mathbb{R}$ is Archimedean.

Proof: The basic assertion is Steps (0)-(4). Step (5) proves 1, Step (6) proves 3.

1.6 Properties of $\mathbb{R}$

Notation: think of $\mathbb{R}$ as numbers, not cut notation.

Proposition: $\mathbb{R}$ satisfies the following:

Theorem: For $p, q \in \mathbb{Q}$, the following are true:

1. $\mathbb{R}$ is Archimedean: $\forall x \in \mathbb{R}, x > 0.\ \exists n \in \mathbb{N}.\ x < n$
2. $\mathbb{N} \subset \mathbb{R}$ is not bounded above
3. $\inf\{\frac{1}{n} \mid n \in \mathbb{N}, n \geq 1\} = 0$
4. $\forall x \in \mathbb{R}$ the set $B(x) = \{m \in \mathbb{Z} \mid x < m\}$ has a minimum in $\mathbb{Z}$.
5. $\forall x, y \in \mathbb{R}, x < y.\ \exists q \in \mathbb{Q}.\ x < q < y$

Remarks:

1. (5) is interpreted as "the density of $\mathbb{Q} \subseteq \mathbb{R}$". Any element $x \in \mathbb{R}$ can be approximated to arbitrary accuracy by elements of $\mathbb{Q}$.
2. (4) allows us to define the integer part of any $x \in \mathbb{R}$. We can set $\lfloor x \rfloor = \min B(x) - 1 \in \mathbb{Z}$. Then $\lfloor x \rfloor \leq x < \lfloor x \rfloor + 1$.

Next we show that $\mathbb{R}$ does not have the "holes" we saw in $\mathbb{Q}$.

Theorem: Let $x \in \mathbb{R}$ satisfy $x > 0$ and $n \in \mathbb{N}, n \geq 1$. Then $\exists! y \in \mathbb{R}.\ y > 0 \wedge y^n = x$.

Proof: The case $n = 1$ is trivial so assume $n \geq 2$.

Set $E = \{z \in \mathbb{R} \mid z > 0 \wedge z^n < x\}$. We want to show $E \neq \varnothing$ and is bounded above. Set $t = \frac{x}{1+x}$; then $0 < t < 1$ and $t < x$. Hence $0 < t^n < t < x$, and so $t \in E$ and $E \neq \varnothing$.

Set $s = 1 + x$. Then $1 < s \wedge x < s \implies x < s < s^n$; so if $z \in E$ then $z^n < x < s^n \implies z < s$. Then s is an upper bound of E.

By least upper bound property, $\exists y \in \mathbb{R}.\ y = \sup E$. Since $t \in E$, $0 < t < y$, so $y > 0$. We claim that $y^n < x$ and $y^n > x$ are both impossible (proof is exercise), so $y^n = x$.

Definition: Let $n \geq 1$; for $x \in \mathbb{R}, x > 0$, we write $x^{\frac{1}{n}} = y$ where $y^n = x$. We set $0^{\frac{1}{n}} = 0$.

1.6.1 Absolute Value

For $x \in \mathbb{R}$, we define the function $|\cdot| : \mathbb{R} \to \{r \in \mathbb{R} \mid r \geq 0\}$:

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

Proposition (Properties of $|\cdot|$):

1. $\forall x \in \mathbb{R}.\ |x| \geq 0$ and $|x| = 0 \iff x = 0$
2. $\forall x, y \in \mathbb{R}.\ |x| < y \implies -y < x < y$
3. $\forall x, y \in \mathbb{R}.\ |xy| = |x||y|$
4. $\forall x, y \in \mathbb{R}.\ |x + y| \leq |x| + |y|$ (Triangle Inequality)
5. $\forall x, y \in \mathbb{R}.\ ||x| - |y|| \leq |x - y|$

2 Sequences

2.1 Convergence and Bounds

Definition: We say a sequence $\{a_n\}_{n=l}^{\infty} \subseteq \mathbb{R}$ converges if $\exists a \in \mathbb{R}.\ a_n \to a$ as $n \to \infty$; i.e. $\forall \epsilon \in \mathbb{R}.\ \exists N.\ n \geq N \implies |a_n - a| < \epsilon$.

