Math 230A Notes

Fall, 2024

Contents

Chapter 1

Defining the Reals

Chapter 2

Basic Topology

2.1 Compactness

Definition 2.1.1. (Compact) Let (X, d) be a metric space and let $K \subseteq X$. K is said to be compact if every open cover of K has a finite subcover. That is, if $\{O_\alpha\}_{\alpha\in\Lambda}$ is any open cover of K, then

$$\exists \alpha_1, ..., \alpha_n \text{ such that } K \subseteq O_{\alpha_1} \cup ... \cup O_{\alpha_n}$$

Example 2.1.1. Let (X, d) be a metric space and let $E \subseteq X$.
If E is finite, then E is compact.

Proof. The reason is as follows:
Let $\{O_\alpha\}_{\alpha\in\Lambda}$ be any open cover of E. Our goal is to show that this open cover has a finite subcover.
If $E = \emptyset$, there is nothing to prove.
If $E \neq \emptyset$, denote the elements of E by $x_1, ...x_n$:

$$E = \{x_1, ..., x_n\}$$

. We have:

$$\begin{aligned}
x_1 \in E \subseteq \bigcup_{\alpha\in\Lambda} O_\alpha &\implies \exists \alpha_1 \in \Lambda \text{ such that } x_1 \in O_{\alpha_1} \\
x_2 \in E \subseteq \bigcup_{\alpha\in\Lambda} O_\alpha &\implies \exists \alpha_2 \in \Lambda \text{ such that } x_2 \in O_{\alpha_2} \\
&\vdots \\
x_n \in E \subseteq \bigcup_{\alpha\in\Lambda} O_\alpha &\implies \exists \alpha_n \in \Lambda \text{ such that } x_n \in O_{\alpha_n}
\end{aligned}$$

Hence,

$$E = x_1, ..., x_n \subseteq O_{\alpha_1} \cup ... \cup O_{\alpha_n}$$

So, $O_{\alpha_1}, ..., O_{\alpha_n}$ is a finite subcover of E. □

Example 2.1.2. Consider $(\mathbb{R}, ||)$ and let $E = \{\frac{1}{n} : n \in \mathbb{N}\} \cup \{0\}$.
Prove that E is compact. (In general, if $a_n \to a$ in $\mathbb{R}$ then $F = \{a_n : n \in \mathbb{N}\} \cup \{a\}$ is compact.)

Proof. Let $\{O_\alpha\}_{alpha\in\Lambda}$ be any open cover of E. Our goal is to show that this open cover has a finite subcover.

$$\left.\begin{array}{l} 0 \in E \\ E \subseteq \bigcup_{\alpha\in\Lambda} O_\alpha \end{array}\right\} \implies 0 \in \bigcup_{\alpha\in\Lambda} O_\alpha \implies \exists \alpha_0 \in \Lambda \text{ such that } 0 \in O_{\alpha_0} \qquad (I)$$

$$\left.\begin{array}{l} 0 \in O_{\alpha_0} \\ O_{\alpha_0} \text{ is open} \end{array}\right\} \implies \exists \epsilon > 0 \text{ such that } (-\epsilon, \epsilon) \subseteq O_{\alpha_0}$$

By the archimedean property of $\mathbb{R}$,

$$\exists m \in \mathbb{N} \text{ such that } \frac{1}{n} < \epsilon$$

so

$$\forall n \geq m \quad \frac{1}{n} < \epsilon.$$

Hence

$$\forall n \geq m \quad \frac{1}{n} \in (-\epsilon, \epsilon) \subseteq O_{\alpha_0} \tag{II}$$

Notice that $E = \{0, \frac{1}{1}, \frac{1}{2}, \frac{1}{3}, ..., \frac{1}{m-1}, \frac{1}{m}, \frac{1}{m+1}, \frac{1}{m+2}, ...\}$ for $m \in \mathbb{N}$. All that remains is to find a subcover for the elements $\frac{1}{1}, ..., \frac{1}{m-1}$:

$$\begin{aligned}
1 \in E &\implies \exists \alpha_1 \in \Lambda \text{ such that } 1 \in O_{\alpha_1} \\
\frac{1}{2} \in E &\implies \exists \alpha_2 \in \Lambda \text{ such that } \frac{1}{2} \in O_{\alpha_2} \\
&\vdots \\
\frac{1}{m-1} \in E &\implies \exists \alpha_{m-1} \in \Lambda \text{ such that } \frac{1}{m-1} \in O_{\alpha_{m-1}} \qquad (III)
\end{aligned}$$

By (I), (II), and (III), we have

$$E \subseteq O_{\alpha_0} \cup ... \cup O_{\alpha_{m-1}}$$

Thus, $\{O_\alpha\}_{\alpha \in \Lambda}$ has a finite subcover. Therefore E is compact. □

Remark. If X itself is compact, we say (X, d) is a compact metric space. If $\{O_\alpha\}_{\alpha \in \Lambda}$ is any collection of open sets such that $X = \bigcup_{\alpha \in \Lambda} O_\alpha$, then

$$\exists \alpha_1, ..., \alpha_n \in \Lambda \text{ such that } X = O_{\alpha_1} \cup ... \cup O_{\alpha_n}.$$

Theorem 2.1.1. Compact subsets of metric spaces are closed.

Proof. Let (X, d) be a metric space and let $K \subseteq X$ be compact. We want to show that K is closed. It is enough to show that K^c is open. To this end, we need to show that every point of K^c is an interior point. Let $a \in K^c$. Our goal is to show that

$$\exists \epsilon > 0 \text{ such that } N_\epsilon(a) \subseteq K^c.$$

That is, we want to show that

$$\exists \epsilon > 0 \text{ such that } N_\epsilon(a) \cap K = \emptyset.$$

We have

$$\begin{aligned}
a \in K^c &\implies a \notin K \\
&\implies \forall x \in K \quad d(x, a) > 0.
\end{aligned}$$

For all $x \in K$, let

$$\epsilon_x = \frac{1}{4} d(x, a).$$

Clearlly,

$$\forall x \in K \quad N_{\epsilon_x}(x) \cap N_{\epsilon_x}(a) = \emptyset.$$

Notice that

$$\{N_{\epsilon_x}(x)\}_{x \in K} \text{ is an open cover of } K.$$

Since K is compact, there is a finite subcover

$$\exists x_1, ..., x_n \in K \text{ such that } K \subseteq N_{\epsilon_{x_1}}(x_1) \cup ... \cup N_{\epsilon_{x_n}}(x_n)$$

and of course

$$\begin{cases}
N_{\epsilon_{x_1}}(x_1) \cap N_{\epsilon_{x_n}}(a) = \emptyset \\
\vdots \\
N_{\epsilon_{x_n}}(x_n) \cap N_{\epsilon_{x_n}}(a) = \emptyset
\end{cases}$$

Let $\epsilon = \min\{\epsilon_{x_1}, ..., \epsilon_{x_n}\}$. Clearly,

$$N_\epsilon(a) \subseteq N_{\epsilon_{x_i}}(a) \quad \forall 1 \leq i \leq n.$$

Hence

$$\begin{cases} N_{\epsilon_{x_1}}(x_1) \cap N_\epsilon(a) = \emptyset \\ \vdots \\ N_{\epsilon_{x_n}}(x_n) \cap N_\epsilon(a) = \emptyset \end{cases}$$

Therefore

$$N_\epsilon(a) \cap [N_{\epsilon_{x_1}}(x_1) \cup ... \cup N_{\epsilon_{x_n}}(x_n)] = \emptyset.$$

So,

$$N_\epsilon(a) \cap K = \emptyset.$$

□

Note. So, it has been shown that compact $\implies$ closed and bounded ✓. However, it is not necessarily the case that closed and bounded $\implies$ compact.

Theorem 2.1.2. Let (X, d) be a metric space and let $K \subseteq X$ be compact . Let $E \subseteq K$ be closed. Then E is compact.

Proof. Let $\{O_\alpha\}_{\alpha\in\Lambda}$ be an open cover of E. Our goal is to show that this cover has a finite subcover. Not that

$$E \text{ is closed} \implies E^c \text{ is open}.$$

We have

$$E \subseteq K \subseteq X = E \cup E^c \subseteq \left(\bigcup_{\alpha\in\Lambda} O_\alpha\right) \cup E^c$$

Therefore, E^c together with $\{O_\alpha\}_{\alpha\in\Lambda}$ is an open cover for the compact set K. Since K is compact, this open cover has a finite subcover:

$$\exists \alpha_1, ..., \alpha_n \in \Lambda \text{ such that } K \subseteq O_{\alpha_1} \cup ... \cup O_{\alpha_n} \cup E^c.$$

Considering $E \subseteq K$, we can write

$$E \subseteq O_{\alpha_1} \cup ... \cup O_{\alpha_n} \cup E^c.$$

However, $E \cap E^c = \emptyset$, so

$$E \subseteq O_{\alpha_1} \cup ... \cup O_{\alpha_n}.$$

So, $O_{\alpha_1}, ..., O_{\alpha_n}$ can be considered as the finite subcover that we were looking for. □

Corollary 2.1.1. If F is closed and K is compact, then $F \cap K$ is compact. ($F \cap K$ is a closed subset of the compact set K)

Consider $X = \mathbb{R}$ and $Y = [0, \infty)$ (Y is a subspace of X). Then

$$[0, \epsilon) \text{ is open in } Y \text{ because } [0, \epsilon) = (-\epsilon, \epsilon) \cap Y.$$

Theorem 2.1.3. Let (X, d) be a metric space and let $K \subseteq Y \subseteq X$ with $Y \neq \emptyset$. K is compact relative to X if and only if K is compact relative to Y.

Proof. ($\Leftarrow$) Suppose K is compact relative to Y. We want to show K is compact relative X. Let $\{O_\alpha\}_{\alpha\in\Lambda}$ be a collection of open sets in X that covers K. Our goal is to show that this cover has a finite subcover. Note that

$$K = K \cap Y \subseteq \left(\bigcup_{\alpha\in\Lambda} O_\alpha\right) \cap Y = \bigcup_{\alpha\in\Lambda} (O_\alpha \cap Y).$$

By Theorem 2.30, for each $\alpha \in \Lambda$, $O_\alpha \cap Y$ is an open set in the metric space (Y, d^Y). So, $\{O_\alpha \cap Y\}_{\alpha\in\Lambda}$ is a collection of open sets in (Y, d^Y) that covers K. Since K is compact relative to Y, there exists a finite subcover:

$$\begin{aligned}\exists \alpha_1, ..., \alpha_n \in \Lambda \text{ such that } K &\subseteq (O_{\alpha_1} \cap Y) \cup ... \cup (O_{\alpha_n} \cap Y)\\ &\subseteq (O_{\alpha_1} \cup ... \cup O_{\alpha_n}) \cap Y\\ &\subseteq O_{\alpha_1} \cup ... \cup O_{\alpha_n}\\ &\implies K \subseteq O_{\alpha_1} \cup ... \cup O_{\alpha_n} (\text{we have a finite subcover})\end{aligned}$$

($\Rightarrow$) Now suppose K is compact relative to X. We want to show K is compact relative to Y. Let $\{G_\alpha\}_{\alpha \in \Lambda}$ be a collection of open sets in (Y, d^Y) that covers K. Our goal is to show that this cover has a finite subcover. It follows from Theorem 2.30 that

$$\forall \alpha \in \Lambda \;\; \exists O_{\alpha_{\text{open}}} \subseteq X \text{ such that } G_\alpha = O_\alpha \cap Y.$$

We have

$$K \subseteq \bigcup_{\alpha \in \Lambda} G_\alpha = \bigcup_{\alpha \in \Lambda} (O_\alpha \cap Y) = \left(\bigcup_{\alpha \in \Lambda} O_\alpha\right) \cap Y \subseteq \bigcup_{\alpha \in \Lambda} O_\alpha.$$

So, $\{O_\alpha\}_{\alpha \in \Lambda}$ is an open cover for K in the metric space (X, d). Since K is compact,

$$\exists \alpha_1, ..., \alpha_n \in \Lambda \text{ such that } K \subseteq O_{\alpha_1} \cup ... \cup O_{\alpha_n}.$$

Therefore,

$$K = K \cap Y \subseteq (O_{\alpha_1} \cup ... \cup O_{\alpha_n}) \cap y = (O_{\alpha_1} \cap Y) \cup ... \cup (O_{\alpha_n} \cap Y) = G_{\alpha_1} \cup ... \cup G_{\alpha_n}.$$

(We have found the finite subcover we were looking for) □

Consider $X = \mathbb{R}$ and $Y = (0, \infty)$.
$(0, 2]$ is closed and bounded in Y, but it is not closed and bounded in $\mathbb{R}$.

$$(0, 2] = [-2, 2] \cap Y$$

Theorem 2.1.4. If E is an infinite subset of a compact set K, then E has a limit point in K. $E' \cap K \neq \emptyset$.

