# MAS241 해석학 I
# Note

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# Contents

# Chapter 1

# Structure of the Real Numbers

## 1.1 Completeness of the Real Numbers

**Definition 1.1.1: Cauchy Sequence**

Let $X$ be a space. A sequence $\{x_n\}_{n\in\mathbb{N}}$ is a *Cauchy sequence* if $\|x_n - x_m\| \to 0$ as $n, m \to \infty$.

**Definition 1.1.2: Completeness**

A set $X$ is *complete* if every Cauchy sequnce has a limit in X, i.e.,

$$x_n \to x_\infty \in X.$$

**Definition 1.1.3: Boundedness**

Let $\varnothing \neq S \subseteq \mathbb{R}$.

a) $S$ is *bounded above* if $\exists M \in \mathbb{R}$, $\forall x \in S$, $x \leq M$.
   - $M$ is called an *upper bound* of $S$.

b) $S$ is *bounded below* if $\exists M \in \mathbb{R}$, $\forall x \in S$, $x \geq M$.
   - $M$ is called an *lower bound* of $S$.

c) $S$ is bounded if $S$ is bounded above and below.

**Theorem 1.1.1** Archimedes' Principle

Let $\varepsilon$ and $M$ be any two possible real numbers. Then, there exists a $k$ in $\mathbb{N}$ such that $M < k\varepsilon$.

The proof of Theorem 1.1.1 can be done by integrating Theorem 1.1.2 and Theorem 1.1.4.

**Definition 1.1.4: Supremum and Infimum**

a) Let $S$ be bounded above. Then, the smallest upper bound is called the *supremum* of $S$, $\sup S$.

b) Let $S$ be bounded below. Then, the largest lower bound is called the *infimum* of $S$, $\inf S$.

**Example 1.1.1**

Let $S = \left\{(-1)^k(1-1/k) \,\middle|\, k \in \mathbb{N}\right\}$. It is clear that $-1 < S < 1$; 1 is an upper bound and $-1$ is a lower bound. We now claim that $\sup S = 1$. To show this, let us assume that $M < 1$ is an upper bound of $S$. By Archimedes' principle, there exists an natural number $k_0$ such that $(1-M)/2 < k_0$, which implies $(-1)^{2k_0}\big(1-1/(2k_0)\big) > M$; $M$ is not an upper bound. Therefore, 1 is the smallest upper bound. It can be similarly shown that $\inf S = -1$.

**Theorem 1.1.2** Completeness Axiom for $\mathbb{R}$

If $\varnothing \neq S \subseteq \mathbb{R}$ and $S$ is bounded above, then $\sup S$ exists in $\mathbb{R}$.

**Corollary 1.1.1**

If $\varnothing \neq S \subseteq \mathbb{R}$ and $S$ is bounded below, then $\inf S$ exists in $\mathbb{R}$.

***Proof.*** Let $B := \{-x \mid x \in S\}$. Then, $M = \sup S \in \mathbb{R}$ by Theorem 1.1.2. We now claim that $\inf S = -M$.

For all $x \in S$, $-x \in B$, which implies $-x \leq M$, and therefore $x \geq -M$. Thus, $-M$ is a lower bound of $S$.

Suppose there is a $M_1 > -M$ such that $M_1$ is a lower bound of $S$. For all $x \in S$, $x \geq M_1$, which implies $-x \leq -M_1$. Thus, $-M_1$ is an upper bound of $B$ but $-M_1 < M = \sup B$, #.

Therefore, $\inf S = -M \in \mathbb{R}$. □

**Example 1.1.2**

- $S := \left\{\sum_{j=0}^{k} \frac{1}{j!} \,\middle|\, k \in \mathbb{N}\right\}$. $S$ is bounded above.

$$\sum_{j=0}^{k} \frac{1}{j!} = 1 + \sum_{j=1}^{k} \frac{1}{j!} \leq 1 + \sum_{j=1}^{k} \frac{1}{2^{j-1}} < 3$$

  In fact, $e := \sup S$.

- $S := \left\{\left(1+\frac{1}{k}\right)^k \,\middle|\, k \in \mathbb{N}\right\}$. $S$ is bounded above.

$$\left(1+\frac{1}{k}\right)^k = \sum_{j=0}^{k} \binom{k}{j} \frac{1}{k^j} \leq \sum_{j=0}^{k} \frac{1}{j!} \leq e$$

**Theorem 1.1.3**

Let $S$ be a finite nonempty subset of $\mathbb{R}$. Then, $\sup S \in S$ and $\inf S \in S$.

***Proof.*** (Induction on $|S|$) For $S = \{x\}$, $x = \inf S = \sup S \in S$.

Take any $k \in \mathbb{N}$ and suppose the statement holds for every $S$ with $|S| = k$. Now, take any $S' \subseteq \mathbb{R}$ such that $|S'| = k+1$. Let $x \in S'$, $\mu := \sup(S' \setminus \{x\})$, and $\nu := \inf(S' \setminus \{x\})$. By the induction hypothesis, $\mu, \nu \in S' \setminus \{x\}$. Letting $\mu' := \max(\mu, x)$ and $\nu' := \min(\nu, x)$, $\mu'$ and $\nu'$ are the supremum and infimum of $S'$, respectively. Moreover, $\mu'$ and $\nu'$ are elements of $S'$. □

**Theorem 1.1.4**

Let $\varnothing \neq S \subseteq \mathbb{R}$.

- If $S$ is bounded above, then "$\mu = \sup S$ if and only if $\mu$ is an upper bound and $\forall\, \varepsilon \in \mathbb{R}_+,\ \exists\, x \in S,\ \mu - \varepsilon < x \leq \mu$".
- If $S$ is bounded below, then "$\nu = \inf S$ if and only if $\nu$ is an lower bound and $\forall\, \varepsilon \in \mathbb{R}_+,\ \exists\, x \in S,\ \nu \leq x < \nu + \varepsilon$".

***Proof.*** Let $S$ be bounded above. If there is no $x \in S$ in $(\mu - \varepsilon, \mu]$, then $\mu - \varepsilon$ would be a smaller upper bound.

For the converse, assume $M$ is an upper bound and $M < \mu$. Let $\varepsilon := \mu - M > 0$. Then, there is some $x \in S$ such that $M = \mu - \varepsilon < x \leq \mu$, # to $M$ is an upper bound. Therfore, $\mu$ is the least upper bound.

The same logic may be applied for bounded below $S$. □

***Proof of Theorem 1.1.1.*** Let $S := \{k\varepsilon \mid k \in \mathbb{N}\}$. Assume $S$ is bounded above and nonempty. Then, by Theorem 1.1.2, there is $\mu = \sup S$. We also know, from Theorem 1.1.4, that there is $k \in \mathbb{N}$ such such that $\mu - \varepsilon < k\varepsilon \leq \mu$, which implies $\mu < (k+1)\varepsilon$. Since $(k+1)\varepsilon \in S$, $\mu$ is not an upper bound of $S$, which is a contradiction. Therefore, $S$ is not bounded above. In other words, for any $M > 0$, there is some $k \in \mathbb{N}$ such that $M < k\varepsilon$. □

**Theorem 1.1.5**

Theorem 1.1.1 (Archimedes' principle) is equivalent to the following statement:

$$\forall\, c \in \mathbb{R}_+,\ \exists\, k \in \mathbb{N},\ k - 1 \leq c < k.$$

***Proof.*** Assume Archimedes' principle. If $c < 1$, $k = 1$ satisfies, and it is done. Now, let us suppose $c \geq 1$. By Theorem 1.1.1, there is a $k \in \mathbb{N}$ such that $c < k$. We may let $k_0 := \min\{k \in \mathbb{N} \mid k > c\}$ by Well-Ordering of $\mathbb{N}$. We note that $k_0 - 1 \leq c$ since $k_0 - 1 \in \mathbb{N}$ since $k_0 > 1$. Therefore, $k_0 - 1 \leq c < k_0$.

Now, assume "$\forall\, c \in \mathbb{R}_+,\ \exists\, k \in \mathbb{N},\ k - 1 \leq c < k$". Take any $M > 0$ and $\varepsilon \in \mathbb{R}_+$ and let $c := M/\varepsilon$. The assumption tells the existence of a $k \in \mathbb{N}$ such that $M/\varepsilon = c < k$, which directly implies $M < k\varepsilon$. □

**Theorem 1.1.6**

Let $c$ and $d$ be real numbers with $c < d$. Then, $\exists\, x \in \mathbb{Q},\ c < x < d$.