Definition: We say a sequence $\{a_n\}_{n=l}^{\infty} \subseteq \mathbb{R}$ is bounded iff. $\exists M \in \mathbb{R}, M > 0.\ |a_n| < M\ (\forall n \geq l)$.

Lemma: If a sequence converges, then it is bounded.

Definition: Given $\{a_n\}, \{b_n\} \subseteq \mathbb{R}$ we define $\{a_n + b_n\} \subseteq \mathbb{R}$ to be the sequence whose elements are $a_n + b_n$. We simiplary define $\{ca_n\}$ for a fixed $c \in \mathbb{R}$, $\{a_n b_n\}$, and $\{a_n / b_n\}$ where $b_n \neq 0, n \geq l$.

Theorem (algebra of convergence): Let $\{a_n\}, \{b_n\} \subseteq \mathbb{R}, c \in \mathbb{R}$, and assume that $a_n \to a, b_n \to b$ as $n \to \infty$. Then the following hold:

1. $a_n + b_n \to a + b$ as $n \to \infty$
2. $c_a n \to ca$ as $n \to \infty$
3. $a_n b_n \to ab$ as $n \to \infty$
4. If $b_n \neq 0$ and $b \neq 0$, then $a_n / b_n \to a/b$ as $n \to \infty$.

Proof: (1), (2) are in next week's HW.

(3): Note that $|a_n b_n - ab| = |a_n b_n - ab_n + ab_n - ab| \leq |a_n b_n - ab_n| + |ab_n - ab| = |b_n||a_n - a| + |a||b_n - b|$. Since $b_n \to b$ we know that $\exists M > 0.\ |b_n| < M (\forall n \geq l)$.

Let $\epsilon > 0$. Since $a_n \to a$ and $b_n \to b$ we may choose N_1 such that $n \geq N_1 \implies |a_n - a| < \frac{\epsilon}{2M}$; and N_2 where $n \geq N_2 \implies |b_n - b| < \frac{\epsilon}{2(1+|a|)}$.

Then set $N = \max(N_1, N_2)$. So if $n \geq N$ we know that $|a_n b_n - ab| \leq |b_n||a_n - a| + |a||b_n - b| < M|a_n - a| + |a||b_n - b| < M \cdot \frac{\epsilon}{2M} + |a| \cdot \frac{\epsilon}{2(1+|a|)} < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon$.

Since ϵ was arbitrary, we deduce that $a_n b_n \to ab$.

(4): We know $|\frac{a_n}{b_n} - \frac{a}{b}| = |\frac{a_nb - ab_n}{b_nb}| = |\frac{a_nb - ab + ab - ab_n}{b_nb}| \le \frac{|a_nb - ab|}{|b_n||b|} + \frac{|ab - ab_n|}{|b||b_n|} = \frac{|a_n - a|}{|b_n|} + \frac{|a|}{|b||b_n|}|b_n - b|$.

Let $\epsilon > 0$. Since $b_n \to b \neq 0$ we know that $\exists N_1$ such that $n \ge N_1 \implies |b_n - b| < \frac{|b|}{2}$. Then $n \ge N \implies 0 < |b| = |b - b_n + b_n| \le |b - b_n| + |b_n| < \frac{|b|}{2} + |b_n| \implies 0 < \frac{|b|}{2} \le |b_n| \implies 0 < \frac{1}{|b_n|} < \frac{2}{|b|}$.

Similarly, $a_n \to a \implies \exists N_2. (n \ge N_2 \implies |a_n - a| < \frac{\epsilon}{4}|b|$; and $b_n \to b \implies \exists N_3. (n \ge N_3 \implies |b_n - b| < \frac{\epsilon|b|^2}{4(1+|a|)}$.

Set $N = \max(N_1, N_2, N_3)$. Then $n \ge N \implies |\frac{a_n}{b_n} - \frac{a}{b}| \le \frac{|a_n - a|}{|b_n|} + \frac{|a|}{|b_n||b|}|b_n - b| < \frac{2}{|b||a_n - a|} + \frac{2|a|}{|b|^2}|b_n - b| < \frac{\epsilon}{2} + \frac{\epsilon}{2}\frac{|a|}{1+|a|} < \epsilon$.