Proof. Assume foolishly that $E' \cap K = \emptyset$; for every point you select in K, that point will not be a limit point of E. That is,

$$\begin{cases}\forall a \in E & a \notin E'\\ \forall b \in K \backslash E & b \notin E'\end{cases}$$

Therefore,

$$\begin{cases}\forall a \in E \; \exists \epsilon_a > 0 \text{ such that } N_{\epsilon_a}(a) \cap (E \backslash \{a\}) = \emptyset\\ \forall b \in K \backslash E \; \exists \delta_b > 0 \text{ such that } N_{\delta_b}(b) \cap (E \backslash \{b\}) = \emptyset\end{cases}$$

Thus

$$\begin{cases}\forall a \in E \; \exists \epsilon_a > 0 \text{ such that } N_{\epsilon_a}(a) \cap E = \{a\}\\ \forall b \in K \backslash E \; \exists \delta_b > 0 \text{ such that } N_{\epsilon_b}(b) \cap E = \emptyset\end{cases}$$

Clearly, $K \subseteq \left(\bigcup_{a \in E} N_{\epsilon_a}(a)\right) \cup \left(\bigcup_{b \in K \backslash E} N_{\delta_b}(b)\right)$. Since K is compact,

$\exists a_1, ..., a_n \in E, b_1, ..., b_n \in K \backslash E$ such that $E \subseteq K \subseteq \big(N_{\epsilon_{a_1}}(a_1) \cup ... \cup N_{\epsilon_{a_n}}(a_n)\big) \cup \big(N_{\delta_{b_1}}(b_1) \cup ... \cup N_{\delta_{b_n}}(b_n)\big)$
Since for all $b \in K \backslash E$, $N_{\delta_b}(b) \cap E = \emptyset$, we can conclude that

$$E \subseteq \big(N_{\epsilon_{a_1}}(a_1) \cup ... \cup N_{\epsilon_{a_n}}(a_n)\big)$$

Hence,

$$\begin{aligned}E &= E \cap \big[N_{\epsilon_{a_1}} a_1 \cup ... \cup N_{\epsilon_{a_n}} a_n\big]\\ &= \big[E \cap N_{\epsilon_{a_1}}(a_1)\big] \cup ... \cup \big[E \cap N_{\epsilon_{a_n}}(a_n)\big]\\ &= \{a_1\} \cup ... \cup \{a_n\}\\ &= \{a_1, ..., a_n\}.\end{aligned}$$

This contradicts the assumption that E is infinite. □

Remark. 1. K is compact

2. Every infinite subset of K has a limit point in K

3. Every sequence in K has a subsequence that converges to a point in K

$\overset{A_1}{[1,\infty]}, \overset{A_2}{[2,\infty]}, \overset{A_3}{[3,\infty]}, \overset{A_4}{[4,\infty]}, ...$

$$A_2 \cap A_3 \cap A_4 = [4,\infty) = A_4$$
$$A_1 \cap A_3 \cap A_4 = A_4$$
$$\bigcap_{n=1}^{\infty} A_n = \emptyset$$

Theorem 2.1.5. Let (X, d) be a metric space , and let $\{K_\alpha\}_{\alpha\in\Lambda}$ be a collection of compact sets. Every finite intersection is nonempty.

Proof. Assume for contradiction that $\bigcap_{\alpha\in\Lambda} K_\alpha = \emptyset$. Let $\alpha_0 \in \Lambda$. We have

$$K_{\alpha_0} \cap \left(\bigcap_{\alpha\neq\alpha_0} K_alpha \right) = \emptyset$$

So,

$$k_{alpha_0} \subseteq \left(\bigcup_{\alpha\in\Lambda,\alpha\neq\alpha_0} K_\alpha \right)^c \implies K_{\alpha_0} \subseteq \bigcup_{a\alpha\in Lambda,\alpha\neq\alpha_0} K_\alpha^c$$

So, $\{K_\alpha^c\}_{\alpha\in\Lambda,\alpha\neq\alpha_0}$ is an open cover of K_{α_0}. Since K_{α_0} is compact,

$$\exists \alpha_1, ..., \alpha_n \text{ such that } K_{\alpha_0} \subseteq K_{\alpha_1}^c \cap ... \cap K_{\alpha_n}^c \subseteq \left(\bigcap_{i=1}^{n} K_{\alpha_i} \right)^c$$

So,

$$K_{\alpha_0} \cap \left(\bigcap_{i=1}^{n} K_{\alpha_i} \right) = \emptyset.$$

This contradicts the assumption that every finite intersection is nonempty. □

2.2 K-Cells

Last time, we talked about:

1. Compact $\implies$ closed and bounded.
2. Closed subsets of compact sets are compact.
3. If $\{K_\alpha\}_{\alpha \in \Lambda}$ is compact and every finite intersection is nonempty, then $\bigcap_{\alpha \in \Lambda} K_\alpha \neq \emptyset$

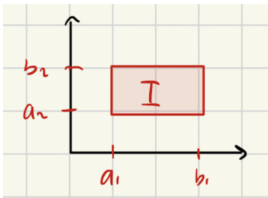
Corollary 2.2.1. If $K_1 \supseteq K_2 \supseteq K_3 \supseteq K_4 \supseteq ...$ is a sequence of nonempty compact sets, then $\bigcap_{i=1}^{\infty} K_n$ is nonempty.

Property 2.2.1. (Nested Interval Property) If $I_n = [a_n, b_n]$ is a sequence of closed intervals in $\mathbb{R}$ such that $I_1 \supseteq I_2 \supseteq I_3 \supseteq ...$, then $\bigcap_{n=1}^{\infty} I_n$ is nonempty.

In $\mathbb{R}^k$, closed and bounded implies compactness.

Definition 2.2.1. (K-Cell) The set $I = [a_1, b_1] \times ... \times [a_k, b_k]$ is called a k-cell in $\mathbb{R}^k$.

For example, $I = [a_1, b_1] \times [a_2, b_2]$ in $\mathbb{R}^2$



:

Theorem 2.2.1. (Nested Cell Property) If $I_1 \supseteq I_2 \supseteq I_3 \supseteq ...$ is a nested sequence of k-cells, then $\bigcap_{n=1}^{\infty} I_n \neq \emptyset$.

Proof. For each $n \in \mathbb{N}$, let

$$I_n = [a_1^{(1)}, b_1^{(1)}] \times ... \times [a_k^{(k)}, b_k^{(k)}].$$

Also, let

$$\forall n \in \mathbb{N} \;\; \forall 1 \leq i \leq k \;\; A_i^{(i)} = [a_i^{(n)}, b_i^{(n)}].$$

So,

$$\forall n \in \mathbb{N} \;\; I_n = A_1^{(n)} \times ... \times A_k^{(n)}.$$

Since for each $n \in \mathbb{N}$, $I_n \supseteq I_{n+1}$, we have

$$\forall 1 \leq i \leq k \;\; A_i^{(n)} \supseteq A_i^{(n+1)}$$

That is,

$$\begin{aligned} I_1 &= A_1^{(1)} \times ... \times A_k^{(1)} \\ I_2 &= A_2^{(2)} \times ... \times A_k^{(2)} \\ &\vdots \\ I_n &= A_n^{(1)} \times ... \times A_n^{(n)} \\ &\vdots \end{aligned}$$

Hence, it follows from the nested interval property that

$$\exists x_1 \in \bigcap_{n=1}^{\infty} A_1^{(n)}, \exists x_2 \in \bigcap_{n=1}^{\infty} A_2^{(n)}, ... \exists x_k \in \bigcap n = 1^{\infty} A_k^{(n)}$$

Thus,

$$\begin{aligned}(x_1, ..., x_n) &\in \left[\bigcap_{n=1}^{\infty} A_1^{(n)}\right] \times \left[\bigcap_{n=1}^{\infty} A_2^{(n)}\right] \times ... \times \left[\bigcap_{n=1}^{\infty} A_k^{(n)}\right] \\ &\subseteq \bigcap_{n=1}^{\infty} \left[A_1^{(1)} \times ... \times A_k^{(n)}\right] \\ &= \bigcap_{n=1}^{\infty} I_n\end{aligned}$$

So, $\bigcap\limits_{n=1}^{\infty} I_n \neq \emptyset$. □

Theorem 2.2.2. Every k-cell in $\mathbb{R}^k$ is compact.

Proof. Here we will prove the claim for 2-cells. The proof for a general k-cell is completely analogous. Let $I = [a_1, b_1] \times [a_2, b_2]$ be a 2-cell. Let $\overrightarrow{a} = (a_1, a_2)$ and $\overrightarrow{b} = (b_1, b_2)$. Let $\delta = d(\overrightarrow{a}, \overrightarrow{b}) = ||\overrightarrow{a} - \overrightarrow{b}||_2 = sqrt(a_1 - b_1)^2 + (a_2 - b_2)^2$. Noe that if $\overrightarrow{x} = (x_1, x_2)$ and $\overrightarrow{y} = (y_1, y_2)$ are any two points in I, then

$$\begin{cases} x_1, y_1 \in [a_1, b_1] & \implies |x_1 - y_1| \leq |b_1 - a_1| \\ x_2, y_2 \in [a_2, b_2] & \implies |x_2 - y_2| \leq |b_2 - a_2| \end{cases} \implies \sqrt{|x_1 - y_1|^2 + |x_2 - y_2|^2} \leq \sqrt{|a_1 - b_1|^2 + |a_2 - b_2|^2} = \delta$$

So,

$$d(\overrightarrow{x}, \overrightarrow{y}) \leq \delta.$$

Let's assume for contradiction that I is not compact. So, there exists an open cover $\{G_\alpha\}_{\alpha\in\Lambda}$ of I that does not have a finite subcover. For each $1 \leq i \leq 2$, divide $[a_i, b_i]$ into two subintervals of equal length:

$$c_i = \frac{a_i + b_i}{2}, \quad [a_i, b_i] = [a_i, c_i] \cup [c_i, b_i]$$

These subintervals determine four 2-cells. There is at least one of these four 2-cells that is not covered by any finite subcollection of $\{G_\alpha\}_{\alpha\in\Lambda}$. Let's call it I_1. Notice that

$$\forall \overrightarrow{x}, \overrightarrow{y} \in I_1 \quad ||\overrightarrow{x}, \overrightarrow{y}||_2 \leq \frac{\delta}{2}.$$

Now, subdivide I_1 into four 2-cells and continue this process. We will obtain a sequence of 2-cells

$$I_1, I_2, I_3, ...$$

such that

$$\begin{aligned}&(i) I \supseteq I_1 \supseteq I_2 \supseteq ... \\ &(ii) \forall \overrightarrow{x}, \overrightarrow{y} \in I_n \quad ||\overrightarrow{x} - \overrightarrow{y}|| \leq \frac{\delta}{2^n} \\ &(iii) \forall n \in \mathbb{N}, I_n \text{ cannot be covered by a finite subcollection of } \{G_\alpha\}_{\alpha\in\Lambda}.\end{aligned}$$

By the nested cell property,

$$\exists \overrightarrow{x}^* \in I \cap I_1 \cap I_2 \cap ...$$

In particular,

$$\overrightarrow{x}^* \in I \subseteq \{G_\alpha\}_{\alpha\in\Lambda} \implies \exists \alpha_0 \text{ such that } \overrightarrow{x}^* \in G_{\alpha_0}$$

We have

$$\left.\begin{matrix} \overrightarrow{x}^* \in G_{\alpha_0} \\ G_{\alpha_0} \text{ is open} \end{matrix}\right\} \implies \exists r > 0 \text{ such that } N_r(\overrightarrow{x}^*) \subseteq G_{\alpha_0}$$

Choose $n \in \mathbb{N}$ such that $\frac{\delta}{2^n} < r$. We claim that $I_n \in N_r(\overrightarrow{x}^*)$. Indeed, suppose $\overrightarrow{y} \in I_n$, we have

$$\begin{cases} \overrightarrow{y} \in I_n \\ \overrightarrow{x}^* \in I_n \end{cases}$$

so $||\overrightarrow{y} - \overrightarrow{x}|| \leq \frac{\delta}{2^n} < r$. Hence $\overrightarrow{y} \in N_r(\overrightarrow{x}^*)$. We have

$$\left.\begin{matrix} I_n \subseteq N_r(\overrightarrow{x}^*) \\ N_r(\overrightarrow{x}^*) \subseteq G_{\alpha_0} \end{matrix}\right\} \implies I_n \subseteq G_{\alpha_0}$$

This contradicts (iii). □

Theorem 2.2.3. (Heine-Borel Theorem) Let $E \subseteq \mathbb{R}^k$. The following statements are equivalent:

1. E is closed and bounded.
2. E is compact.
3. Every infinite subset of E has a limit point in E.

Proof. We will show 1. $\implies$ 2. $\implies$ 3. $\implies$ 1.
1. $\implies$ 2. : Suppose E is closed and bounded. We want to show that E is compact. Since E is bounded, there exists a k-cell, I, that containes E. We have

$$\left.\begin{aligned} &E \subseteq I \\ &I \text{ is compact} \\ &E \text{ is closed} \end{aligned}\right\} \implies E \text{ is compact.}$$

2. $\implies$ 3. : Supposed E is compact. We want to show E is limit point compact. This was proved last time, in Theorem 2.37.