***Proof.*** There are three cases: $0 < c < d$, $c \leq 0 < d$, or $c < d \leq 0$.

Case 1) By Archimedes' principle, $\exists\, q \in \mathbb{N},\ 1 < (d - c)q$, which implies $cq + 1 < dq$. By Theorem 1.1.5, $\exists q \in \mathbb{N},\ p - 1 \leq cq < p$ since $cq > 0$. To sum up, $p - 1 \leq cq < p \leq cq + 1 < dq$, which implies $c < p/q < d$.

Case 2) By Archimedes' principle, $\exists\, q \in \mathbb{N},\ 1 < dq$. Then, $c \leq 0 < 1/q < d$ holds.

Case 3) By case 1 and 2, there is $r \in \mathbb{Q}$ such that $-d < r < -c$. Then, $c < -r < d$ holds. □

## 1.2 Neighborhoods and Limit Points

**Definition 1.2.1: Neighborhood and Deleted Neighborhood**

For each $x \in \mathbb{R}$ and $r \in \mathbb{R}_+$,

$$N(x;r) := \{y \in \mathbb{R} : |y-x| < r\} = (x-r, x+r)$$

is called the *neighborhood* of $x$ with radius $r$, and

$$N'(x;r) := \{y \in \mathbb{R} : 0 < |y-x| < r\} = N(x;r) \setminus \{x\}$$

is called the *deleted neighborhood* of $x$ with radius $r$.

**Definition 1.2.2: Limit Point and Isolated Point**

For $\varnothing \neq S \subseteq \mathbb{R}$, $x \in \mathbb{R}$ is a *limit point* of $S$ if

$$\forall \varepsilon \in \mathbb{R}_+,\ N'(x,\varepsilon) \cap S \neq \varnothing.$$

If $x \in \mathbb{R}$ is not a limit point of $S$, then it is called an *isolated point* of $S$.

**Definition 1.2.3: Discrete Set**

If $\varnothing \neq S \subseteq \mathbb{R}$ has no limit points, then $S$ is said to be *discrete*.

**Example 1.2.1**

Let $S := \left\{(-1)^k(1+1/k) \,\middle|\, k \in \mathbb{N}\right\}$. Then, 1 and $-1$ are limit points of $S$.
To see 1 is a limit point, take any $\varepsilon \in \mathbb{R}_+$ and, using Theorem 1.1.1, choose a $k \in \mathbb{N}$ such that $1 < (2\varepsilon)k$. Then, $1 < 1 + \frac{1}{2k} = (-1)^{2k}\left(1+\frac{1}{2k}\right) < 1+\varepsilon$; $N'(1,\varepsilon) \cap S \neq \varnothing$. Therefore, 1 is a limit point.

**Theorem 1.2.1**

Let $\varnothing \neq S \subseteq \mathbb{R}$. Then, $x \in \mathbb{R}$ is a limit point of $S$ if and only if

$$\exists \varepsilon_0 \in \mathbb{R}_+,\ \forall \varepsilon \in (0,\varepsilon_0),\ N'(x,\varepsilon) \cap S \neq \varnothing.$$

***Proof.*** Trivial; $0 < \varepsilon_1 < \varepsilon_2$ implies $N'(x,\varepsilon_1) \subsetneq N'(x,\varepsilon_2)$. □

**Theorem 1.2.2**

Let $\varnothing \neq S \subseteq \mathbb{R}$ and $x \in \mathbb{R}$ be a limit point of $S$. Then, every deleted neighborhood of $x$ must contain infinitely many points of $S$.

***Proof.*** Assume $N'(x;\varepsilon) \cap S$ were to contain only finitely many points, namely, $N'(x;\varepsilon) \cap S = \{x_1, x_2, \cdots, x_k\}$. Let $S_1 := \left\{|x-x_i| : i \in [k]\right\}$. Since $S_1$ is finite, we may let $x_j$ be an element of $N'(x;\varepsilon) \cap S$ that satisfies $|x-x_j| = \min S_1 = \inf S_1 > 0$. If we let $\varepsilon_0 := |x-x_j|/2$, $N'(x;\varepsilon_0) \cap S = \varnothing$, #. □

**Corollary 1.2.1**

If $S$ is a finite subset of $\mathbb{R}$, then $S$ has no limit point.

**Example 1.2.2**

$\mathbb{Z}$ has no limit point.

**Theorem 1.2.3** Bolzano–Weierstra Theorem

If $S \subseteq \mathbb{R}$ is bounded and has an infinite number of elements, then $S$ has a limit point.

***Proof.*** Since $S$ is bounded, $a_0 := \inf S$ and $b_0 := \sup S$ exist; $S \subseteq [a_0, b_0]$. At least one of $[a_0, (a_0 + b_0)/2]$ and $[(a_0 + b_0)/2, b_0]$ has an infinite number of elements in $S$, otherwise $S$ must be finite. Choose whichever has an infinite number of elements in $S$, and let us denote it as $[a_1, b_1]$. Since, $S \cap [a_1, b_1]$ is bounded and has an infinite number of elements, we may find $a_2$ and $b_2$ in the same manner. Note that

(a) for every natural number $k$, $S \cap [a_k, b_k]$ has an infinite number of elements,

(b) $\forall k \in \mathbb{N}$, $b_k - a_k = (b_0 - a_0)/2^k > 0$, and

(c) $\forall k \in \mathbb{N}$, $a_{k-1} \leq a_k < b_k \leq b_{k-1}$.

The sequence $\{a_k\}_{k=0}^{\infty}$ is bounded above by $b_0$, and the sequence $\{b_k\}_{k=0}^{\infty}$ is bounded below by $a_0$. Therefore, we may let $\alpha := \sup\{a_k\}$ and $\beta := \inf\{b_k\}$.

Since $a_j$ is a lower bound of $\{b_k\}_{k=0}^{\infty}$ for all $j \in \mathbb{N}$, $\forall j \in \mathbb{N}$, $a_j \leq \beta$. This implies $\beta$ is an upper bound of $\{a_k\}_{k=0}^{\infty}$, therefore $\alpha \leq \beta$. Since $a_j \leq \alpha \leq \beta \leq b_j$ for all $j \in \mathbb{N}$, we get $0 \leq \beta - \alpha \leq b_j - a_j = (b_0 - a_0)/2^j$. Therefore, $\beta - \alpha = 0$.

We now claim that $\alpha$ is a limit point of $S$. Take any $\varepsilon \in \mathbb{R}_+$. By Theorem 1.1.4, $\exists k_0 \in \mathbb{N}$, $\alpha - \varepsilon < a_{k_0} \leq \alpha$. We may take $k \in \mathbb{N}$ such that $k > k_0$ and $|b_k - a_k| < \varepsilon$ thanks to (b). Since $\alpha \in [a_k, b_k]$, $\alpha - \varepsilon < a_{k_0} \leq a_k \leq \alpha \leq b_k < \alpha + \varepsilon$, which implies $[a_k, b_k] \subseteq N(\alpha; \varepsilon)$.

In conclusion, $S \cap [a_k, b_k]$ has infinitely many elements by (a), and so does $(S \cap [a_k, b_k]) \setminus \{\alpha\}$. $S \cap N'(\alpha; \varepsilon)$ is, therefore, nonempty. $\square$

**Definition 1.2.4: Bolzano–Weierstra Property**

We say that a nonempty set $X$ has the *Bolzano–Weierstra property* if every bounded, infinite subset $S$ of $X$ has a limit point in $X$.

## 1.3 The Limit of a Sequence

**Definition 1.3.1: Cluster Point**

$c \in \mathbb{R}$ is a *cluster point* of the sequence $\{x_k\}$ if,

$$\forall(\varepsilon, k) \in \mathbb{R}_+ \times \mathbb{N},\ \exists k_1 \in \mathbb{N}_{>k},\ x_{k_1} \in N(c;\varepsilon).$$

**Lemma 1.3.1**

$c \in \mathbb{R}$ is a cluster point of $\{x_k\}$ if and only if $\left\{k \in \mathbb{N} \,\middle|\, x_k \in N(c;\varepsilon)\right\}$ is infinite for every $\varepsilon \in \mathbb{R}_+$.

***Proof.*** ($\Rightarrow$) Suppose $S := \left\{k \in \mathbb{N} \,\middle|\, x_k \in N(c;\varepsilon)\right\}$ is finite for some $\varepsilon \in \mathbb{R}_+$. If $S$ were empty, then, $c$ is not a cluster point by Definition 1.3.1. Therefore, $S$ is nonempty and has a maximum element $k_0 := \max S$ by Theorem 1.1.3. Since $c$ is a cluster point, there is a natural number $k_1 > k_0$ such that $x_{k_1} \in N(c;\varepsilon)$; $k_1 \in S$. This contradicts the maximality of $k_0$.