Since $\epsilon > 0$ was arbitrary, we deduce $\frac{a_n}{b_n} \to \frac{a}{b}$ as $n \to \infty$.

Lemma: Let $\{a_n\}_{n=l}^{\infty}$ converge to $a \in \mathbb{R}$. Then $\forall \epsilon > 0. \exists N. m, n \ge N \implies |a_n - a_m| < \epsilon$.

Definition: We say $\{a_n\}_{n=l}^{\infty} \subseteq \mathbb{R}$ is *Cauchy* iff $\forall \epsilon > 0. \exists N. m, n \ge N \implies |a_n - a_m| < \epsilon$.

Lemma: If $\{a_n\}$ is Cauchy, then it's bounded.

Proof: Let $\epsilon = 1$. Then $\exists N. m, n \ge N \implies |a_m - a_n| < 1$. Then $n \ge N \implies |a_n - a_N| < 1 \implies |a_n| < |a_n - a_N| + |a_N| < 1 + |a_N|$. Set $M = \max(1 + |a_N|, k)$, where $k = \max\{|a_l|, \ldots, |a_{N-1}|\}$. Then $|a_n| < M(\forall n \ge l)$, and $\{a_n\}$ is bounded.

Theorem: Let $\{a_n\} \subseteq \mathbb{R}$. Then $\{a_n\}$ converges $\iff$ $\{a_n\}$ is Cauchy.

Proof: $\implies$ is covered by 2nd-previous lemma. We show the converse:

Suppose $\{a_n\}$ is Cauchy. Then $|a_n| < M(\forall n \ge l)$ by the last lemma.

Set $E = \{x \in \mathbb{R} \mid \exists N. n \ge N \implies x < a_n\}$. Note that $-M < a_n(\forall n \ge l)$, and so $-M \in E$ and $E \neq \varnothing$.

Also, $x \in E \implies \exists N_x. n \ge N_x \implies x < a_n < M$, and so M is an upper bound of E. By the least upper bound property of $\mathbb{R}$, $\exists a = \sup E \in \mathbb{R}$. We claim that $a_n \to a$ as $n \to \infty$.

Let $\epsilon > 0$. Then since $\{a_n\}$ is Cauchy, $\exists N. m, n \ge N \implies |a_n - a_m| < \frac{\epsilon}{2}$. In particular, $|a_n - a_N| < \frac{\epsilon}{2}$ when $n \ge N$. Then $n \ge N \implies a_N - \frac{\epsilon}{2} < a_n \implies a_N - \frac{\epsilon}{2} \in E \implies a_N - \frac{\epsilon}{2} \le a$.

If $x \in E$, then $\exists E_x. (n \ge N_x \implies x < a_n < a_N + \frac{\epsilon}{2})$. Hence $a_N + \frac{\epsilon}{2}$ is an upper bound of $E \implies a \le a_N + \frac{\epsilon}{2}$. Then $|a - a_N| < \frac{\epsilon}{2}$.

But if $n \ge N$, then $|a_n - a| \le |a_n - a_N| + |a_N - a| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon$. Hence $a_n \to a$.

2.1.1 Squeeze Lemma

Lemma: Let $\{a_n\}_{n=l}^{\infty}, \{b_n\}, \{c_n\} \subseteq \mathbb{R}$ and suppose that $a_n \to a, c_n \to a$ as $n \to \infty$. If $\exists k \ge l$ such that $a_n \le b_n \le c_n(\forall n \ge k)$, then $b_n \to a$ as $n \to \infty$.

Examples:

1. Suppose $a_n \to 0$ and $\{b_n\}$ is bounded, i.e. $|b_n| \le M(\forall n \ge l)$. Then $|a_nb_n| = |a_n||b_n| \le |a_n|M$. But $c_n \to 0 \iff |c_n| \to 0$. Then $0 \le |a_nb_n| \le |a_n|M$, both sides of which go to 0; and by the squeeze lemma, $|a_nb_n| \to 0 \implies a_nb_n \to 0$.

2. Fix $k \in \mathbb{N}$ with $k \geq 1$. Set $a_n = \frac{1}{n^k}, n \geq 1$. Then $0 \leq \frac{1}{n^k} \leq \frac{1}{n}$, and by squeeze lemma $\frac{1}{n^k} \to 0$.