3. $\implies$ 1. Suppose E is limit point compact. We want to show that E is closed and bounded. This will be done in HW 6. $\square$

Theorem 2.2.4. (Bolzano-Weierstrass Theorem) If $E \subseteq \mathbb{R}^k$, E is infinite, and E is bounded, then $E' \neq \emptyset$.

Proof. If E is bounded, then there exists a k-cell I such that $E \subseteq I$. By Theorem 2.40, I is compact. By Theorem 2.41, I is limit point compact. So every infinite set in I has a limit point in I. In particular, E has a limit point in I. So, $E' \neq \emptyset$. $\square$

2.3 Separated Sets, Disconnected Sets, and Connected Sets

Definition 2.3.1. (Separated, Disconnected, Connected) Let (X, d) be a metric space .

(i) Two sets $A, B \subseteq X$ are said to be disjoint if $A \cap B = \emptyset$.

(ii) Two sets $A, B \subseteq X$ are said to be separated if $\overline{A} \cap B = \emptyset = A \cap \overline{B}$.

(iii) A set $E \subseteq X$ is said to be disconnected if it can be written as a union of two nonempty separated sets A and B ($E = A \cup B$).

(iv) A set $E \subseteq X$ is said to be connected if it is not disconnected.

Example 2.3.1. Consider $\mathbb{R}$ with the standard metric.

$*)$ $A = (1, 2)$ and $B = (2, 5)$ are serparated.

$$\overline{A} \cap B = [1, 2] \cap (2, 5) = \emptyset$$
$$A \cap \overline{B} = (1, 2) \cap [2, 5] = \emptyset$$
$$\implies E = A \cup B \text{ is disconnected.}$$

$*)$ $C = (1, 2]$ and $D - (2, 5)$ are disjoint but not separated.

$$C \cap \overline{D} = (1, 2] \cap [2, 5] = \{2\}$$
$$C \cup D = (1, 5) \text{ is indeed connected.}$$

Theorem 2.3.1. The following are equivalent:

(i) A nonempty subset of $\mathbb{R}$ is connected $\iff$ it is a singleton or an interval.

(ii) Let $E \subseteq \mathbb{R}$. E is connected $\iff$ if $x, y \in E$ and $x < z < y$, then $z \in E$.

Proof. HW 6 □

So, in $\mathbb{R}$, connected $\iff$ interval $\iff$ path connected.

Definition 2.3.2. (Perfect Set) Let (X, d) be a metric space and let $E \subseteq X$..

(i) E is said to be perfect if $E' = E$.

(ii) E is said to be perfeect if $E' \subseteq E$ and $E \subseteq E'$.

(iii) E is said to be perfect if E is closed and every point of E is a limit point.

(iv) E is said to be perfect if E is closed and E does not have isolated points.

Example 2.3.2.

$*)$ $E = [0, 1] \implies E' = [0, 1]$, so $E = E' \implies E$ is perfect.

$*)$ $E = [0, 1] \cup \{2\} \implies 2$ is an isolated point of $E \implies E$ is not perfect.

$*)$ $E = \{\frac{1}{n} : n \in \mathbb{N}\} \implies E' = 0$ so $E \neq E'$, so E is not perfect. Is E' perfect?

$$E' = 0 \implies (E')' = \emptyset, \text{ so } E' \text{ is not perfect.}$$

Theorem 2.3.2. Let P be a nonempty perfect set in $\mathbb{R}^k$. Then P is uncountable. (An exmaple of an immediate consequence: $[0, 1]$ is uncountable)

Proof. In our proof, we will use the following Lemmas:

Lemma 2.3.1. Let (X,d) be a metric space and let $E \subseteq X$ be perfect. If V is any open set in X such that $V \cap E \neq \emptyset$, then $V \cap E$ is an infinite set.

Proof. Let $q \in V \cap E$. Then

$$\begin{cases} q \in V \implies \exists \delta > 0 \text{ such that } N_\delta(a) \subseteq V \\ q \in E \implies q \in E' \end{cases} \tag{1}$$

$$q \in E' \implies N_\delta(q) \cap E \text{ is an infinite set.} \tag{2}$$

$(1), (2) \implies V \cap E$ is infinite. □

Lemma 2.3.2. Let $q \in \mathbb{R}^k$. Let $r > 0$. Then

$$\overline{N_r(q)} = \overline{\{z \in \mathbb{R}^k : \|z - q\|_2 < r\}} = \{z \in \mathbb{R}^k : \|z - q\|_2 \leq r\} = C_r(q).$$

Proof. HW 6 □

Notice that

$$\left.\begin{matrix} P' = P \\ P \neq \emptyset \end{matrix}\right\} \implies P' \neq \emptyset \implies P \text{ is infinite.}$$

Assume for contradiction P is countable. Let's denote the distinct elements of P by $x_1, x_2, x_3, \ldots$:

$$P = \{x_1, x_2, x_3, \ldots\}$$

In what follows, we will construct a sequence of neighborhoods $V_1, V_2, V_3, \ldots$ such that

(i) $\forall n \in \mathbb{N}$ $\overline{V} \subseteq V_n$

(ii) $\forall n \in \mathbb{N}$ $x_n \notin \overline{V_{n+1}}$

(iii) $\forall n \in \mathbb{N}$ $V_n \cap P \notin \emptyset$

First, let's assume we have constructed these neighborhoods. Then for each $n \in \mathbb{N}$, let

$$K_n = \overline{V_n} \cap P \neq \emptyset$$

Note that

(I) $\overline{V_{n+1}} \subseteq V_n \subseteq \overline{V_n}$ so $\overline{V_{n+1}} \cap P \subseteq \overline{V_n} \cap P \implies K_{n+1} \subseteq K_n$ for each n.

(II) $$\left.\begin{matrix} \overline{V} \text{ is a closed and bounded set in } \mathbb{R}^k \implies \overline{V_n} \text{ is compact.} \\ P \text{ is perfect} \implies P \text{ is closed.} \end{matrix}\right\} \implies K_n = \overline{V_n} \cap P \text{ is compact.}$$

$$(I), (II) \overset{Thm2.36}{\implies} \bigcap_{n=1}^{\infty} K_n \neq \emptyset \tag{$*$}$$

Recall that $\forall n, K_n \subseteq P$, so

$$\bigcap_{n=1}^{\infty} K_n \subseteq P$$

However, if $b \in P$ then $b \notin \bigcap_{n=1}^{\infty} K_n$; indeed

$$b \in P \implies b = x_m \text{ for some } m \in \mathbb{N}$$

But $x_m \notin \overline{V_{m+1}}$ so $x_m \notin \overline{V_{m+1}} \cap P = K_{m+1}$. So $x_m \notin \bigcap_{n=1}^{\infty} K_n$. This tells us

$$\bigcap_{n=1}^{\infty} K_n = \emptyset \tag{$**$}$$

$$(*), (**) \implies \text{contradiction.}$$

It remains to show that there exists a seequence of neighborhoods $V_1, V_2, V_3, \ldots$ satisfying $(i), (ii), (iii)$. We construct these sequences inductively.

Step 1: Fix $r_1 > 0$. Let $V_1 = N_{r_1}(x_1)$. Clearly, $V_1 \cap P \neq \emptyset$.

Step 2: Our goal is to construct a neighborhood V_2 such that

(i) $\overline{V_2} \subseteq V_1$

(ii) $x_1 \notin V_2$

(iii) $V_2 \cap P \neq \emptyset$

We can do this just by using the fact that $V_1 \cap P \neq \emptyset$..

$$V_1 \cap P \neq \emptyset \overset{\text{lem2.3.1}}{\Longrightarrow} \exists y_1 \in V_1 \cap P \text{ such that } y_1 \neq x_1$$
$$y_1 \in V_1 \overset{V \text{ is open}}{\Longrightarrow} \exists \delta_1 > 0 \text{ such that } N_{\delta_1}(y_1) \subseteq V_1.$$

Let $r_2 = \frac{1}{2}\min\{d(x_1, y_1), \delta_1\}$. Let $V_2 = N_{r_2}(y_1)$. We claim V_2 has all the desired properties. Indeed,

(i) $\overline{V_2} = \overline{N_{r_2}(y_1)} = \{z \in \mathbb{R}^k : \|z - y_1\|_2 \leq r_2\}$
$\subseteq \{z \in \mathbb{R}^k : \|z - y_1\|_2 < \delta_1\} = N_{\delta_1}(y_1)$ since $r_2 < \delta_1$
$\subseteq V_1$

(ii) $d(x_1, y_1) > r_2 \implies x_1 \notin \overline{N_{r_2}(y_1)} = \{z \in \mathbb{R}^k : \|z - y_1\|_2 \leq r_2\}$

(iii) $y_1 \in V_2$ and $y_1 \in P \implies V_2 \cap P \neq \emptyset$

Step 3: Repeat the process to find V_3:

(i) $\overline{V_3} \subseteq V_2$

(ii) $x_2 \notin \overline{V_3}$

(iii) $V_3 \cap P \neq \emptyset$

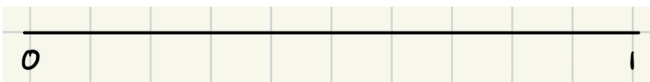
Similarly, for each $k \geq 3$, we can construct V_{k+1} using only the fact that $V_k \cap P \neq \emptyset$.

$\square$

Consider the following construction:

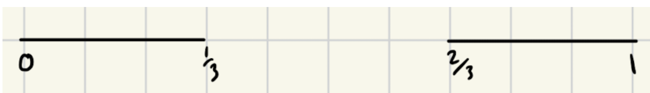
Stage 0:

Let $E_0 = [0, 1]$.



Stage 1:

Remove the segment $(\frac{1}{3}, \frac{2}{3})$. That is, remove the middle third of the interval, and define $E_1 = [0, \frac{1}{3}] \cup [\frac{2}{3}, 1]$.

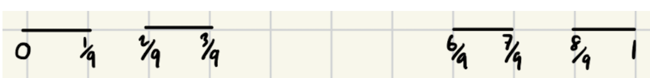


Stage 2:

Take each of the intervals $[0, \frac{1}{3}]$ and $[\frac{2}{3}, 1]$ and remove the middle third of each those, and define

$$E_2 = \left[0, \frac{1}{9}\right] \cup \left[\frac{2}{9}, \frac{3}{9}\right] \cup \left[\frac{6}{9}, \frac{7}{9}\right] \cup \left[\frac{8}{9}, 1\right]$$

.