($\Leftarrow$) Take any $\varepsilon \in \mathbb{R}_+$ and $k_0 \in \mathbb{N}$. If there is no $k_1 \in \mathbb{N}$ such that $k_1 > k_0$ and $x_{k_1} \in N(c;\varepsilon)$, $S$ will be bounded above by $k_0$ and finite, which is a contradiction. Therefore, $c$ is a cluster point of $S$.

□

**Definition 1.3.2: Convergence and Divergence of a Sequnce**

The sequnce $\{x_k\}$ *converges* to $x_0$ and $x_0$ is the *limit* of $\{x_k\}$ if,

$$\forall \varepsilon \in \mathbb{R}_+,\ \exists k_0 \in \mathbb{N},\ \forall k \in \mathbb{N}_{\geq k_0},\ x_k \in N(x_0;\varepsilon).$$

We write $\lim\limits_{k\to\infty} x_k = x_0$. If there is no such $x_0$, then $\{x_k\}$ *diverges*.

**Lemma 1.3.2**

$\lim\limits_{x\to\infty} x_k = x_0$ if and only if $\left\{k \in \mathbb{N} \,\middle|\, x_k \notin N(x_0;\varepsilon)\right\}$ is finite for every $\varepsilon \in \mathbb{R}_+$.

***Proof.*** ($\Rightarrow$) Take any $\varepsilon \in \mathbb{R}_+$. There is some $k_0 \in \mathbb{N}$ such that $k \in N(x_0;\varepsilon)$ for all natural numbers $k \geq k_0$. Therefore, $\left\{k \in \mathbb{N} \,\middle|\, x_k \notin N(x_0;\varepsilon)\right\} \subseteq [k_0]$ and thus finite.

($\Leftarrow$) Take any $\varepsilon \in \mathbb{R}_+$. Let $k_0 := \max\left\{k \in \mathbb{N} \,\middle|\, x_k \notin N(x_0;\varepsilon)\right\}$. Then, for every natural number $k$ larger than $k_0$ satisfies $x_k \in N(x_0;\varepsilon)$. □

**Lemma 1.3.3**

The limit $x_0$ of a sequence, if it exists, is a cluster point of the sequence.

**Theorem 1.3.1** Uniqueness of the Limit

The limit of a convergent sequence of $\mathbb{R}$ is unique.

***Proof.*** Suppose $a$ and $b$ are two limits of a sequence $\{x_k\}$ and $a \neq b$. Let $\varepsilon := |b-a|/2$. Then, by Lemma 1.3.2, $A := \{k \in \mathbb{N} \mid x_k \notin N(a;\varepsilon)\}$ and $B := \{k \in \mathbb{N} \mid x_k \notin N(b;\varepsilon)\}$ are both finite, which means $A \cup B = \mathbb{N}$ is finite, #. □

**Theorem 1.3.2**

If a sequence has two (or more) cluster points, then it diverges.

***Proof.*** Suppose $x_0$ is the limit of $\{x_k\}$. Since, by Lemma 1.3.3, $x_0$ is a cluster point, there is another cluster point $c$ different from $x_0$. Let $\varepsilon := |x_0 - c|/2$.

Although $S := \{k \in \mathbb{N} \ x_k \notin N(x_0; \varepsilon)\}$ should be finite by Lemma 1.3.2, $\{k \in \mathbb{N} \mid x_k \in N(c; \varepsilon)\}$, a subset of $S$, is infinite by Lemma 1.3.1, #. □

**Theorem 1.3.3**

A convergent sequence is bounded.

***Proof.*** Let $x_0$ is the limit of $\{x_k\}$. There is some $k_0 \in \mathbb{N}$ such that $|x_k - x_0| < 1$ for all $k \in \mathbb{N}_{k_0}$. Let $A := \{x_k \mid k \in \mathbb{N} \text{ and } k \leq k_0\}$ and $B := \{x_k \mid k \in \mathbb{N} \text{ and } k \geq k_0\}$. Then, $A$ is finite and $B$ is bounded above and below by $x_0 + 1$ and $x_0 - 1$, respectively. Therefore, $\{x_k\}$ is bounded above by $\max(\max A, x_0 + 1)$ and below by $\min(\min A, x_0 - 1)$. □

**Corollary 1.3.1**

An unbounded sequence diverges.

**Lemma 1.3.4**

The following hold.

(i) $\lim_{k\to\infty} x_k = 0 \iff \lim_{k\to\infty} |x_k| = 0$

(ii) $\lim_{k\to\infty} x_k = x_0 \implies \forall c \in \mathbb{R}, \lim_{k\to\infty} cx_k = cx_0$

***Proof of (ii).*** If $c = 0$, then it is done; so suppose $c \neq 0$. Take any $\varepsilon \in \mathbb{R}_+$. Then, there is some $k_0 \in \mathbb{N}$ such that $|x_k - x_0| < \varepsilon/|c|$ for all $k \geq k_0$. This directly implies for all $k \geq k_0$, $|cx_k - cx_0| = |c| \cdot |x_k - x_0| < |c| \cdot \varepsilon/|c| = \varepsilon$. □

**Theorem 1.3.4**

A bounded, monotone sequence converges.

***Proof.*** Suppose $\{x_k\}$ is a monotone increasing sequence. Since it is bounded, $\{x_k\}$ has $\mu := \sup\{x_k \mid k \in \mathbb{N}\}$. Take any $\varepsilon \in \mathbb{R}_+$. By Theorem 1.1.4, there is some $k_0 \in \mathbb{N}$ such that $\mu - \varepsilon < x_{k_0} \leq \mu$. Then, for all $k \in \mathbb{N}_{\geq k_0}$, $\mu - \varepsilon < x_{k_0} \leq x_k \leq \mu$, which implies $|x_k - \mu| < \varepsilon$. Therefore $\lim_{k\to\infty} x_k = \mu$. □

**Theorem 1.3.5** The Squeeze Play

Let $\{x_k\}$, $\{y_k\}$, and $\{z_k\}$ be sequences that satisfy $x_k \leq y_k \leq z_k$ for $k \in \mathbb{N}$. If both $\{x_k\}$ and $\{z_k\}$ converges to $L \in \mathbb{R}$, then $\{y_k\}$ also converges to $L$.

***Proof.*** Take any $\varepsilon > 0$. There is $k_1 \in \mathbb{N}$ such that $\forall k \in \mathbb{N}_{\geq k_1}$, $x_k \in N(L; \varepsilon)$. Similarly, there is $k_2 \in \mathbb{N}$ such that $\forall k \in \mathbb{N}_{\geq k_2}$, $x_k \in N(L; \varepsilon)$. Then, for all $k \in \mathbb{N}$ not smaller than $\max\{k_1, k_2\}$, $L - \varepsilon < x_k \leq y_k \leq z_k < L + \varepsilon$ holds, which implies $y_k \in N(L; \varepsilon)$. □

**Theorem 1.3.6** Limit is Order Preserving on Convergent Sequences

If both $\{x_k\}$ and $\{y_k\}$ converge and if $x_k \le y_k$ for each $k \in \mathbb{N}$, then

$$\lim_{k\to\infty} x_k \le \lim_{k\to\infty} y_k.$$

***Proof.*** Let $L_x := \lim_{k\to\infty} x_k$ and $L_y := \lim_{k\to\infty} y_k$, and suppose $L_x > L_y$. Let $\varepsilon := (L_x - L_y)/2 > 0$. Then, there is $k \in \mathbb{N}$ such that $x_k \in N(L_x;\varepsilon)$ and $y_k \in N(L_y;\varepsilon)$, which implies $y_k < L_y + \varepsilon = L_x - \varepsilon < x_k$, #. □

**Definition 1.3.3: Subsequence**

Let $\{x_k\}$ be any sequence. Choose any strictly monotone increasing sequnce $k_1 < k_2 < k_3 < \cdots$ of natural numbers. For each $j \in \mathbb{N}$, let $y_j := x_{k_j}$. The sequence $\{y_j\}_{j=1}^{\infty}$ is called an *subsequence* of $\{x_k\}$.

**Theorem 1.3.7**

The point $c$ is a cluster point of $\{x_k\}$ if and only if there exists a subsequence of $\{x_k\}$ that converges to $c$.

***Proof.*** $(\Rightarrow)$ Let $\{\varepsilon_k\}$ be an arbitrary sequence of positive real numbers that converges to 0. (e.g. $\varepsilon_k = 1/k$) Define $\{k_j\}_{j=1}^{\infty}$ by the inductive definition below.