3. Fix $k \in \mathbb{N}$ with $k \geq 2$. Let $a_n = \frac{1}{k^n}, n \geq 0$. We know $\forall n \in \mathbb{N}.\ n \leq k^n$ (proof by induction). Then $0 \leq \frac{1}{k^n} \leq \frac{1}{n}$, and by squeeze $\frac{1}{k^n} \to 0$.

2.2 Monotonicity and limsup, liminf

Definition: Let $\{a_n\}_{n=l}^{\infty} \subseteq \mathbb{R}$. We say $\{a_n\}$ is:

1. increasing iff. $a_n < a_{n+1} (\forall n \geq l)$,
2. non-decreasing iff. $a_n \leq a_{n+1} (\forall n \geq l)$,
3. decreasing iff. $a_{n+1} < a_n (\forall n \geq l)$,
4. non-increasing iff. $a_{n+1} \leq a_n (\forall n \geq l)$.

We say $\{a_n\}$ is *monotone* iff. it is either non-increasing or non-decreasing.

Remark: increasing $\implies$ non-decreasing, decreasing $\implies$ non-increasing.

Theorem: Suppose that $\{a_n\}_{n=l}^{\infty} \subseteq \mathbb{R}$ is monotone. Then $\{a_n\}$ is bounded iff $\{a_n\}$ is convergent.

Proof: $\impliedby$ is done in a previous lemma.

$\implies$: We'll prove when the sequence is non-decreasing (other case handled by similar argument).

Set $E = \{a_n \mid n \geq l\} \subseteq \mathbb{R}$. Clearly $E \neq \varnothing$. Also, since $\{a_n\}$ is bounded, E is as well (in particular above). By least upper bound property of $\mathbb{R}$, $\exists a = \sup(E) \in \mathbb{R}$. We claim that $a = \lim_{n\to\infty} a_n$.

Let $\epsilon > 0$. Since $a = \sup(E)$ we know that $a - \epsilon$ is not an upper bound of E; hence $\exists (N \geq l).\ a - \epsilon < a_N$. Also, since the sequence is non-decreasing, $a_n \leq a_{n+1} (\forall n \geq l)$, and so $n \geq N \implies a_N \leq a_n$. Then $n \geq N \implies a - \epsilon < a_N \leq a_n \leq a$ because a is an upper bound of E.

So $n \geq N \implies -\epsilon < a_n - a \leq 0 \implies |a_n - a| < \epsilon$. Since $\epsilon > 0$ was arbitrary, we deduce that $a_n \to a$ as $n \to \infty$.

Lemma: Suppose that $\{a_n\}$ is bounded. Set $S_m = \sup\{a_n \mid n \geq m\}$ and $I_m = \inf\{a_n \mid n \geq m\}$. Then $S_m, I_m \in \mathbb{R}$ are well-defined $\forall m \geq l$; $\{S_m\}$ is non-increasing; and $\{I_m\}$ is non-decreasing. Both sequences are bounded.

Definition: Suppose $\{a_n\} \subseteq \mathbb{R}$ is bounded. We set $\lim_{n\to\infty} \sup a_n = \lim_{m\to\infty} S_m \in \mathbb{R}$ and $\lim_{n\to\infty} \inf a_n = \lim_{m\to\infty} I_m \in \mathbb{R}$. Both limits exist by the lemma and previous theorem. We know that $\lim_{n\to\infty} \inf a_n \leq \lim_{n\to\infty} \sup a_n$ from HW.

2.3 Subsequences

Definition: Let $\phi : \{n \in \mathbb{Z} \mid n \geq l\} \to \{n \in \mathbb{Z} \mid n \geq l\}$ be order preserving (increasing), i.e. $m < n$ then $\phi(m) < \phi(n)$. Let $\{a_n\}_{l=k}^{\infty} \subseteq \mathbb{R}$ be a sequence. We say $\{a_{\phi(k)}\}_{k=l}^{\infty}$ is a *subsequence* of $\{a_n\}$.

Remarks:

1. $\phi(k) = k$ is order preserving, so every sequence is a subsequence of itself.