Continuing this process, we will obtain a sequence of compact sets:

$$E_1, E_2, E_3, \ldots$$

such that

1. $E_1 \supseteq E_2 \supseteq E_3 \supseteq \ldots$
2. For each $n \in \mathbb{N}$, E_n is the union of 2^n intervals of length $\frac{1}{3^n}$.

Definition 2.3.3. (The Cantor Set) The Cantor set is the set

$$P = \bigcap_{n=1}^{\infty} E_n$$

where each E_n is defined from above.

Observation. Notice that in order to obtain E_n, we remove intervals of the form $(\frac{3k+1}{3^n}, \frac{3k+2}{3^n})$.

Theorem 2.3.3. (Properties of the Cantor set) Let P denote the Cantor set. Then

(*i*) P is compact

(*ii*) P is nonempty

(*iii*) P contains no segment

(*iv*) P is perfect (and so uncountable)

(*v*) P has measure zero

Proof. (*i*) P is an intersection of compact sets

(*ii*) By Theorem 2.1.5, the intersection of a sequence of nested, nonempty, compact sets is nonempty

(*iii*) Our goal is to show that P does not contain any set of the form (α, β) (where $0 \leq \alpha,\ \beta \leq 1$). Note that, by construction of P, the intervals of the form

$$I_{k,n} = (\frac{3k+1}{3^n}, \frac{3k+2}{3^n}) \quad n \in \mathbb{N},\ 0 \leq k \text{ such that } 3k+2 < 3^n$$

have no intersection with P. However, (α, β) contains at least one of $I_{k,n}$'s. Indeed,

$$\begin{aligned} &(\alpha, \beta) \text{ contains } (\frac{3k+1}{3^n}, \frac{3k+2}{3^n}) \\ \iff &\alpha < \frac{3k+1}{3^n} \text{ and } \frac{3k+2}{3^n} < \beta \\ \iff &\frac{3^n\alpha - 1}{3} < k < \frac{3^n\beta - 2}{3}. \end{aligned}$$

So, to ensure (α, β) contains aty least one of $I_{k,n}$, it is enough to choose $n \in \mathbb{N}$ such that

(1) $(\frac{3^n\beta-2}{3}) - (\frac{3^n\alpha-1}{3}) > 1$

(2) $\frac{3^n\beta-2}{3} > 1$

We have

(1) $\iff \frac{3^n(\beta-\alpha)-1}{3} > 4 \iff 3^n(\beta - \alpha) > 4 \iff 3^{-n} < \frac{\beta-\alpha}{4}$

(2) $\iff 3^n\beta - 2 > 3 \iff 3^n\beta > 5 \iff 3^{-n} < \frac{\beta}{5}$

So, if we choose $n \in \mathbb{N}$ such that $\frac{1}{3^n} < \min\{\frac{\beta-\alpha}{4}, \frac{\beta}{5}\}$, then we can be sure that (α, β) contains $I_{k,n}$ for some positive integer k.

(*iv*) P is perfect. We know that P is closed (because it's an intersection of closed sets). So, in order to prove that P is perfect, it is enough to show that every point of P is a limit point of P. Let $x \in P$. We want to show $x \in P'$. That is,

$$\forall \epsilon > 0 \quad N_\epsilon(x) \cap (P \backslash \{x\}) \neq \emptyset.$$

We have

$$x \in P = \bigcap_{n=1}^{\infty} E_n \implies \forall n \in \mathbb{N}\ x \in E_n \implies \forall n \in \mathbb{N}\ \ \exists I_n \subseteq E_n \text{ such that } x \in I_n.$$

Choose n large enough such that $|I_n| < \frac{\epsilon}{2}$. We have

$$x \in I_n \text{ and } |I_n| < \frac{\epsilon}{2} \implies I_n \subseteq (x-\epsilon, x+\epsilon).$$

At least one of these endpoints of I_n is not x, let's call it y. Then

$$y \in P,\ y \neq x,\ y \in I_n \subseteq (x-\epsilon, x+\epsilon).$$

So,

$$y \in (x-\epsilon, x+\epsilon) \cap (P \backslash \{x\}).$$

Therefore,

$$(x-\epsilon, x+\epsilon) \cap (P \backslash \{x\}) \neq \emptyset.$$

$\square$

Chapter 3

Numerical Sequences and Series

3.1 Sequences and Convergence

Definition 3.1.1. (Convergence of a Sequence) Let (X, d) be a metric space and let (x_n) be a sequence in X. (x_n) converges to a limit $x \in X$ if and only if for every $\epsilon > 0$, we can find $N \in \mathbb{N}$ such that if $n > N$, $d(x_n, x) < \epsilon$.

Notation .

1. $x_n \to x$ as $n \to \infty$
2. $x_n \to x$
3. $\lim_{x\to\infty} x_n = x$

Remark. (i) $x_n \to x \iff \forall \epsilon > 0 \;\; \exists N \in \mathbb{Z}$ such that $\forall n > N \;\; d(x_n, x) < \epsilon$.

(ii) If (x_n) does not converge, we say it diverges.

(iii) $x_n \to x \iff \forall \epsilon > 0 \;\; \exists N \in \mathbb{Z}$ such that $\forall n > N \;\; d(x_n, x) < \epsilon$
$x_n \to x \iff \forall \epsilon > 0 \;\; \exists N \in \mathbb{R}$ such that $\forall n > N \;\; d(x_n, x) < \epsilon$

Definition 3.1.2. (Bounded Sequence) Let (X, d) be a metric space and let (x_n) be a seqence in X. (x_n) is said to be bounded if the set $\{x_n : n \in \mathbb{N}\}$ is a bounded set in the metric space X.

$$\begin{aligned}(x_n) \text{ is bounded } &\iff \exists q \in X \; \exists r > 0 \text{ such that } \{x_n : n \in \mathbb{N}\} \subseteq N_r(q)\\ &\iff \exists q \in X \; \exists r > 0 \text{ such that } d(x, q) < r\end{aligned}$$

Example 3.1.1. Consider $\mathbb{R}$ equipped with the standard metric.

(i) $x_n = (-1)^n$: this sequence is bounded, has a finite range $\{-1, 1\}$, and diverges.

(ii) $x_n = \frac{1}{n}$: this sequence is bounded, has an infinite range, and converges to 0.

(iii) $x_n = 1$: this sequence is bounded, has a finite range, and converges to 1.

(iv) $x_n = n^2$: this sequence is undbounded, has an infinite range, and diverges.

Example 3.1.2. Consider $Y = (0, \infty)$ with the induced metric from $\mathbb{R}$. $x_n = \frac{1}{n}$: this sequence is bounded, has infinite range, and diverges.

Theorem 3.1.1. (An equivalent characterization of convergence) Let (X, d) be a metric space .

$$x_n \to x \iff \forall \epsilon > 0 \; N_\epsilon(x) \text{ contains } x_n \text{ for all but at most finitely many } n.$$

Proof.

$$\begin{aligned} x_n \to x &\iff \forall \epsilon > 0\ \exists N \in \mathbb{N} \text{ such that } \forall n > N\ d(x_n, x) < \epsilon \\ &\iff \forall \epsilon > 0\ \exists N \in \mathbb{N} \text{ such that } \forall n > N\ x_n \in N_\epsilon(x) \\ &\iff \forall \epsilon > 0\ \exists N \in \mathbb{N} \text{ such that } N_\epsilon(x) \text{ contains } x_n\ \forall n > N \\ &\iff \forall \epsilon > 0\ N_\epsilon(x) \text{ contains } x_n \text{ for all but at most finitely many } n. \end{aligned}$$

Theorem 3.1.2. (Uniqueness of a Limit) Let (X, d) be a metric space and let (x_n) be a sequence in X. If $x_n \to x$ in X and $x_n \to \bar{x}$ in X, then $x = \bar{x}$.

To prove this theorem, we make use of the following lemma:

Lemma 3.1.1. Suppose $a \geq 0$. If $a < \epsilon\ \forall \epsilon > 0$, then $a = 0$.

Proof. In order to prove that $x = \bar{x}$, it is enough to show that $d(x, \bar{x}) = 0$. To this end, according to Lemma 3.1.1, it is enough to show that

$$\forall \epsilon > 0\ d(x, \bar{x}) < epsilon.$$

Let $\epsilon > 0$ be given.

$$\begin{aligned} x_n \to x &\implies \exists N_1 \text{ such that } \forall n > N_1\ d(x_n, x) < \frac{\epsilon}{2} \\ x_n \to \bar{x} &\implies \exists N_2 \text{ such that } \forall n > N_2\ d(x_n, \bar{x}) < \frac{\epsilon}{2} \end{aligned}$$

Let $N = \max\{N_1, N_2\}$. Pick any $n > N$. We have

$$\begin{aligned} d(x, \bar{x}) &\leq d(x, x_n) + d(x_n, \bar{x}) \\ &< \frac{\epsilon}{2} + \frac{\epsilon}{2} \\ &= \epsilon. \end{aligned}$$

□

Theorem 3.1.3. (Convergent $\implies$ bounded) Let (X, d) be a metric space and let (x_n) be a sequence in X. If $x_n \to x$ in X, then (x_n) is bounded.

Proof. By definition of convergence with $\epsilon = 1$, we have

$$\exists N \in \mathbb{N} \text{ such that } \forall n > N\ x_n \in N_1(x).$$

Now, let $r = \max\{1, d(x_1, x), d(x_2, x), ..., d(x_n, x)\} + 1$. Then, clearly,

$$\forall n \in \mathbb{N}\ d(x_n, x) < r$$

Hence,

$$\forall n \in \mathbb{N}\ x_n \in N_r(x).$$

Therefore, (x_n) is bounded. □

Corollary 3.1.1. (contrapositive) If (x_n) is NOT bounded in X, then (x_n) diverges in X.

Theorem 3.1.4. (Limit Point is a Limit of a Sequence) Let (X, d) be a metric space and let $E \subseteq X$. Suppose $x \in E'$. Then there exists a sequence $x_1, x_2, ...$ of distinct points in $E \backslash \{x\}$ that converges to x.

Proof. Since $x \in E'$,

$$\forall \epsilon > 0\ N_\epsilon(x) \cap (E \backslash \{x\}) \text{ is infinite.}$$

In particular,

$$\begin{aligned}
&\text{for } \epsilon = 1 \ \exists x_1 \in E\backslash\{x\} \text{ such that } d(x_1, x) < 1 \\
&\text{for } \epsilon = \frac{1}{2} \ \exists x_2 \in E\backslash\{x\} \text{ such that } x_2 \neq x_1 \wedge d(x_2, x) < \frac{1}{2} \\
&\text{for } \epsilon = \frac{1}{3} \ \exists x_3 \in E\backslash\{x\} \text{ such that } x_3 \neq x_2 \wedge d(x_3, x) < \frac{1}{3} \\
&\vdots \\
&\text{for } \epsilon = \frac{1}{n} \ \exists x_n \in E\backslash\{x\} \text{ such that } x_n \neq x_1, x_2, x_3, \ldots \wedge d(x_n, x) < \frac{1}{n} \\
&\vdots
\end{aligned}$$

In this way we obtain a sequence $x_1, x_2, x_3, \ldots$ of distinct points in $E\backslash\{x\}$ that converges to x. Let $\epsilon > 0$ be given. We need to find N such that if $n > N$ then $d(x_n, x) < \epsilon$. Let N be such that $\frac{1}{N} < \epsilon$ (archimedean property). Then $\forall n > N$ $d(x_n, n) < \frac{1}{n} < \frac{1}{N} < \epsilon$ as desired. □

3.2 Subsequences

Definition 3.2.1. (Subsequences) Let (X,d) be a metric space and let (x_n) be a sequence in X. Let $n_1 < n_2 < n_3 < \ldots$ be a strictly increasing sequence of natural numbers. Then $(x_{n_1}, x_{n_2}, x_{n_3}, \ldots)$ is called a subsequence of $(x_1, x_2, x_3, \ldots)$, and is denoted by (x_{n_k}), where $k \in \mathbb{N}$ indexes the subsequence.

Example 3.2.1. Let $(x_n) = (1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \ldots)$.