- $k_0 := 0$
- For each $j \in \mathbb{N}$, $k_j \in \{k \in \mathbb{N} \mid k > k_{j-1} \text{ and } x_k \in N(c;\varepsilon)\}$.

Since $c$ is a cluster point, $\{k \in \mathbb{N} \mid k > k_{j-1} \text{ and } x_k \in N(c;\varepsilon)\} \neq \varnothing$ for all $j \in \mathbb{N}$. Therefore, $\{k_j\}$ is well-defined. It is immediate that $\lim_{j\to\infty} x_{k_j} = c$.

$(\Leftarrow)$ Let $\{x_{k_j}\}_{j=1}^{\infty}$ be a sequence such that $\lim_{j\to\infty} x_{k_j} = c$. Take any $\varepsilon \in \mathbb{R}_+$ and $k \in \mathbb{N}$. Then, there is some $j_0 \in \mathbb{N}$ such that $\forall j \in \mathbb{N}_{\ge j_0}$, $x_{k_j} \in N(c;\varepsilon)$. Let $k_0 := \min\{k_j \in \mathbb{N} \mid j > j_0 \text{ and } k_j > k\}$. Then, $x_{k_0} \in N(c;\varepsilon)$ and $k_0 > k$. Therefore, $c$ is a cluster point. □

**Theorem 1.3.8**

Any bounded sequence $\{x_k\}$ has a cluster point.

***Proof.*** If the set $S := \{x_k \mid k \in \mathbb{N}\}$ is finite, there is some $x_{k_0}$ that is repeated infinitely. Then, $x_{k_0}$ is surely a cluster point.

Now, suppose $S$ is infinite. Then, by Theorem 1.2.3, $S$ has a limit point $\ell$. To prove $\ell$ is a cluster point, take any $\varepsilon \in \mathbb{R}_+$ and $k \in \mathbb{N}$.

Let $S' := \{x_{k'} \mid k' \in \mathbb{N}_{>k}\}$. We first claim that $\ell$ is a limit point of $S'$. Take any $\varepsilon' \in \mathbb{R}_+$ less than $m = \min\{|x_{k'} - \ell| \in \mathbb{R}_+ \mid k' \in \mathbb{N}_{\le k}\}$. ($m$ exists due to Theorem 1.1.3.) Then, $S' \cap N'(\ell;\varepsilon') = S \cap N'(\ell;\varepsilon')$ is nonempty. Therefore, $\ell$ is a limit point of $S'$ by Theorem 1.2.1.

Finally, we can say $S' \cap N(\ell;\varepsilon)$ is nonempty. This implies there is some $k_0 \in \mathbb{Z}_{>k}$ such that $x_{k_0} \in N(\ell;\varepsilon)$. Therefore, $\ell$ is a cluster point of $\{x_k\}$. □

**Corollary 1.3.2**

If a sequence has no cluster point, then the sequence is unbounded.

**Corollary 1.3.3**

Any bounded sequence converges if and only if it has exactly one cluster point.

**Corollary 1.3.4**

A sequence $\{x_k\}$ diverges if and only if at least one of the following conditions holds.
- $\{x_k\}$ has two or more cluster points.
- $\{x_k\}$ is unbounded.

***Proof.*** ($\Rightarrow$) Suppose $\{x_k\}$ is diverging and bounded. By Theorem 1.3.8, it has at least one cluster point. Also, if it had exactly one cluster point, it would converge by Corollary 1.3.3.

($\Leftarrow$) It is direct from Theorem 1.3.2 and Corollary 1.3.1. $\square$

**Theorem 1.3.9**

A sequence $\{x_k\}$ converges if and only if every subsequence of $\{x_k\}$ converges.

***Proof.*** ($\Rightarrow$) Take any subsequence $\{x_{k_i}\}_{i=1}^{\infty}$ of $\{x_k\}_{k=1}^{\infty}$ and $\varepsilon \in \mathbb{R}_+$. There is $i_0 \in \mathbb{N}$ such that $\forall i \in \mathbb{N}_{\geq i_0}$, $|x_i| < \varepsilon$. Since $k_i \geq i$ for all natural number $i$, $\forall i \in \mathbb{N}_{\geq i_0}$, $|x_{k_i}| < \varepsilon$.

($\Leftarrow$) $\{x_k\}$ is a subsequence of itself. $\square$

**Definition 1.3.4: Limit Superior and Inferior**

Let $\{x_k\}$ be a sequence and $C$ be a set of cluster points of the sequence.

- $$\limsup x_k \triangleq \begin{cases} \sup C & \text{if } \{x_k\} \text{ is bounded} \\ \infty & \text{if } \{x_k\} \text{ is unbounded above} \\ \sup C & \text{if } \{x_k\} \text{ is bounded above but unbounded below and } C \neq \varnothing \\ -\infty & \text{if } \{x_k\} \text{ is bounded above but unbounded below and } C = \varnothing \end{cases}$$
  is called *limit superior* of $\{x_k\}$.
- $$\liminf x_k \triangleq \begin{cases} \inf C & \text{if } \{x_k\} \text{ is bounded} \\ -\infty & \text{if } \{x_k\} \text{ is unbounded below} \\ \inf C & \text{if } \{x_k\} \text{ is bounded below but unbounded above and } C \neq \varnothing \\ \infty & \text{if } \{x_k\} \text{ is bounded below but unbounded above and } C = \varnothing \end{cases}$$
  is called *limit inferior* of $\{x_k\}$.

**Note:-**

In all cases, $\liminf x_k \leq \limsup x_k$.

**Theorem 1.3.10**

- If $\mu = \limsup x_k$ is finite, then $\mu$ is in $C$. ($\mu = \max C$)
- If $\nu = \liminf x_k$ is finite, then $\nu$ is in $C$. ($\nu = \min C$)

***Proof.*** Suppose $\mu = \limsup x_k$ is finite. Take any $\varepsilon \in \mathbb{R}_+$ and $k \in \mathbb{N}$. The finiteness of $\mu$ implies $\mu = \sup C$. By Theorem 1.1.4, there is some $c \in C$ such that $\mu - \varepsilon < c \leq \mu$. If $c = \mu$, then we are done. So let $c < \mu$.

Choose any positive $\varepsilon_1$ less than $\min\{c-(\mu-\varepsilon), \mu-c\}$ so $N(c;\varepsilon_1) \subseteq N(\mu;\varepsilon)$. Then, $\{k \in \mathbb{N} \mid x_k \in N(\mu;\varepsilon)\}$ is infinite since it has an infinite set $\{k \in \mathbb{N} \mid x_k \in N(c;\varepsilon_1)\}$ as its subset. (See Lemma 1.3.1.)

The second part can be proven analogously. □

**Theorem 1.3.11**

Let $\{x_k\}$ be any bounded sequence in $\mathbb{R}$. Fix any $\varepsilon \in \mathbb{R}_+$.

- Let $\mu = \limsup x_k$.
  - $\exists k_0 \in \mathbb{N}, \forall k \in \mathbb{N}_{\geq k_0}, x_k < \mu + \varepsilon$.
  - $\forall k \in \mathbb{N}, \exists k_1 \in \mathbb{N}_{>k}, x_{k_1} > \mu - \varepsilon$.
- Let $\nu = \liminf x_k$.
  - $\exists k_0 \in \mathbb{N}, \forall k \in \mathbb{N}_{\geq k_0}, x_k > \nu - \varepsilon$.
  - $\forall k \in \mathbb{N}, \exists k_1 \in \mathbb{N}_{>k}, x_{k_1} < \nu + \varepsilon$.

***Proof.*** Take any $\varepsilon \in \mathbb{R}_+$. Then, $\{k \in \mathbb{N} \mid x_k \geq \mu + \varepsilon\}$ is finite. If it were not, then there would be a cluster point larger than $\mu$ since Theorem 1.3.8 implies the existence of a cluster point in a subsequence of $\{x_k\}$ which is composed of $x_k$'s not smaller than $\mu + \varepsilon$. Therefore, if $k_0 := \max\{k \in \mathbb{N} \mid x_k \geq \mu + \varepsilon\} + 1$, then $x_k < \mu + \varepsilon$ for all $k$ not smaller than $k_0$.

Also, since $\mu$ is a cluster point by Theorem 1.3.10, $\forall k \in \mathbb{N}, \exists k_1 \in \mathbb{N}_{>k}, x_{k_1} > \mu - \varepsilon$. (See Lemma 1.3.1.)

The second part can be proven analogously. □

**Theorem 1.3.12**

Let $\{x_k\}$ be any sequence in $\mathbb{R}$.

(i) $\{x_k\}$ converges to $x_0$ if and only if $\liminf x_k = \limsup x_k = x_0$.