2. Not every a_n has to be in the subsequence $\{a_{\phi(k)}\}$.
   For example, if $l = 0$ then $\phi(k) = 2k$ is order preserving. In this case a_n, n odd does not appear in the subsequence $\{a_{\phi(k)}\}$.
3. We will often write $n_k = \phi(k)$ to simplify notation, so $\{a_{n_k}\}$ denotes a subsequence.
4. From HW1, we know $k \leq \phi(k)$ $(\forall k \geq l)$.

Proposition: Suppose $\{a_n\}$ satisfies $a_n \to a \in \mathbb{R}$ as $n \to \infty$. Then any subsequence of $\{a_n\}$ also converges to a.

Proof:

Let $\{a_{\phi(k)}\}$ be a subsequence of $\{a_n\}$. Let $\epsilon > 0$. Since $a_n \to a$ as $n \to \infty$, we know $\exists N \geq l.\ n \geq N \implies |a_n - a| < \epsilon$. We claim $\exists K \geq l.\ k \geq K \implies \phi(k) \geq N$.

If not, then $\phi(k) < N (\forall k \geq l)$; but $k \leq \phi(k) < N (\forall k \geq l)$ is a contradiction. Then the claim is true, and $k \geq K \implies \phi(k) \geq N \implies |a_{\phi(k)} - a| < \epsilon$. Since $\epsilon > 0$ was arbitrary, we deduce $\{a_{\phi(k)}\} \to a$ as $k \to \infty$.

Remark: Converse fails. Example: $a_n = (-1)^n$; $a_{2n} = +1 \to +1$, but $a_{2n+1} = -1 \to -1$.

2.3.1 Limsup Theorem

Theorem: Let $\{a_n\} \subseteq \mathbb{R}$ be bounded. The following hold:

1. Every subsequence of $\{a_n\}$ is bounded.
2. If $\{a_{n_k}\}$ is a subsequence, then $\lim_{k\to\infty} \sup a_{n_k} \leq \limsup_{n\to\infty} a_n$.
3. If $\{a_{n_k}\}$ is a subsequence, then $\lim_{n\to\infty} \inf a_n \leq \liminf_{n\to\infty} a_{n_k}$.
4. There exists a subsequence $\{a_{n_k}\}$ such that $\lim_{k\to\infty} a_{n_k} = \limsup_{n\to\infty} a_n$.
5. There exists a subsequence $\{a_{n_k}\}$ such that $\lim_{k\to\infty} a_{n_k} = \liminf_{n\to\infty} a_n$ $(\neq (4))$.

Proof:

1. Trivial.
2. Since $k \leq \phi(k)$, $\{a_{\phi(n)} \mid n \geq k\} \subseteq \{a_n \mid n \geq k\}$ for every order-preserving ϕ. Hence $S_k = \sup\{a_{\phi(n)}\} \mid n \geq k\} \subseteq \sup\{a_n \mid n \geq k\} = T_k$. But:
   $\limsup_{n\to\infty} a_{\phi(n)} = \lim_{k\to\infty} \sup\{a_{\phi(n)} \mid n \geq k\} \leq \limsup_{k\to\infty}\{a_n \mid n \geq k\} = \limsup_{n\to\infty} a_n$.
3. Similar to (2); exercise to reader.
4. Too lazy to LaTeX; exercise to reader.
5. Exercise to reader.

Theorem: Suppose $\{a_n\} \subseteq \mathbb{R}$; the following are equivalent:

1. $a_n \to a$ as $n \to \infty$
2. $\{a_n\}$ is bounded, and every convergent subsequence converges to a.
3. $\{a_n\}$ is bounded, and $\limsup_{n\to\infty} a_n = \liminf_{n\to\infty} a_n$.

Proof: (1) $\implies$ (2) proven already.

(2) $\implies$ (3)
Limsup theorem (4,5) $\implies$ $\exists \{a_{\phi(k)}\}, \{a_{\gamma(k)}\}$ subsequences such that $a_{\phi(k)} \to \limsup_{n\to\infty} a_n$, $a_{\gamma(k)} \to \liminf_{n\to\infty} a_n$ as $k \to \infty$. By (2) the limits must agree.

(3) $\implies$ (1)

Theorem (Bolzano-Weierstrass): If $\{a_n\} \subseteq \mathbb{R}$ is bounded then there exists a convergent subsequence. Proof from (4) or (5) of Limsup Theorem.