(i) $(1, \frac{1}{3}, \frac{1}{5}, \frac{1}{7}, \ldots)$ is a subsequence.

(ii) $(\frac{1}{100}, \frac{1}{1000}, \frac{1}{10000}, \ldots)$ is a subsequence.

(iii) $(1, \frac{1}{5}, \frac{1}{3}, \frac{1}{7}, \frac{1}{2}, \ldots)$ is not a subsequence (we do not have $n_1 < n_2 < n_3 < \ldots$).

Remark. Suppose $(x_{n_1}, x_{n_2}, x_{n_3}, \ldots)$ is a subsequence of $(x_1, x_2, x_3, \ldots)$. Notice that $n_i \in \mathbb{N}$ and $n_1 < n_2 < n_3 < \ldots$ so

(i) $n_1 \geq 1$

(ii) For each $k \geq 2$, there are at least $k-1$ natural numbers, namely $n_1, \ldots, n_{k-1}$, strictly less than n_k, so $n_k \geq k$.

Theorem 3.2.1. Let (X,d) be a metric space and let (x_n) be a sequence in X. If $\lim\limits_{n\to\infty} x_n = x$, then every subsequence of (x_n) converges to x.

Proof. Let (x_{n_k}) be a subsequence of (x_n). Our goal is to show that $\lim\limits_{k\to\infty} x_{n_k} = x$. That is, we want to show

$$\forall \epsilon > 0\ \exists N \in \mathbb{N} \text{ such that } \forall k > N\ d(x_{n_k}, x) < \epsilon.$$

Let $\epsilon > 0$ be given. Our goal is to find N such that

$$\text{if } k > N, \text{ then } d(x_{n_k}, x) < \epsilon \tag{I}$$

Since $x_n \to x$, we have

$$\exists \hat{N} \text{ such that } \forall n > \hat{N}\ d(x_n, x) < \epsilon \tag{II}$$

We claim that this $\hat{N}$ can be used as the N we are looking for. Indeed, if we let $N = \hat{N}$, then if $k > N$ we can conclude that $n_k \geq k > N$ and so, by (II)

$$d(x_{n_k}, x) < \epsilon$$

□

Corollary 3.2.1. (contrapositive)

(i) If a subsequence of (x_n) does not converge to x, then (x_n) does not converge to x.

(ii) If (x_n) has a pair of subsequences converging to different limits, then (x_n) does not converge.

Example 3.2.2. Let $x_n = (-1)^n$ in $\mathbb{R}$.

1. The subsequence $(x_1, x_3, x_5, \ldots) = (-1, -1, -1, \ldots)$ converges to -1.
2. The subsequence$(x_2, x_4, x_6, \ldots) = (1, 1, 1, \ldots)$ converges to 1.

By (i) and (ii), (x_n) does not converge.

Theorem 3.2.2. Let (X,d) be a metric space and let (x_n) be a sequence in X. The subsequential limits of (x_n) form a closed set in X.

Proof. Let $E = \{b \in X : b \text{ is a limit of a subsequence of } x_n\}$. Our goal is to show that $E' \subseteq E$. To this end, we pick an arbitrary element $a \in E'$ and we will prove that $a \in E$. That is, we will show that there is a subsequence of (x_n) that converges to a. We may consider two cases:

Case 1: $\forall n \in \mathbb{N}\ x_n = a$**.** In this case, (x_n) and any subsequence of (x_n) converges to a. So $a \in E$.

Case 2: $\exists n_1 \in \mathbb{N}$ **such that** $x_{n_1} \neq a$. Let $\delta = d(a, x_{n_1}) > 0$. Since $a \in E'$, $N_{\frac{\delta}{2^2}}(a) \cap (E \backslash \{a\}) \neq \emptyset$. So,

$$\exists b \in E\backslash\{a\} \text{ such that } d(b,a) < \frac{\delta}{2^2}.$$

Since $b \in E$, b is a limit of a subsequence of (x_n), so

$$\exists n_2 > n_1 \text{ such that } d(x_{n_2}, b) < \frac{\delta}{2^2}.$$

Now note that

$$d(x_{n_2}, a) \leq d(x_{n_2}, b) + d(b,a) < \frac{\delta}{2^2} + \frac{\delta}{2^2} = \frac{\delta}{2}.$$

Since $a \in E'$, $N_{\frac{\delta}{2^3}}(a) \cap (E \backslash \{a\}) \neq \emptyset$. So,

$$\exists b \in E\backslash\{a\} \text{ such that } d(b,a) < \frac{\delta}{2^3}.$$

Since $b \in E$, b is a limit of a subsequence of (x_n), so

$$\exists n_3 > n_2 \text{ such that } \ d(x_{n_3}, b) < \frac{\delta}{2^3}.$$

Now note that

$$d(x_{n_3}, a) \leq d(x_{n_3}, b) + d(b,a) < \frac{\delta}{2^3} + \frac{\delta}{2^3} = \frac{\delta}{2^2}.$$

In this way, we obtain a subsequence $x_{n_1}, x_{n_2}, x_{n_3}, \dots$ of (x_n) such that

$$\forall k \geq 2 \ \ d(x_{n_k}, a) < \frac{\delta}{2^{k-1}}$$

so, clearly, $x_{n_k} \to a$. Hence, $a \in E$. □

Theorem 3.2.3. (Compactness $\Longrightarrow$ Sequential Compactness) Let (X, d) be a compact metric space. Then every sequence in X has a convergent subsequence.

Proof. Let (x_n) be a sequence in the compact metric space X. Let $E = \{x_1, x_2, \dots\}$. If E is infinite, then there exists $x \in X$ and $n_1 < n_2 < n_3 < \dots$ such that

$$x_{n_1} = x_{n_2} = x_{n_3} = \dots = x.$$

Clearly, the subsequence $(x_{n_1}, x_{n_2}, \dots)$ converges to x. If E is infinite, then since X is compact, by Theorem 2.37, E has a limit point $x \in X$. Since $x \in E'$,

$$\forall \epsilon > 0 \ N_\epsilon(x) \cap (E\backslash\{x\}) \text{ is infinite.}$$

In particular,

$$\begin{aligned}
&\text{for } \epsilon = 1,\ \exists n_1 \in \mathbb{N} \text{ such that } d(x_{n_1}, x) < 1 \\
&\text{for } \epsilon = 2,\ \exists n_2 \in \mathbb{N} \text{ such that } d(x_{n_2}, x) < \frac{1}{2} \\
&\text{for } \epsilon = 3,\ \exists n_3 \in \mathbb{N} \text{ such that } d(x_{n_3}, x) < \frac{1}{3} \\
&\vdots \\
&\text{for } \epsilon = m,\ \exists n_m \in \mathbb{N} \text{ such that } d(x_{n_m}, x) < \frac{1}{m} \\
&\vdots
\end{aligned}$$

In this way, we obtain a subsequence $x_{n_1}, x_{n_2}, x_{n_3}, \dots$ of (x_n) that converges to x. □

Corollary 3.2.2. (Bolzano-Weierstrass) Every bounded sequence in $\mathbb{R}^k$ has a convergent subsequence.

Proof. Let (x_n) be a bounded sequence in $\mathbb{R}^k$.

$$\implies \exists q \in \mathbb{R}^k \text{ and } r > 0 \text{ such that } \{x_1, x_2, x_3, ...\} \subseteq N_r(q).$$

Note that $N_r(q)$ is bounded and so $\overline{N_r(q)}$ is closed and bounded. So, $\overline{N_q(r)}$ is a compact subset of $\mathbb{R}^k$. So, $\overline{N_q(r)}$ is a compact metric space and (x_n) is a sequence in $\overline{N_q(r)}$. By Theorem 3.2.3, there exists a subsequence (x_{n_k}) of (x_n) that converges in the metric space $\overline{N_r(q)}$. Since the distance function in $\overline{N_r(q)}$ is the same as the distance function in $\mathbb{R}^k$, we can conclude that (x_{n_k}) converges in $\mathbb{R}^k$ as well. □

Recall:

$$x_n \to x \iff \forall \epsilon > 0 \; \exists N \text{ such that } \forall n > N \; d(x_n, x) < \epsilon.$$

This is useful *IF* we know that a sequence converges. How do we first determine that a sequence converges? Perhaps, given a sequence (x_n), we can determine convergence by comparing two consecutive terms:

$$\text{If } \forall \epsilon > 0 \; \exists N \text{ such that } d(x_{n+1}, x_n) < \epsilon, \text{ then the sequence converges.}$$

Unfortunately, this will not do. Consider $\mathbb{R} : x_n = \sqrt{n}$ diverges (it is unbounded) yet

$$x_{n+1} - x_n = \sqrt{n+1} - \sqrt{n} = \frac{n+1-n}{\sqrt{n+1}+\sqrt{n}} = \frac{1}{\sqrt{n+1}+\sqrt{n}} \to 0.$$

Cauchy proposed that instead of comparing the distance between two consecutive terms, we compare the distance between *any* two terms after a certain index:

$$\text{If } \forall \epsilon > 0 \; \exists N \text{ such that } \forall n, m > N \; d(x_m, d_n) < \epsilon, \text{ then the sequence converges.}$$

Definition 3.2.2. (Cauchy Sequence) Let (X, d) be a metric space A sequence (x_n) in X is said to be a Cauchy Sequence if

$$\forall \epsilon > 0 \; \exists N \text{ such that } \; \forall n, m > N \; d(x_m, x_n) < \epsilon.$$

Theorem 3.2.4. (Convergent $\implies$ Cauchy) Let (X, d) be a metric space and let (x_n) be a sequence in X. Then

$$(x_n) \text{ converges } \implies (x_n) \text{ is a Cauchy sequence}$$

Proof. Assume there exists $x \in X$ such that $x_n \to x$. Our goal is to show that

$$\forall \epsilon > 0 \; \exists N \text{ such that } \forall n, m > N \; d(x_n, x_m) < \epsilon \qquad (I)$$

Informal Discussion

We want to make $d(x_n, x_m)$ less than ϵ using the fact that $d(x_n, x)$ and $d(x_m, x)$ can be made as small as we like for large enough m and n. It would be great if we could bound $d(x_n, x_m)$ with a combination of $d(x_n, x)$ and $d(x_m, x)$. Note that

$$d(x_n, x_m) \leq d(x_n, x) + d(x, x_m)$$

so it is enough to make each piece on the RHS less than $\epsilon/2$

We have

$$x_n \to x \implies \exists \hat{N} \text{ such that } \forall n > \hat{N} \; d(x_n, x) < \epsilon/2.$$

We claim that this $\hat{N}$ can be used as the N that we were looking for. Indeed, if we let $N = \hat{N}$, (I) will hold because $\forall n, m > \hat{N}$,

$$\begin{aligned} d(x_m, x_n) &\leq d(x_m, x) + d(x, x_n) \\ &< \epsilon/2 + \epsilon/2 \\ &= \epsilon, \end{aligned}$$

as desired. □

Remark. The converse in general is not true. Eg, consider $\mathbb{Q}$ as a subspace of $\mathbb{R}$. In $\mathbb{Q}$, it is not true that every Cauchy sequence is convergent. For example, let (q_n) be a sequence in $\mathbb{Q}$ such that $q_n \to \sqrt{2}$.

$$\begin{aligned} q_n \to \sqrt{2} \text{ in } \mathbb{R} &\implies (q_n) \text{ is convergent in } \mathbb{R} \\ &\implies (q_n) \text{ is Cauchy in } \mathbb{R} \\ &\implies (q_n) \text{ is Cauchy in } \mathbb{Q} \end{aligned}$$

but (q_n) does not converge in Q.

It is desirable to define a metric space in which Cauchy sequences imply convergence.

Definition 3.2.3. (Complete Metric Space) A metric space in which every Cauchy sequence is convergent is called a complete metric space.