(ii) $\{x_k\}$ diverges if and only if one of the following holds.
- Either $\liminf x_k$ or $\limsup x_k$ is infinite.
- Both $\liminf x_k$ or $\limsup$ are finite and $\liminf x_k < \limsup x_k$.

***Proof.***

(i) $(\Rightarrow)$ $C = \{x_0\}$, therefore $\liminf x_k = \limsup x_k = x_0$.
$(\Leftarrow)$ Take any $\varepsilon \in \mathbb{R}_+$. There are natural numbers $k_1$ and $k_2$ such that $\forall k \in \mathbb{N}_{\geq k_1}, x_k < x_0 + \varepsilon$ and $\forall k \in \mathbb{N}_{\geq k_0}, x_k > x_0 - \varepsilon$. Then, for all natural number $k$ not smller than $k_0 := \max\{k_1, k_2\}$, $x_0 - \varepsilon < x_k < x_0 + \varepsilon$ holds.

(ii) If it is not $\liminf x_k = \limsup x_k \in \mathbb{R}$, then it is either "One of them is infinite." or "They are both finite but they are different."

□

**Exercise 1.3.1**

Let $\{x_k\}$ be a bounded sequence of positive numbers. For each $k \in \mathbb{N}$ define $y_k := x_{k+1}/x_k$ and $z_k := (x_k)^{1/k}$. Prove that $\liminf y_k \leq \liminf z_k \leq \limsup z_k \leq \limsup y_k$.

***Solution:*** ($\liminf y_k \leq \liminf z_k$) Let $L := \liminf y_k$. Now, we claim that

$$\forall \varepsilon \in \mathbb{R}_+, \exists k_0 \in \mathbb{N}, \forall\, k \in \mathbb{N}_{\geq k_0}, z_k > L - \varepsilon.$$

If $L = 0$, then it is done. Therefore, suppose $L > 0$. To prove this, take any $\varepsilon \in \mathbb{R}_+$ smaller than $L$. Then, there is some $k_1 \in \mathbb{N}$ such that $y_k > L - \varepsilon/2$ for all $k$ not smaller than $k_1$ by

Theorem 1.3.11. Then, for all $k \in \mathbb{N}_{k \geq k_1}$, $x_k > (L - \varepsilon/2)^{k-k_1} x_{k_1}$, which is equivalent to

$$z_k = x_k^{1/k} > \left(L - \frac{\varepsilon}{2}\right) \left[ \left(L - \frac{\varepsilon}{2}\right)^{-k_1} x_{k_1} \right]^{1/k}.$$

Since $\lim_{k\to\infty} \left[ (L-\varepsilon/2)^{-k_1} x_{k_1} \right]^{1/k} = 1$, there is some $k_2 \in \mathbb{N}$ such that

$$\left[ \left(L - \frac{\varepsilon}{2}\right)^{-k_1} x_{k_1} \right]^{1/k} > 1 - \frac{\varepsilon/2}{L-\varepsilon/2} = \frac{L-\varepsilon}{L-\varepsilon/2}.$$

for all $k \in \mathbb{N}_{\geq k_2}$. Thus, for every natural number $k$ not smaller than $\max\{k_1, k_2\}$,

$$z_k > \left(L - \frac{\varepsilon}{2}\right) \left[ \left(L - \frac{\varepsilon}{2}\right)^{-k_1} x_{k_1} \right]^{1/k} > \left(L - \frac{\varepsilon}{2}\right) \cdot \frac{L-\varepsilon}{L-\varepsilon/2} = L - \varepsilon.$$

The claim is now proven.

For the main proof, assume that $\liminf z_k < L$ for the sake of contradiction. Take $\varepsilon_0 := (L - \liminf z_k)/2$. Then, by the previous claim, $\exists k_3 \in \mathbb{N}$, $\forall k \in \mathbb{N}_{\geq k_3}$, $z_k > L - \varepsilon_0 = (L + \liminf x_k)/2$.

Nevertheless, by Theorem 1.3.11, there is some $k_4 \in \mathbb{N}_{>k_3}$ such that $z_{k_4} < \liminf x_k + \varepsilon_0 = (L + \liminf x_k)/2$, which is a contradiction.

$\limsup z_k \leq \limsup y_k$ can be proven analogously.

□

## 1.4 Cauchy Sequences

**Definition 1.4.1: Cauchy Seqeuence**

A seqeuence $\{x_k\}$ in $\mathbb{R}$ is called a *Cauchy sequence* if

$$\forall \varepsilon \in \mathbb{R}_+,\ \exists k_0 \in \mathbb{N},\ \forall k, m \in \mathbb{N}_{\geq k_0},\ |x_k - x_m| < \varepsilon.$$

**Theorem 1.4.1**

If $\{x_k\}$ is a convergent sequence of real numbers, then $\{x_k\}$ is a Cauchy sequence.

***Proof.*** Let $x_0 := \lim_{k\to\infty} x_k$. Take any $\varepsilon \in \mathbb{R}_+$. Then, there is some $k_0 \in \mathbb{N}$ such that $|x_k - x_0| < \varepsilon/2$ for all $k \in \mathbb{N}$ not smaller than $k_0$. Then, for all $k, m \in \mathbb{N}$ greater than $k_0$, $|x_k - x_m| \leq |x_k - x_0| + |x_k - x_m| < \varepsilon/2 + \varepsilon/2 = \varepsilon$. □

**Theorem 1.4.2**

If $\{x_k\}$ is a Cauchy sequence, then $\{x_k\}$ is bounded.

***Proof.*** There is $k_0 \in \mathbb{N}$ such that $|x_k - x_m| < 1$ for all $k, m \in \mathbb{N}_{\geq k_0}$. It implies that $|x_k - x_{k_0}| < 1$, for all $k \in \mathbb{N}_{\geq k_0}$, which impliees $|x_k| < |x_{k_0}| + 1$. Therefore, for all $k \in \mathbb{N}$, $|x_k| \leq \max\left\{ |x_1|, |x_2|, \cdots, |x_{k_0}|, |x_{k_0}| + 1 \right\}$. □

**Theorem 1.4.3**

A Cauchy sequence has exactly one cluster point.

***Proof.*** Since a Cauchy sequence is bounded, it has at least one cluster point by Theorem 1.3.8. So, we should prove that the sequence does not have more than one cluster point. Assume $c_1$ and $c_2$ are cluster points for the sake of contradiction. Let $\varepsilon := |c_1 - c_2|/3$. Choose $k_0 \in \mathbb{N}$ such that $\forall k, m \in \mathbb{N}_{\geq k_0}$, $|x_k - x_m| < \varepsilon$. Also, there are $k_1, k_2 \in \mathbb{N}_{>k_0}$ such that $|x_{k_1} - c_1| < \varepsilon$ and $|x_{k_2} - c_2| < \varepsilon$. Note that $|c_1 - c_2| \leq |c_1 - x_{k_1}| + |x_{k_1} - x_{k_2}| + |x_{k_2} - c_2|$. Nevertheless, then

$$\begin{aligned}\varepsilon > |x_{k_1} - x_{k_2}| &\geq |c_1 - c_2| - |c_1 - x_{k_1}| - |c_2 - x_{k_2}| \\ &> 3\varepsilon - \varepsilon - \varepsilon = \varepsilon,\end{aligned}$$

which is a contradiction. □

**Theorem 1.4.4** Cauchy Completeness of $\mathbb{R}$

A sequence in $\mathbb{R}$ is convergent if and only if it is a Cauchy sequence.

***Proof.*** By Corollary 1.3.3, a Cauchy sequence is convergent since it is bounded (Theorem 1.4.2) and has exactly one cluster point (Theorem 1.4.3). A convergent sequence in $\mathbb{R}$ is Cauchy. (Theorem 1.4.1) □

**Definition 1.4.2: Cauchy Completeness**

A set $X$ is said to be *Cauchy complete* if every Cauchy sequence in $X$ converges to a point of $X$.

**Example 1.4.1**

$\mathbb{R}$ is Cauchy complete.

**Definition 1.4.3: Contractive Sequence**

A sequence $\{x_k\}$ is said to be *contractive* if there exists a constant $C$, with $0 < C < 1$, such that

$$\forall k \in \mathbb{N}_{>1},\ |x_{k+1} - x_k| \leq C|x_k - x_{k-1}|.$$

**Theorem 1.4.5**

Any contractive sequence in $\mathbb{R}$ is a Cauchy sequence.