3.3 Diameter of a Set

Definition 3.3.1. (Diameter of a Set) Let (X, d) be a metric space and let E be a nonempty subset in X. The diameter of E, denoted by $diamE$, is defined as follows:

$$diamE = sup\{d(a, b) : a, b \in E\}$$

Remark. Note that if $\neq A \subseteq B \subseteq X$, then

$$\{d(a, b) : a, b \in A\} \subseteq \{d(a, b) : a, b \in B\}.$$

Hence,

$$sup\{d(a, b) : a, b \in A\} \subseteq sup\{d(a, b) : a, b \in B\}$$

. That is,

$$diamA \leq diamB.$$

Observation. Let (x_n) be a sequence in X. $\forall n \in \mathbb{N}$ let $E_n = \{x_{n+1}, x_{n+2}, ...\}$. Then

$$(x_n) \text{ is Cauchy } \iff \lim_{n\to\infty} diamE_n = 0.$$

Proof. Note that

$$\begin{aligned} E_1 &= \{x_2, x_3, x_4, ...\} \\ E_2 &= \{x_3, x_4, x_5, ...\} \\ E_3 &= \{x_4, x_5, x_6, ...\} \\ &\vdots \end{aligned}$$

Clearly, $E_1 \supseteq E_2 \supseteq E_3 \supseteq ...$, so

$$diamE_1 \supseteq diamE_2 \supseteq diamE_3 \supseteq ...$$

$(\implies)$ Supposed (x_n) is Cauchy. Our goal is to show that

$$\forall \epsilon > 0 \ \exists N \text{ such that } \forall n > N \ |diamE_n - 0| < \epsilon.$$

Let $\epsilon > 0$ be given. Our goal is to find a number N such that if $n > N$, then $diamE_n < \epsilon$ $(*)$. For the given $\epsilon > 0$, since (x_n) is Cauchy, there exists $\hat{N}$ such that

$$\forall n, m > \hat{N} \ d(x_n, x_m) < \epsilon/2.$$

We claim that this $\hat{N}$ can be used as the N that we were looking for. Indeed, if we let $N = \hat{N}$, then $(*)$ will hold becuase:

$$E_{\hat{N}} = \{x_{\hat{N}+1}, x_{\hat{N}+2}, x_{\hat{N}+3}\}$$

so $\forall a, b \in E_{\hat{N}}$ $d(a, b) < \epsilon/2$. Then

$$diamE_{\hat{N}} = sup\{d(a, b) : a, b \in E_{\hat{N}}\} \leq \epsilon/2 < \epsilon$$

so if $n > \hat{N}$, then

$$diamE_n \leq diamE_{\hat{N}} < \epsilon$$

as desired.
$(\impliedby)$ Suppose $\lim_{n\to\infty} diamE_n = 0$. Our goal is to show that

$$\forall \epsilon > 0 \ \exists N \text{ such that } \forall n, m > N \ d(x_m, x_n) < \epsilon.$$

Let $\epsilon > 0$ be given. Our goal is to find a number N such that

$$\text{if } n, m > N, \text{ then } d(x_n, x_m) < \epsilon. \tag{$*$}$$

Since $\lim_{n\to\infty} diamE_N = 0$, for this ϵ, there exists $\hat{N}$ such that

$$\forall n > \hat{N} \ diamE_n < \epsilon$$

We claim that $N = \hat{N} + 1$ can be used as the N that we were looking for. Indeed, if we let $N = \hat{N} + 1$, then $(*)$ will hold:

$$\text{if } n, m > \hat{N} + 1, \text{ then } x_n, x_m \in E_{\hat{N}+1}$$

and so

$$d(x_m, x_n) \le diamE_{\hat{N}+1} < \epsilon$$

□

Theorem 3.3.1. (diam$\overline{E}$ = diam E) Let (X, d) be a metric space and let $\emptyset \neq E \subseteq X$. Then

$$\text{diam}\overline{E} = \text{diam } E$$

Proof. Note that since $E \subseteq \overline{E}$, we have diam$E$ $\le$diam$\overline{E}$. In what follows, we will prove that diam$\overline{E}$ $\le$diam$E$ by showing that

$$\forall \epsilon > 0 \text{ diam}\overline{E} \le \text{diam}E + \epsilon.$$

Let $\epsilon > 0$ be given. Our goal is to show that

$$\sup\{d(a, b) : a, b \in \overline{E}\} \le \text{diam}E + \epsilon.$$

To this end, it is enough to show that diam$E + \epsilon$ is an upper bound for $\{d(a, b) : a, b \in \overline{E}\}$. Suppose $a, b \in \overline{E}$. We have

$$a \in \overline{E} \implies N_{\epsilon/2}(a) \cap E \neq \emptyset \implies \exists x \in E \text{ such that } d(x, a) < \frac{\epsilon}{2}$$
$$b \in \overline{E} \implies N_{\epsilon/2}(b) \cap E \neq \emptyset \implies \exists y \in E \text{ such that } d(y, b) < \frac{\epsilon}{2}.$$

Therefore,

$$\begin{aligned} d(a, b) &\le d(a, x) + d(x, y) + d(y, b) \\ &< \frac{\epsilon}{2} + d(x, y) + \frac{\epsilon}{2} \\ &\le \frac{\epsilon}{2} + \text{diam}E + \frac{\epsilon}{2} \\ &= \epsilon + \text{diam}E \end{aligned}$$

□

Theorem 3.3.2. Let (X, d) be a metric space and let $K_1 \supseteq K_2 \supseteq K_3 \supseteq ...$ be a nested sequence of nonempty compact sets.

Proof. Let $K = \bigcap_{n=1}^{\infty} K_n$. By Theorem 2.36, we know that $K \neq \emptyset$. In order to show that K has only one element, we suppose $a, b \in K$ and we will prove $a = b$. In order to show $a = b$, we will prove $d(a, b) = 0$ and to this end show

$$\forall \epsilon > 0 \ d(a, b) < \epsilon.$$

Let $\epsilon > 0$ be given. Since $\lim_{n\to\infty}$ diam$K_n = 0$, there exists N such that

$$\forall n > N \text{ diam}K_n < \epsilon.$$

In particular, diam$K_{N+1} < \epsilon$. Now we have

$$\left.\begin{aligned} a \in \bigcap_{n=1}^{\infty} K_n &\implies a \in K_{N+1} \\ b \in \bigcap_{n=1}^{\infty} K_n &\implies b \in K_{N+1} \end{aligned}\right\} \implies d(a, b) \le \text{diam}K_{N+1} < \epsilon$$

□

Theorem 3.3.3. (Compact Space $\implies$ Complete Space) Any compact metric space is complete.

Proof. Let (X, d) be a compact metric space. Let (x_n) be a Cauchy sequence in X. Our goal is to show that (x_n) converges in X. For each $n \in \mathbb{N}$, let $E_n = \{x_{n+1}, x_{n+2}, x_{n+3}, ...\}$. We know that

(1) $E_1 \supseteq E_2 \supseteq E_3 \supseteq ...$

(2) (x_n) is Cauchy $\implies \lim_{n\to\infty} \mathrm{diam} E_n = 0$

It follows from (1) that

$$\overline{E_1} \supseteq \overline{E_2} \supseteq \overline{E_3} \supseteq ... \tag{I}$$

Since closed subsets of a compact space are compact, (I) is a nested sequence of nonempty compact sets. Since $\mathrm{diam} E_n = \mathrm{diam}\overline{E_n}$, it follows from (2) that $\lim_{n\to\infty}\mathrm{diam}\overline{E_n} = 0$. Hence, by Theorem 3.3.2, $\bigcap_{n=1}^{\infty} \overline{E_n}$ has exactly one point. Let's call this point "a":

$$\bigcap_{n=1}^{\infty} \overline{E_n} = \{a\}$$

In what follows, we will prove that $\lim_{n\to\infty} x_n = a$. To this end, it's enough to show that

$$\forall \epsilon > 0 \ \exists N \text{ such that } \forall n > N \ d(a_n, a) < \epsilon.$$

Let $\epsilon > 0$ be given. Our goal is to find N such that

$$\text{if } n > N, \text{ then } d(x_n, a) < \epsilon \tag{$*$}$$

Since $\lim_{n\to\infty}\mathrm{diam}\overline{E} = 0$, for this given ϵ there exists $\hat{N}$ such that

$$\forall n > \hat{N} \ \mathrm{diam}\overline{E_n} < \epsilon.$$

We claim that $\hat{N} + 1$ can be used as the N that we are looking for. Indeed, if we let $N = \hat{N} + 1$, then $(*)$ holds:

$$\text{If } n > \hat{N} + 1, \text{ then } \left.\begin{array}{l} x_n \in E_{\hat{N}+1} \implies x_n \in \overline{E_{\hat{N}+1}} \\ a \in \bigcap_{n=1}^{\infty} \overline{E_n}, \text{ so } a \in \overline{E_{\hat{N}+1}} \end{array}\right\} \implies d(x_n, a) \le \mathrm{diam}\overline{E_{\hat{N}+1}} < \epsilon$$

$\square$

Theorem 3.3.4. ($\mathbb{R}^k$ is Complete) $\mathbb{R}^k$ is a complete metric space.

Proof. Let (x_n) be a Cauchy sequence in $\mathbb{R}^k$.

$$\begin{aligned} &\overset{\text{HW 7}}{\implies} (x_n) \text{ is bounded} \\ &\implies \exists p \in \mathbb{R}^k, \ \epsilon > 0 \text{ such that } \forall n \in \mathbb{N} \ x_n \in N_\epsilon(p). \end{aligned}$$

Note that $\overline{N_\epsilon(p)}$ is closed and bounded in $\mathbb{R}^k$, so it's compact.

$$\left.\begin{array}{l} \overline{N_\epsilon(p)} \text{ is a compact metric space} \\ (x_n) \text{ is Cauchy in } \overline{N_\epsilon(p)} \end{array}\right\} \implies (x_n) \text{ converges to a point } x \in \overline{N_\epsilon(p)}.$$

Since the distance function in $\overline{N_\epsilon(p)}$ is exactly the same as the distance function in $\mathbb{R}^k$, we can conclude that $x_n \to x$ in $\mathbb{R}^k$. $\square$

3.4 Divergence of a Sequence

Theorem 3.4.1. (Algebraic Limit Theorem) Suppose (a_n) and (b_n) are sequences of real numbers, and $\lim_{n\to\infty} a_n = a$ and $\lim_{n\to\infty} b_n = b$. Then

(i) $\lim_{n\to\infty}(a_n + b_n) = a + b$

(ii) $\lim_{n\to\infty}(ca_n) = ca$

(iii) $\lim_{n\to\infty}(a_n b_n) = ab$

(iv) $\lim_{n\to\infty} \frac{a_n}{b_n} = \frac{a}{b}$, provided $b \neq 0$

So far, we have studied limits of sequences that were convergent. We now discuss what it means to not converge.

Definition 3.4.1. (Divergence of a Limit) Consider $\mathbb{R}$ with its standard metric. Let (x_n) be a sequence of real numbers. If (x_n) does not converge, we say (x_n) diverges.
Divergence appears in three forms:

(i) (x_n) becomes arbitrarily large as $n \to \infty$. More precisely,

$$\forall M > 0\ \exists N \in \mathbb{N} \text{ such that } \forall n > N\ x_n > M$$

In this case, we say (x_n) diverges to ∞.

Notation . $x_n \to \infty$ or $\lim_{x\to\infty} x_n = \infty$.

(ii) -x_n becomes arbitrarily large as $n \to \infty$. More precisely,

$$\forall M > 0\ \exists N \in \mathbb{N} \text{ such that } \forall n > N\ \ -x_n > M.$$

In this case, we say (x_n) diverges to -∞.

Notation . $x_n \to -\infty$ or $\lim_{n\to\infty} x_n = -\infty$.

(iii) (x_n) is not convergent and does not diverge to $\pm\infty$.

Example 3.4.1. The following are examples of the different types of divergence in $\mathbb{R}$:

(i) $x_n = n^2,\ x_n \to \infty$

(ii) $x_n = -n,\ x_n \to \infty$

(iii) $(x_n) = ((-1)^n) = (-1, 1, -1, 1, ...)$

Definition 3.4.2. (Increasing, Decreasing, Monotone) Consider $\mathbb{R}$ with the standard metric.

(i) (a_n) is said to be increasing if and only if for all $n,\ a_n \leq a_{n+1}$

(ii) (a_n) is said to be decreasing if and only if for all $n,\ a_n \geq a_{n+1}$

(iii) (a_n) is said to be monotone if and only if it is incresing or decreasing, or both

(iv) (a_n) is said to be strictly increasing if and only if for all $n,\ a_n < a_{n+1}$

(v) (a_n) is said to be strictly decreasing if and only if for all $n,\ a_n > a_{n+1}$

Theorem 3.4.2. (Monotone Convergence Theorem) Consider $\mathbb{R}$ with its standard metric.

(i) If (a_n) is increasing and bounded, then (a_n) converges to $\sup\{a_n : n \in \mathbb{N}\}$

(ii) If (a_n) is decreasing and bounded, then (a_n) converges to $\inf\{a_n : n \in \mathbb{N}\}$

(iii) If (a_n) is increasing and unbounded, then $(a_n) \to \infty$

(iv) If (a_n) is decreasing and unbounded, then $(a_n) \to -\infty$

Proof. Here, we will prove item (i). Suppose (a_n) is increasing and bounded. We want to show $a_n \to S$ where $S = \sup\{a_1, a_2, a_3, ...\}$. First, note that since $\{a_1, a_2, a_3, ...\}$ is a bounded set, $\sup\{a_1, a_2, a_3, ...\} = S$ exists and is a real number. Our goal is to prove that

$$\forall \epsilon > 0\ \exists N \in \mathbb{N} \text{ such that } \forall n > N\ |a_n - S| < \epsilon.$$

Let $\epsilon > 0$ be given. We want to find N such that

$$\text{if } n > N, \text{ then } S - \epsilon < a_n < S + \epsilon$$

$$\begin{aligned} S = \sup\{a_1, a_2, a_3, ...\} &\implies S - \epsilon \text{ is not an upper bound of } \{a_n : n \in \mathbb{N}\} \\ &\implies \exists a_i \in \{a_n : n \in \mathbb{N}\} \text{ such that } a_i > S - \epsilon \\ &\implies \exists \hat{N} \in \mathbb{N} \text{ such that } a_{\hat{N}} > S - \epsilon \end{aligned}$$

Let $N = \hat{N}$, then

(1) If $n > \hat{N}$, then $a_n \geq a_N > S - \epsilon$ since (a_n) is increasing.

(2) If $n > \hat{N}$, then $a_n \leq S < S + \epsilon$ since (a_n) is bounded.

(1),(2) $\implies$ if $n > N$, then $S - \epsilon < a_n < S + \epsilon$ as desired. □

Example 3.4.2. Define the sequence (a_n) recursively by $a_1 = 1$ and

$$a_{n+1} = \frac{1}{2}a_n + 1.$$

(i) Show that $a_n \leq 2$ for every n.

(ii) Show that (a_n) is an increasing sequence.

(iii) Explain why (i) and (ii) prove that (a_n) converges.

(iv) Prove $(a_n) \to 2$.

Proof. (i) We proceed by induction.

Base Case: Clearly, $a_1 = 1 \leq 2$.

Inductive Step: Suppose $a_k \leq 2$ for some $k \in \mathbb{N}$. Then

$$\begin{aligned} a_{k+1} &= \frac{1}{2}a_k + 1 \\ &\leq \frac{1}{2}(2) + 1 \\ &= 2. \end{aligned}$$

By mathematical induction, $a_n \leq 2$ for every $n \in \mathbb{N}$.

(ii) We proceed by induction.

Base Case: $a_1 = 1$ and $a_2 = \frac{1}{2}(1) + 1 = \frac{3}{2} \implies a_1 \leq a_2$.

Inductive Step: Suppose $a_k \leq a_{k+1}$ for some $k \in \mathbb{N}$. Then

$$\begin{aligned} a_{k+2} &= \frac{1}{2}(a_{k+1}) + 1 \\ &\geq \frac{1}{2}a_k + 1 \\ &= a_{k+1}. \end{aligned}$$

By mathematical induction, $a_n \leq a_n + 1\ \forall n \geq 1$.

(iii) By the Monotone Convergence Theorem (MCT), $(i), (ii) \implies (a_n)$ converges.

(*iv*) Let $A = \lim_{n\to\infty} a_n$. We have

$$\begin{aligned} A &= \lim_{n\to\infty} a_{n+1} \\ &= \lim_{n\to\infty} [\frac{1}{2}a_n + 1] \\ &= \frac{1}{2}(\lim_{n\to\infty} a_n) + 1 \\ &= \frac{1}{2}(A) + 1 \\ &\implies A = 2. \end{aligned}$$

Therefore, $a_n \to 2$. $\square$

3.5 The Extended Real Numbers

Definition 3.5.1. (The Extended Real Numbers) The set of extended real numbers, denoted by $\overline{\mathbb{R}}$, consists of all real numbers and two symbols, $-\infty, +\infty$:

$$\overline{\mathbb{R}} = \mathbb{R} \cup \{-\infty, \infty\}$$

$*$) $\overline{\mathbb{R}}$ is equpped with an order. We preserve the original order in $\mathbb{R}$ and we define

$$\forall x \in \mathbb{R} \ -\infty < x < \infty$$

$*$) $\overline{\mathbb{R}}$ is not a field, but it is customary to make the following conventions:

$$\begin{array}{lrl}
\forall x \in \mathbb{R} \text{ with } x > 0: & x \cdot (+\infty) = +\infty & x \cdot (-\infty) = -\infty \\
\forall x \in \mathbb{R} \text{ with } x < 0: & x \cdot (+\infty) = -\infty & x \cdot (-\infty) = +\infty \\
\forall x \in \mathbb{R} & x + \infty = +\infty & \\
\forall x \in \mathbb{R} & x - \infty = -\infty & \\
 & +\infty + \infty = +\infty & \\
 & -\infty - \infty = -\infty & \\
\forall x \in \mathbb{R} & \dfrac{x}{+\infty} = \dfrac{x}{-\infty} = 0 &
\end{array}$$

Please note that we did not define the following:

$$-\infty + \infty, +\infty - \infty, \frac{\infty}{\infty}, \frac{-\infty}{-\infty}, ..., 0 \cdot \infty, \infty \cdot 0, 0 \cdot -\infty, -\infty \cdot 0$$

$*$) If $A \subset \overline{\mathbb{R}}$,

$$\begin{aligned}
\sup A &= \text{least upper bound} \\
\inf A &= \text{greatest lower bound}
\end{aligned}$$

$*$) $\sup A = +\infty \iff$ either $+\infty \in A$ or $A \subseteq \mathbb{R} \cup \{-\infty\}$ and A is not bounded above in $\mathbb{R} \cup \{-\infty\}$

$*$) $\inf A = -\infty \iff$ either $-\infty \in A$ or $A \subseteq \mathbb{R} \cup \{+\infty\}$ and A is not bounded below in $\mathbb{R} \cup \{+\infty\}$

$*$) $\sup \emptyset = -\infty$, $\inf \emptyset = +\infty$

Remark. Let (a_n) be a sequence in $\overline{\mathbb{R}}$. Let $a \in \mathbb{R}$.

(i) $\lim_{n\to\infty} a_n = a \iff \forall \epsilon > 0\ \exists N \in \mathbb{N}$ such that $\forall n > N\ |a_n - a| < \epsilon$

(ii) $\lim_{n\to\infty} a_n = +\infty \iff \forall M > 0\ \exists N \in \mathbb{N}$ such that $\forall n > N\ a_n > M$

(iii) $\lim_{n\to\infty} a_n = -\infty \iff \forall M > 0\ \exists N \in \mathbb{N}$ such that $\forall n > N\ -a_n > M$

Limits in $\overline{\mathbb{R}}$ have theorems that are analogous to the limit theorems in $\mathbb{R}$.

Theorem 3.5.1. (Algebraic Limit Theorem in $\overline{\mathbb{R}}$) Suppose $a_n \to a$ in $\overline{\mathbb{R}}$ and $b_n \to b$ in $\overline{\mathbb{R}}$. Then

(i) If $c \in \mathbb{R}$, then $ca_n \to ca$

(ii) $a_n + b_n \to a + b$, provided $\infty - \infty$ does not appear

(iii) $a_n b_n \to ab$, provided $(\pm\infty) \cdot 0$ or $0 \cdot (\pm\infty)$ does not appear

(iv) If $a = \pm\infty$, then $\frac{1}{a_n} \to 0$

(v) If $a_n \to 0$ and $a_n > 0$ (or $a_n < 0$), then $\frac{1}{a_n} \to \infty$ (or $\frac{1}{a_n} \to -\infty$)

Theorem 3.5.2. (Order Limit Theorem in $\overline{\mathbb{R}}$) Suppose $a_n \to a$ in $\overline{\mathbb{R}}$ and $b_n \to b$ in $\overline{\mathbb{R}}$. Then

(i) If $a_n \leq b_n$, then $a \leq b$

(ii) If $a_n \leq e_n$ and $a_n \to \infty$, then $e_n \to \infty$.

(iii) If $e_n \leq a_n$ and $a_n \to -\infty$, then $e_n \to -\infty$

Theorem 3.5.3. (Monotone Convergence Theorem in $\overline{\mathbb{R}}$) Let (a_n) be a sequence in $\overline{\mathbb{R}}$.

(i) If (a_n) is increasing, then $a_n \to \sup\{a_n : n \in \mathbb{N}\}$

(ii) If (a_n) is decreasing, then $a_n \to \inf\{a_n : n \in \mathbb{N}\}$

Remark. $\overline{\mathbb{R}}$ can be equipped with the following metric:

$$f(x) = \begin{cases} -\frac{\pi}{2} & x = -\infty \\ \arctan x & -\infty < x < \infty \\ \frac{\pi}{2} & x = +\infty \end{cases}$$

Define $\overline{d}(x, y) = |f(x) - f(y)|\ \forall x, y \in \overline{\mathbb{R}}$.

1) The closure of $\mathbb{R}$ in $(\overline{\mathbb{R}}, \overline{d})$ is $\overline{\mathbb{R}}$.

2) If (a_n) is a sequence in $\mathbb{R}$, then $a_n \to a \in \overline{\mathbb{R}} \iff (a_n)$ converges to a in the metric space $(\overline{\mathbb{R}}, \overline{d})$.

3) The closure of $\overline{\mathbb{R}}$ in the metric space $(\overline{\mathbb{R}}, \overline{d})$ is $\overline{\mathbb{R}}$.

4) Every set in $(\overline{\mathbb{R}}, \overline{d})$ is bounded:

$$\forall x, y \in \overline{\mathbb{R}}\ \overline{d}(x, y) \leq \pi.$$

Definition 3.5.2. (Characterization of lim sup and lim inf 1) Let (x_n) be a sequence of real numbers. Let

$$S = \{x \in \overline{\mathbb{R}} : \exists (x_{n_k}) \text{ of } (x_n) \text{ such that } x_{n_k} \to x\}$$

We define

$$\limsup x_n = \sup S$$
$$\liminf x_n = \inf S$$

Definition 3.5.3. (Characterization of lim sup and lim inf 2) Let (x_n) be a sequence of real numbers. For each $n \in \mathbb{N}$, let $F_n = \{x_k : k \geq n\}$. Clearly,

$$F_1 \supseteq F_2 \supseteq F_3 \supseteq \ldots$$

So,

$$\sup F_1 \geq \sup F_2 \geq \sup F_3 \geq \ldots$$

and

$$\inf F_1 \leq \inf F_2 \leq \inf F_3 \leq \ldots$$

By the MCT (in $\overline{\mathbb{R}}$), we know that $\lim_{n\to\infty} \sup F_n$ and $\lim_{n\to\infty} \inf F_n$ exist in $\overline{\mathbb{R}}$. We define

$$\limsup x_n = \lim_{n\to\infty} (\sup F_n)$$
$$\liminf x_n = \lim_{n\to\infty} (\inf F_n).$$

That is,

$$\limsup x_n = \lim_{n\to\infty} \sup\{x_k : k \geq n\} = \inf(\sup F_n)$$
$$\liminf x_n = \lim_{n\to\infty} \inf\{x_k : k \geq n\} = \sup(\inf F_n)$$

Notation .

$$\limsup x_n = \limsup_{n\to\infty} x_n = \overline{\lim} x_n$$
$$\liminf x_n = \liminf_{n\to\infty} x_n = \underline{\lim} x_n$$