***Proof.*** Suppose $0 < C < 1$ and $\forall k \in \mathbb{N}_{>1}$, $|x_{k+1} - x_k| \leq C|x_k - s_{k-1}|$. If it is trivial when $|x_2 - x_1| = 0$, so supose $|x_2 - x_1| \neq 0$. By induction, $\forall k \in \mathbb{N}_{>1}$, $|x_{k+1} - x_k| \leq C^{k-1}|x_2 - x_1|$.

To prove $\{x_k\}$ is a Cauchy sequence, take any $\varepsilon \in \mathbb{R}_+$. Since $\lim_{k\to\infty} C^{k-1} = 0$,

$$\exists k_0 \in \mathbb{N},\ \forall k \in \mathbb{N}_{\geq k_0},\ C^{k-1} < \frac{(1-C)\varepsilon}{|x_2 - x_1|}.$$

Then, for any $k, m \in \mathbb{N}$ with $k_0 \le m < k$,

$$\begin{aligned}
|x_k - x_m| &= \left|\sum_{j=m}^{k-1}(x_{j+1} - x_j)\right| \le \sum_{j=m}^{k-1}|x_{j+1} - x_j| \\
&\le \sum_{j=m}^{k-1} C^{j-1}|x_2 - x_1| = C^{m-1}|x_2 - x_1| \sum_{j=0}^{k-m-1} C^j \\
&= C^{m-1}|x_2 - x_1|\frac{1 - C^{k-m}}{1 - C} < \frac{C^{m-1}}{1 - C}|x_2 - x_1| \\
&< \frac{(1 - C)\varepsilon}{|x_2 - x_1|} \cdot \frac{1}{1 - C}|x_2 - x_1| = \varepsilon.
\end{aligned}$$

□

## 1.5 The Algebra of Convergent Series

**Theorem 1.5.1**

Let $\{x_k\}$ and $\{y_k\}$ be convergent sequences in $\mathbb{R}$ and $\lim_{k\to\infty} x_k = x_0$ and $\lim_{k\to\infty} y_k = y_0$.

- $\lim_{k\to\infty}(x_k + y_k) = x_0 + y_0$
- $\lim_{k\to\infty} x_k y_k = x_0 y_0$
- $\lim_{k\to\infty} \frac{y_k}{x_k} = \frac{y_0}{x_0}$ if $x_0 \neq 0$.

**Theorem 1.5.2**

Let $\{x_k\}$ and $\{y_k\}$ be convergent sequences in $\mathbb{R}$ and $\lim_{k\to\infty} x_k = x_0$. Then, if $r \in \mathbb{Q}$, then

$$\lim_{k\to\infty} x_k^r = x_0^r.$$

Nevertheless, we requre $x_0 \neq 0$ if $r < 0$.

## 1.6 Cardinality

**Definition 1.6.1: Dense Set**

We say a subset $S$ of $T$ is dense in $T$ if every neighborhood of any point $x \in T$ contains points of $S$.

**Theorem 1.6.1**

- $\mathbb{N}$, $\mathbb{Z}$, and $\mathbb{Q}$ are countably infinite.
- $\mathbb{R}$ is uncountable.
- $\mathbb{Q}$ is dense in $\mathbb{R}$.

# Chapter 2

# Euclidean Spaces

## 2.1 Euclidean $n$-Space

**Definition 2.1.1: Inner Product**

The *inner product* of two vectors $\mathbf{x} = (x_1, x_2, \cdots, x_n)$ and $\mathbf{y} = (y_1, y_2, \cdots, y_n)$ in $\mathbb{R}^n$ is

$$\langle \mathbf{x}, \mathbf{y} \rangle = \sum_{j=1}^{n} x_j y_j.$$

**Theorem 2.1.1**

If $\mathbf{x}$, $\mathbf{y}$, and $\mathbf{z}$ are arbitrary vectors in $\mathbb{R}^n$ and if $a$ and $b$ are real numbers, then the following hold:

(i) The inner product is *additive* in both its variables:

$$\langle \mathbf{x} + \mathbf{y}, \mathbf{z} \rangle = \langle \mathbf{x}, \mathbf{z} \rangle + \langle \mathbf{y}, \mathbf{z} \rangle$$
$$\langle \mathbf{x}, \mathbf{y} + \mathbf{z} \rangle = \langle \mathbf{x}, \mathbf{y} \rangle + \langle \mathbf{x}, \mathbf{z} \rangle$$

(ii) The inner product is *symmetric*: $\langle \mathbf{x}, \mathbf{y} \rangle = \langle \mathbf{y}, \mathbf{x} \rangle$.

(iii) The inner product is *homogeneous* in both its variables: $\langle a\mathbf{x}, b\mathbf{y} \rangle = ab\langle \mathbf{x}, \mathbf{y} \rangle$.

**Definition 2.1.2: Euclidean Norm**

The *Euclidean norm* of a vector $\mathbf{x}$ in $\mathbb{R}^n$ is

$$||\mathbf{x}|| = \sqrt{\langle \mathbf{x}, \mathbf{x} \rangle}.$$

**Theorem 2.1.2** The Cauchy-Schwarz Inequality

If $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$, then

$$|\langle \mathbf{x}, \mathbf{y} \rangle| \le ||\mathbf{x}|| \cdot ||\mathbf{y}||.$$

***Proof.*** For any $t \in \mathbb{R}$, $0 \le ||t\mathbf{x}+\mathbf{y}||^2 = ||\mathbf{x}||^2 t^2 + 2\langle \mathbf{x}, \mathbf{y} \rangle t + ||\mathbf{y}||^2$. Thus, the discriminant $|\langle \mathbf{x}, \mathbf{y} \rangle|^2 - ||\mathbf{x}||^2 ||\mathbf{y}||^2$ is nonpositive. □

**Theorem 2.1.3**

For vectors $\mathbf{x}$ and $\mathbf{y}$ in $\mathbb{R}^n$ and any $c \in \mathbb{R}$, the Euclidean norm has the following properties.

(i) $||\mathbf{x}|| \geq 0$; $||\mathbf{x}|| = 0$ if and only if $\mathbf{x} = \mathbf{0}$. (*Positive Definiteness*)

(ii) $||c\mathbf{x}|| = |c| \cdot ||\mathbf{x}||$. (*Absolute Homogeneity*)

(iii) $||\mathbf{x}+\mathbf{y}|| \leq ||\mathbf{x}|| + ||\mathbf{y}||$. (*Subadditivity*)

***Proof of (iii).***

$$\begin{aligned} 0 \leq ||\mathbf{x}+\mathbf{y}||^2 &= ||\mathbf{x}||^2 + 2\langle \mathbf{x}, \mathbf{y}\rangle + ||\mathbf{y}||^2 \\ &\leq ||\mathbf{x}||^2 + 2||\mathbf{x}||||\mathbf{y}|| + ||\mathbf{y}||^2 = (||\mathbf{x}|| + ||\mathbf{y}||)^2 \end{aligned}$$

□

**Definition 2.1.3: Norm**

A *norm* on $\mathbb{R}^n$ is any function $n \colon \mathbb{R}^n \to \mathbb{R}$ that is positive definite, absolutely homogeneous, and subadditive.

**Definition 2.1.4: Metric**

A *metric* on $\mathbb{R}^n$ is a function from $\mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}$ having the following properties.

(i) $\forall \mathbf{x}, \mathbf{y} \in \mathbb{R}^n$, $d(\mathbf{x}, \mathbf{y}) \geq 0$; $d(\mathbf{x}, \mathbf{y}) = 0 \iff \mathbf{x} = \mathbf{y}$. (*Positive Definiteness*)

(ii) $\forall \mathbf{x}, \mathbf{y} \in \mathbb{R}^n$, $d(\mathbf{x}, \mathbf{y}) = d(\mathbf{y}, \mathbf{y})$. (*Symmetry*)

(iii) $\forall \mathbf{x}, \mathbf{y}, \mathbf{z} \in \mathbb{R}^n$, $d(\mathbf{x}, \mathbf{z}) \leq d(\mathbf{x}, \mathbf{y}) + d(\mathbf{y}, \mathbf{z})$. (*The Triangle Inequality*)

**Definition 2.1.5: Euclidean Metric**

The *Euclidean metric* on $\mathbb{R}^n$ is defined by

$$d(\mathbf{x}, \mathbf{y}) = ||\mathbf{x} - \mathbf{y}|| = \left[ \sum_{j=1}^{n} (x_j - y_j)^2 \right]^{1/2}.$$

**Theorem 2.1.4**

The Euclidean metric is a metric on $\mathbb{R}^n$.

**Definition 2.1.6: Orthogonality**

Two vectors $\mathbf{x}$ and $\mathbf{y}$ in $\mathbb{R}^n$ are said to be *orthogonal* if $\langle \mathbf{x}, \mathbf{y}\rangle = 0$.