Example 3.5.1. $x_n = (-1)^n$

$$\limsup x_n = \lim_{n\to\infty} \sup\{x_k : k \geq n\} = \lim_{n\to\infty} \sup\{x_1, x_2, x_3, ...\} = \lim_{n\to\infty} \sup\{1, -1\} = 1$$
$$\liminf x_n = \lim_{n\to\infty} \inf\{x_k : k \geq n\} = \lim_{n\to\infty} \inf\{x_1, x_2, x_3, ...\} = \lim_{n\to\infty} \inf\{-1, 1\} = -1$$

$(a_n) = (-1, 2, 3, -1, 2, 3, -1, 2, 3, ...)$

$$\limsup a_n = \lim_{n\to\infty} \sup\{-1, 2, 3\} = 3$$
$$\liminf a_n = \lim_{n\to\infty} \inf\{-1, 2, 3\} = -1$$

$b_n = n$

$$\limsup b_n = \lim_{n\to\infty} \sup\{b_k : k \geq n\} = \lim_{n\to\infty} \sup\{b_n, b_{n+1}, b_{n+2}, ...\} = \lim_{n\to\infty} \sup\{n, n+1, n+2, ...\} = +\infty$$
$$\liminf b_n = \lim_{n\to\infty} \inf\{b_k : k \geq n\} = \lim_{n\to\infty} \inf\{n, n+1, n+2, ...\} = \lim_{n\to\infty} n = +\infty$$

Theorem 3.5.4. Let (a_n) be a sequence of real numbers. Then

$$\liminf a_n \leq \limsup a_n$$

Proof. We want to show $\lim_{n\to\infty} \inf\{a_k : k \geq n\} \leq \lim_{n\to\infty} \sup\{a_k : k \geq n\}$. It is enough to show $\exists n_0$ such that $\forall n \geq n_0$ $\inf\{a_k : k \geq n\} \leq \sup\{a_k : k \geq n\}$. Notice that for all $n \in \mathbb{N}$

$$\inf\{a_k : k \geq n\} \leq \sup\{a_k : k \geq n\}$$

Since we already proved that the limits of both sides exist in $\overline{\mathbb{R}}$, it follows from the order limit theorem (OLT, in $\overline{\mathbb{R}}$) that

$$\lim_{n\to\infty} \inf\{a_k : k \geq n\} \leq \lim_{n\to\infty} \sup\{a_k : k \geq n\}$$

That is,

$$\liminf a_n \leq \limsup a_n$$

□

Theorem 3.5.5. Let (a_n) be a sequence of real numbers. Then

$$\lim_{n\to\infty} a_n \text{ exists in } \overline{\mathbb{R}} \iff \limsup a_n = \liminf a_n$$

Moreover, in this case, $\lim a_n = \limsup a_n = \liminf a_n$.

Proof. $(\Longleftarrow)$ Suppose $\limsup a_n = \liminf a_n$. Let $A = limsup a_n = liminf a_n$ $(A \in \overline{\mathbb{R}})$. In what follows, we will show that $\lim a_n = A$. We consider three cases:

Case 1: $A \in \mathbb{R}$

Note that $\forall n \in \mathbb{N}$

$$\inf\{a_k : k \geq n\} \leq a_n \leq \sup\{a_k : k \geq n\}$$

Since $\lim_{n\to\infty} \sup\{a_k : k \geq n\} = \lim_{n\to\infty} \inf\{a_k : k \geq n\} = A$, it follows from the squeeze theorem that $\lim_{n\to\infty} a_n = A$.

Case 2: $A = \infty$

$$\left.\begin{aligned} &\forall n \in \mathbb{N} \quad \inf\{a_k : k \geq n\} \leq a_n \\ &\lim_{\{} a_k : k \geq n\} = \infty \end{aligned}\right\} \implies \lim_{n\to\infty} a_n = \infty$$

Case 3: $A = -\infty$

$$\left.\begin{aligned} &\forall n \in \mathbb{N} \quad a_n \leq \sup\{a_k : k \geq n\} \\ &\lim_{n\to\infty} \sup\{a_k : k \geq n\} \end{aligned}\right\} \implies \lim_{n\to\infty} a_n = -\infty$$

($\implies$) Suppose $\lim_{n\to\infty} a_n$ exists in $\overline{\mathbb{R}}$. Let $A = \lim_{n\to\infty} a_n$ $(A \in \overline{\mathbb{R}})$. In what follows, we will show that $\limsup a_n = A = \liminf a_n$. We consider three cases:

Case 1: $A \in \overline{\mathbb{R}}$
We will show $A \leq \liminf a_n$ and $\limsup a_n \leq A \implies A \leq \liminf a_n \leq \limsup a_n \leq A$. To do this, it is enough to show that

$$\forall \epsilon > 0 \ A - \epsilon \leq \liminf a_n$$
$$\forall \epsilon > 0 \ \limsup a_n \leq A + \epsilon$$

Let $\epsilon > 0$ be given. Since $a_n \to A$, there exists N such that

$$\forall n > N \quad |a_n - A| < \epsilon$$

so,

$$\begin{aligned} *) \ \forall n > N \quad a_n < A + \epsilon &\implies \forall n > N \ A + \epsilon \in UP\{a_k : k \geq n\} \\ &\implies \forall n > N \quad \sup\{a_k : k \geq n\} \leq A + \epsilon \\ &\overset{OLT}{\implies} \lim_{n\to\infty} \sup\{a_k : k \geq n\} \leq \lim_{n\to\infty} A + \epsilon \\ &\implies \limsup a_n \leq A + \epsilon \\ *) \ \forall n > N \quad A - \epsilon < a_n &\implies \forall n > N \quad A - \epsilon \in LO\{a_k : k \geq n\} \\ &\implies \forall n > N \quad \inf\{a_k : k \geq n\} \leq A - \epsilon \\ &\overset{OLT}{\implies} \lim_{n\to\infty} \inf\{a_k : k \geq n\} \geq \lim_{n\to\infty} A - \epsilon \\ &\implies \liminf a_n \geq A - \epsilon \end{aligned}$$

Case 2: $A = \infty$
In order to show $\liminf a_n = \infty$, it's enough to show that

$$\forall M > 0 \quad M \leq \liminf a_n$$

Let $M > 0$ be given. Since $a_n \to \infty$, $\exists N$ such that $\forall n > N$

$$\begin{aligned} &a_n > M \\ &\implies \forall n > N \quad \inf\{a_k : k \geq n\} \geq M \\ &\implies \lim_{n\to\infty} \inf\{a_k : k \geq n\} \geq \lim_{n\to\infty} M \\ &\implies \liminf a_n \geq M \end{aligned}$$

Case 3: $A = -\infty$
Analogous to case 2.

□

Theorem 3.5.6. Let (a_n) and (b_n) be two sequences of $\mathbb{R}$. Then

$$\limsup(a_n + b_n) \leq \limsup a_n + \limsup b_n$$

provided that $\infty - \infty$ or $-\infty + \infty$ does not appear.

Proof.

Informal Discussion

Our goal is to show $\lim_{n\to\infty}\sup\{a_k+b_k : k\geq n\} \leq \lim_{n\to\infty}\sup\{a_l : l\geq n\} + \lim_{n\to\infty}\sup\{b_m : m\geq n\}$. Considering the algebraic limit theorem (ALT) and the OLT it is enough to show that there exists n_0 such that

$$\forall n\geq n_0 \quad \sup\{a_k+b_k : k\geq n\} \leq \sup\{a_l : l\geq n\} + \sup\{b_m : m\geq n\}$$

It is enough to show that if $n\geq n_0$, $\sup\{a_l : l\geq n\} + \sup\{a_m : m\geq n\}$ is an upper bound for $\{a_k+b_k : k\geq n\}$. That is, we want to show

$$\forall k\geq n \; a_k+b_k \leq \sup\{a_l : l\geq n\} + \sup\{b_m : m\geq n\}$$

First, note that since by assumption $\limsup a_n + \liminf a_n$ is not of the form $\infty-\infty$ or $-\infty+\infty$, so there exists n_0 such that

$$\forall n\geq n_0 \quad \sup\{a_k : k\geq n\} + \sup\{b_m : m\geq n\} \text{ is not of the form } \infty-\infty \text{ or } -\infty+\infty$$

For each $n\geq n_0$, we have

$$\forall k\geq n \quad a_k \leq \sup\{a_l : l\geq n\}$$
$$\forall k\geq n \quad b_k \leq \sup\{b_m : m\geq n\}$$

Hence,

$$\forall k\geq n \quad a_k+b_k \leq \sup\{a_l : l\geq n\} + \sup\{b_m : m\geq b\}$$

Therefore,

$$\forall n\geq n_0 \quad \sup\{a_k+b_k : k\geq n\} \leq \sup\{a_l : l\geq n\} + \sup\{b_m : m\geq n\}$$

Passing to the limit $n\to\infty$, we get $\limsup(a_n+b_n) \leq \limsup a_n + \limsup b_n$. □

Theorem 3.5.7. If $|x|<1$, then $\lim_{n\to\infty} x^n = 0$.

Proof. Clearly, if $x=0$ the claim holds. Supposed $x\in(-1,1)$ and $x\neq 0$. Our goal is to show that

$$\forall\epsilon>0\ \exists N \text{ such that } \forall n>N \quad |x^n-0|<\epsilon.$$

Let $\epsilon>0$ be given. Our goal is to find N such that

$$\text{if } n>N \text{ then } |x^n|<\epsilon \tag{$*$}$$

Since $0<|x|<1$, there exists $y>0$ such that $|x|=\frac{1}{1+y}$. Note that

$$|x^n|<\epsilon \iff \frac{1}{(1+y)^n}<\epsilon$$

Also, by the binomial theorem $((1+y)^n \geq 1+ny)$

$$\frac{1}{(1+y)^n} \leq \frac{1}{1+ny} < \frac{1}{ny}$$

Therefore, in order to ensure that $|x^n|<\epsilon$, we just need to choose n large enough so that $1/ny<\epsilon$. To this end, it is enough to choose n larger than $1/ny$. (We can take $N=1/ny$ in $(*)$)

Theorem 3.5.8. If $p>0$, then $\lim_{n\to\infty}\sqrt[n]{p}=1$.

Proof. If $p=1$, the claim obviously holds. If $p\neq 1$, we consider two cases:

Case 1: $p>1$

Let $x_n = \sqrt[n]{p} - 1$. It is enough to show that $\lim_{n\to\infty} x_n = 0$. Note that since $p > 1$, $x_n \geq 0$. Also,

$$\begin{aligned}\sqrt[n]{p} = 1 + x_n &\implies p = (1 + x_n)^n \geq 1 + nx_n \\ &\implies x_n \leq \frac{p-1}{n}\end{aligned}$$

Thus

$$0 \leq x_n \leq \frac{p-1}{n}.$$

It follows from the squeeze theorem that $\lim_{n\to\infty} x_n = 0$.

Case 2: $0 < p < 1$
Since $0 < p < 1$, we have $1 < \frac{1}{p}$. So, by **case 1**,

$$\lim_{n\to\infty} \sqrt[n]{\frac{1}{p}} = 1.$$

By the ALT, we know that if $b_n \to b$ and $b \neq 0$, then $\frac{1}{b_n} \to \frac{1}{b}$. Hence

$$\lim_{n\to\infty} \sqrt[n]{p} = 1.$$

□

Theorem 3.5.9. $\lim_{n\to\infty} \sqrt[n]{n} = 1$.

Proof. Let $x_n = \sqrt[n]{n} - 1$. Clearly, $x_n \geq 0$. We have, for $n \geq 2$,

$$\begin{aligned}\sqrt[n]{n} = 1 + x_n &\implies n = (1 + x_n)^n \geq \binom{n}{k} x_n^2 = \frac{n(n-1)}{2} x_n^2 \\ &\implies \frac{2n}{n(n-1)} \geq x_n^2 \\ &\implies x_n \leq \sqrt{\frac{2}{n-1}}.\end{aligned}$$

Thus,

$$0 \leq x_n \leq \sqrt{\frac{2}{n-1}}.$$

It follows from the squeeze theorem that $x_n \to 0$ and so $\sqrt[n]{n} \to 1$. □