**Definition 2.1.7: Neighborhood and Deleted Neighborhood**

A *neighborhood* $N(\mathbf{x}; r)$ or $\mathbf{x} \in \mathbb{R}^n$ with radius $r$ is the set

$$N(\mathbf{x}; r) = \{ \mathbf{y} \in \mathbb{R}^n \mid ||\mathbf{x} - \mathbf{y}|| < r \}.$$

A *deleted neighborhood* $N'(\mathbf{x}, r)$ of $\mathbf{x}$ is $N'(\mathbf{x}; r) = N(\mathbf{x}; r) \setminus \{\mathbf{x}\}$.

**Definition 2.1.8: Limit Point**

Let $S$ be nonempty subset of $\mathbb{R}^n$. We say that $\mathbf{x}$ is a *limit point* of $S$ if

$$\forall \varepsilon \in \mathbb{R}_+, N'(\mathbf{x}; \varepsilon) \cap S \neq \varnothing.$$

**Theorem 2.1.5**

$\mathbb{Q}^n$ is dense in $\mathbb{R}^n$.

***Proof.*** Take any $\mathbf{y} = (y_1, y_2, \cdots, y_n) \in \mathbb{R}^n$ and $\varepsilon \in \mathbb{R}_+$. For each $j = 1, 2, \cdots, n$, choose a rational $x_j \in N(y_j; \varepsilon/\sqrt{n})$ and form $\mathbf{x} \triangleq (x_1, x_2, \cdots, x_n) \in \mathbb{Q}^n$. Then,

$$\|\mathbf{x}-\mathbf{y}\|^2 = \sum_{j=1}^{n}(x_j - y_j)^2 < n(\varepsilon/\sqrt{n})^2 = \varepsilon^2.$$

Therefore $\mathbf{y}$ is a limit point of $\mathbb{Q}^n$. □

**Definition 2.1.9: Boundedness**

A subset $S$ of $\mathbb{R}^n$ is said to be *bounded* if

$$\exists M \in \mathbb{R}_+,\ \forall \mathbf{x} \in S,\ \|\mathbf{x}\| \le M.$$

### 2.1.1 Sequences in $\mathbb{R}^n$

**Definition 2.1.10: Cluster Point**

$\mathbf{c} \in \mathbb{R}^n$ is a *cluster point* of the sequence $\{\mathbf{x}_k\}$ if,

$$\forall (\varepsilon, k) \in \mathbb{R}_+ \times \mathbb{N},\ \exists k_1 \in \mathbb{N}_{>k},\ \mathbf{x}_{k_1} \in N(\mathbf{c}; \varepsilon).$$

**Definition 2.1.11: Convergence and Divergence of a Sequence**

The sequnce $\{\mathbf{x}_k\}$ *converges* to $\mathbf{x}_0$ and $\mathbf{x}_0$ is the *limit* of $\{\mathbf{x}_k\}$ if,

$$\forall \varepsilon \in \mathbb{R}_+,\ \exists k_0 \in \mathbb{N},\ \forall k \in \mathbb{N}_{\ge k_0},\ \mathbf{x}_k \in N(\mathbf{x}_0; \varepsilon).$$

We write $\lim\limits_{k\to\infty} \mathbf{x}_k = \mathbf{x}_0$. If there is no such $\mathbf{x}_0$, then $\{\mathbf{x}_k\}$ *diverges*.

**Theorem 2.1.6**

Let $\{\mathbf{x}_k\} = (x_1^{(k)}, x_2^{(k)}, \cdots, x_n^{(k)})$ for each $k \in \mathbb{N}$. Let $\mathbf{x}_0 = (x_1^{(0)}, x_2^{(0)}, \cdots, x_n^{(0)})$. The sequence $\{\mathbf{x}_k\}$ converges to $\mathbf{x}_0$ if and only if, for each $j \in [n]$, the sequence $\{x_j^{(k)}\}$ converges to $\{x_j^{(0)}\}$.

***Proof.*** ($\Rightarrow$) Take any $\varepsilon \in \mathbb{R}_+$. There there is $k_0 \in \mathbb{N}$ such that

$$\forall k \in \mathbb{N}_{\ge k_0}, \mathbf{x}_k \in N(\mathbf{x}_0; \varepsilon).$$

Then, for each $j \in [n]$,

$$\left(x_j^{(k)} - x_0^{(k)}\right)^2 \le \sum_{i=1}^{n}\left(x_i^{(k)} - x_0^{(k)}\right)^2 = \|\mathbf{x}_k - \mathbf{x}_0\|^2 < \varepsilon.$$

($\Leftarrow$) Take any $\varepsilon \in \mathbb{R}_+$. Then, for each $j \in [n]$, there is some $k_j \in \mathbb{N}$ such that

$$\forall k \in \mathbb{N}_{\ge k_j},\ x_j^{(k)} \in N(x_0^{(k)}; \varepsilon/\sqrt{n}).$$

Then, for all natural number $k$ not smaller than $\max_{j\in[n]} k_j$,

$$\|\mathbf{x}_k - \mathbf{x}_0\|^2 = \sum_{j=1}^{n} \left(x_j^{(k)} - x_0^{(k)}\right)^2 < n(\varepsilon/\sqrt{n})^2 = \varepsilon^2.$$

□

**Definition 2.1.12: Cauchy Seqeunce**

A seqeunce $\{\mathbf{x}_k\}$ in $\mathbb{R}^n$ is called a *Cauchy sequence* if

$$\forall \varepsilon \in \mathbb{R}_+,\ \exists k_0 \in \mathbb{N},\ \forall k,m \in \mathbb{N}_{\geq k_0},\ \|\mathbf{x}_k - \mathbf{x}_m\| < \varepsilon.$$

**Theorem 2.1.7** Cauchy's Completeness Theorem in $\mathbb{R}^n$

A sequence $\{\mathbf{x}_k\}$ in $\mathbb{R}^n$ is Cauchy if and only if it converges. $\mathbb{R}^n$ is Cauchy complete.

***Proof.*** (⇐) The proof if similar to Theorem 1.4.1.

(⇒) Let some Cauchy sequence $\{\mathbf{x}_k\}$ in $\mathbb{R}^n$ be given. Take any $\varepsilon \in \mathbb{R}_+$. There is some $k_0 \in \mathbb{N}$ such that for every natural number $k$ and $m$ not smaller than $k_0$, $\|\mathbf{x}_k - \mathbf{x}_m\| < \varepsilon$. Then, for each $j \in [n]$, $|x_j^{(k)} - x_j^{(m)}| \leq \|\mathbf{x}_k - \mathbf{x}_m\| < \varepsilon$, which implies each $\{x_j^{(k)}\}_{k\in\mathbb{N}}$ is Cauchy. By Theorem 1.4.4, $\{x_j^{(k)}\}_{j\in\mathbb{N}}$ converges to some number $x_j^{(0)}$. Then, Theorem 2.1.6 ensures that $\lim_{k\to\infty} \mathbf{x}_k = (x_1^{(0)}, x_2^{(0)}, \cdots, x_n^{(0)})$. □

**Theorem 2.1.8** The Generalized Bolzano–Weierstra Theorem

Every bounded infinite set in $\mathbb{R}^n$ has a limit point in $\mathbb{R}^n$.

***Proof.*** Suppose that $S$ is any bounded, infinite set in $\mathbb{R}^n$. Being bounded, $S$ is contained in some $n$-cube $C(2M) = [-M, M]^n$ centered at $\mathbf{0}$. Construct $C_1, C_2, \cdots$ as following.

- $C_1 \triangleq C(2M) = [a_1^{(1)}, b_1^{(1)}] \times \cdots \times [a_n^{(1)}, b_n^{(1)}]$
  - Note that $C_1 \cap S = S$ is infinite.
- For each $k \in \mathbb{N}$, $C_{k+1}$ is any cube of the form $[a_1^{(k+1)}, b_1^{(k+1)}] \times \cdots \times [a_n^{(k+1)}, b_n^{(k+1)}]$ where each $[a_j^{(k+1)}, b_j^{(k+1)}]$ is either $[a_j^{(k)}, (a_j^{(k)} + b_j^{(k)})/2]$ or $[(a_j^{(k)} + b_j^{(k)})/2, b_j^{(k)}]$ so that $C_{k+1} \cap S$ is infinite.
  - This is possible since there is at least one cube among $2^n$ possible choices that $C_{k+1} \cap S$ is infinite.

Then, the main diagonal $d_k$ of $C_k$ equals to $Mn^{1/2}/2^{k-2}$. Also, note that $C_k \supseteq C_{k+1}$ for all $k \in \mathbb{N}$.

Now, we may construct a sequence $\{\mathbf{x}_k\}_{k\in\mathbb{N}}$ as following.

- $\mathbf{x}_1$ is any element in $C_1 \cap S$.
- For each $k \in \mathbb{N}$, $\mathbf{x}_{k+1}$ is arbitrarily taken from $C_{k+1} \cap S \setminus \{\mathbf{x}_1, \mathbf{x}_2, \cdots, \mathbf{x}_k\}$.

We claim that $\{\mathbf{x}_k\}_{k\in\mathbb{N}}$ is a Cauchy sequence. To show this, take any $\varepsilon \in \mathbb{R}_+$. There is some $k_0 \in \mathbb{N}$ such that $d_{k_0} = Mn^{1/2}/2^{k_0-2} < \varepsilon$ by Theorem 1.1.1. Then, for all $k, m \in \mathbb{N}_{\geq k_0}$, $\|\mathbf{x}_k - \mathbf{x}_m\| \leq d_{k_0} < \varepsilon$. Therefore, since $\{\mathbf{x}_k\}$ is Cauchy, and therefore convergent by Theorem 2.1.7.

Clearly, $\mathbf{x}_0 \triangleq \lim_{k\to\infty} \mathbf{x}_k$ is a limit point of $S$ since any deleted neighborhood $N'(\mathbf{x}_0)$ of $\mathbf{x}_0$ intersects infinitely many points with $\{\mathbf{x}_k\}_{k\in\mathbb{N}} \subseteq S$. □

**Definition 2.1.13: Subsequence**

Let $\{\mathbf{x}_k\}$ be any sequence in $\mathbb{R}^n$. Choose any strictly monotone increasing sequnce $k_1 < k_2 < k_3 < \cdots$ of natural numbers. For each $j \in \mathbb{N}$, let $\mathbf{y}_j := \mathbf{x}_{k_j}$. The sequence $\{\mathbf{y}_j\}_{j=1}^{\infty}$ is called an *subsequence* of $\{\mathbf{x}_k\}$.

**Theorem 2.1.9**

The point $\mathbf{c}$ is a cluster point of $\{\mathbf{x}_k\}$ if and only if there exists a subsequence of $\{\mathbf{x}_k\}$ that converges to $\mathbf{c}$.

***Proof.*** Analogous to Theorem 1.3.7. □

**Theorem 2.1.10**

Any bounded sequence $\{\mathbf{x}_k\}$ has a cluster point.

***Proof.*** Analogous to Theorem 1.3.8. □

**Corollary 2.1.1**

If a sequence in $\mathbb{R}^n$ has no cluster point, then the sequence is unbounded.

**Corollary 2.1.2**

Any bounded sequence in $\mathbb{R}^n$ converges if and only if it has exactly one cluster point.

**Corollary 2.1.3**

A sequence $\{\mathbf{x}_k\}$ diverges if and only if at least one of the following conditions holds.
- $\{\mathbf{x}_k\}$ has two or more cluster points.
- $\{\mathbf{x}_k\}$ is unbounded.

## 2.2 Open and Closed Sets

**Definition 2.2.1: Interior/Boundary Point and Open/Closed Set**

Let $S$ be any subset of $\mathbb{R}^n$ and let $\mathbf{x}$ be any point in $\mathbb{R}^n$.

(i) $\mathbf{x}$ is an *interior point* of $S$ if $\exists r \in \mathbb{R}_+$, $N(\mathbf{x}; r) \subseteq S$.

(ii) If every point of $S$ is an interior point of $S$, then $S$ is said to be *open*.

(iii) We call $\mathbf{x}$ is a *boundary point* of $S$ if $\forall r \in \mathbb{R}_+$, $N(\mathbf{x}; r) \cap S \neq \varnothing \wedge N(\mathbf{x}; r) \setminus S \neq \varnothing$.

(iv) If $S$ continas all its boundary points, then $S$ is said to be *closed*.

**Theorem 2.2.1**

The union of any collection of open sets in $\mathbb{R}^n$ is open. The intersection of any finite collection of open sets in $\mathbb{R}^n$ is also open.

***Proof.*** To prove the first assertion, suppose that $\{U_\alpha \mid \alpha \in J\}$ is any collection of open sets in $\mathbb{R}^n$. Let $U \triangleq \bigcup_{\alpha \in J} U_\alpha$. Take any $\mathbf{x} \in U$. Then, there is some $\alpha_0 \in J$ such that $\mathbf{x} \in U_{\alpha_0}$. Since $U_{\alpha_0}$ is open, there is some neighborhood $N(\mathbf{x}; \varepsilon)$ such that $N(\mathbf{x}; \varepsilon) \subseteq U_{\alpha_0}$, which, in turn, $N(\mathbf{x}; \varepsilon) \subseteq U$. Therefore, $\mathbf{x}$ is an interior point of $U$; $U$ is open.

To prove the second assertion, let $U$ be the intersection of any finite collection $\{U_1, U_2, \cdots, U_k\}$ of open sets and take any $\mathbf{x} \in U$. For each $j \in [k]$, since $\mathbf{x} \in U_j$, there is some $r_j \in \mathbb{R}_+$ such that $N(\mathbf{x}; r_j) \subseteq U_j$. Then, take $r_0 \triangleq \min_{j \in [k]} r_j \in \mathbb{R}_+$. Since, for all $j \in [k]$, $N(\mathbf{x}; r_0) \subseteq U_j$, it is implied that $N(\mathbf{x}; r_0) \subseteq U$. Therefore, $\mathbf{x}$ is an interior point of $U$; $U$ is open. □

**Note:-**

Intersection of infinitely many open sets may fail to be open. For instance, consider

$$U_k \triangleq N(\mathbf{0}; 1/k),$$

for each $k \in \mathbb{N}$. Then, $\bigcap_{k\in\mathbb{N}} U_k = \{\mathbf{0}\}$, which is not open.

**Theorem 2.2.2**

A set $C \subseteq \mathbb{R}^n$ is closed if and only if $C^c$ is open.

***Proof.*** TBA □

**Theorem 2.2.3**

The intersection of any collection of closed sets in $\mathbb{R}^n$ is closed. The union of any finite collection of closed sets in $\mathbb{R}^n$ is also closed.

**Definition 2.2.2**

Let $S \subseteq \mathbb{R}^n$.

(i) The *interior* of $S$, denoted $\mathring{S}$, is the set of all interior points of $S$.

(ii) The *boundary* of $S$, denoted $\operatorname{bd} S$, is the set of all boundary points of $S$.

(iii) The *derived set* of $S$, denoted $S'$, is the set of all limit points of $S$.

(iv) The *closure* of $S$, denoted $\overline{S}$, is the union of $S$ and $S'$.

(v) The *complement* of $S$, denoted $S^c$, is the set $\mathbb{R}^n \setminus S$.

**Theorem 2.2.4**

Let $S \subseteq \mathbb{R}^n$. The interior of $S$ is the union of all open sets contained in $S$.

***Proof.*** □

**Corollary 2.2.1**

For any $S \subseteq R[n]$, the set $S^0$ is open.

**Theorem 2.2.5**

The closure of $S$ is the intersection of all closed sets that contain $S$.

**Corollary 2.2.2**

For any $S \subseteq \mathbb{R}^n$, the set $\overline{S}$ is closed.

**Theorem 2.2.6**

Let $S \subseteq \mathbb{R}^n$.

(i) $\mathring{\mathring{S}} = \mathring{S}$

(ii) $\overline{(\overline{S})} = \overline{S}$

(iii) $\mathring{S} \cap \operatorname{bd} S = \varnothing$

(iv) $\mathring{S} \cup \operatorname{bd} S = \overline{S}$

(v) $\overline{S} \cap \overline{(S^c)} = \operatorname{bd} S$

**Definition 2.2.3: Diamter**

Let $\varnothing \neq S \subseteq \mathbb{R}^n$ be a bounded set. The *diameter* of $S$ is defined to be

$$d(S) \triangleq \sup\{\, \|\mathbf{x}-\mathbf{y}\| \mid \mathbf{x},\mathbf{y} \in S \,\}.$$

**Definition 2.2.4: Distance**

Let $\varnothing \neq S \subseteq \mathbb{R}^n$ and $\mathbf{x} \in \mathbb{R}^n$. The distance from $\mathbf{x}$ to $S$ is defined to be

$$d(\mathbf{x},S) \triangleq \inf\{\, \|\mathbf{x}-\mathbf{y}\| \mid \mathbf{y} \in S \,\}.$$