

# MATH255 - Analysis 2

Basic point-set topology; metric spaces; Hölder-Minkowski Inequalities; compactness.

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# 1 INTRODUCTION

## 1.1 Metric Spaces

### ↪ Definition 1.1: Metric Space

A set  $X$  is a *metric space* with distance  $d$  if

1. (symmetric)  $d(x, y) = d(y, x) \geq 0$
2.  $d(x, y) = 0 \iff x = y$
3. (triangle inequality)  $d(x, y) + d(y, z) \geq d(x, z)$

**Remark 1.1.** If 1., 3. are satisfied but not 2.,  $d$  can be called a “pseudo-distance”.

### ↪ Definition 1.2: Open Metric Space

Let  $(X, d)$  be a metric space. A subset  $A \subseteq X$  is open  $\iff \forall x \in A, \exists r = r(x) > 0$  s.t.  $B(x, r(x)) \subseteq A$ .

### ↪ Definition 1.3: Normed Space

Let  $X$  be a vector space over  $\mathbb{R}$ . The norm on  $X$ , denoted  $\|x\| \in \mathbb{R}$ , is a function that satisfies

1.  $\|x\| \geq 0$
2.  $\|x\| = 0 \iff x = 0$
3.  $\|c \cdot x\| = |c| \cdot \|x\|$
4.  $\|x + y\| \leq \|x\| + \|y\|$

If  $X$  is a normed vector space over  $\mathbb{R}$ , we can define a distance  $d$  on  $X$  by  $d(x, y) = \|x - y\|$ .

### ↪ Proposition 1.1

If  $X$  is a normed vector space over  $\mathbb{R}$ , a distance  $d$  on  $X$  by  $d(x, y) = \|x - y\|$  makes  $(X, d)$  a metric space.

Proof. 1.  $d(x, y) = \|x - y\| \geq 0$

$$2. d(x, y) = 0 \iff \|x - y\| = 0 \iff x - y = 0 \iff x = y$$

$$3. d(x, y) + d(y, z) = \|x - y\| + \|y - z\| \geq \|(x - y) + (y - z)\| = \|x - z\| := d(x, z)$$

⊗ **Example 1.1:  $L^p$  distance in  $\mathbb{R}^n$**

Let  $\bar{x} \in \mathbb{R}^n$ ,  $x = (x_1, x_2, \dots, x_n)$ . The  $L^p$  norm is defined

$$||x||_p := (|x_1|^p + |x_2|^p + \dots + |x_n|^p)^{\frac{1}{p}}.$$

In the case  $p = 2, n = 2$ , we simply have the standard Euclidean distance over  $\mathbb{R}^2$ .

Unit Balls: consider when  $||x||_p \leq 1$ , over  $\mathbb{R}^2$ .

- $p = 1 : |x_1| + |x_2| \leq 1$ ; this forms a “diamond ball” in the plane.
- $p = 2 : \sqrt{|x_1|^2 + |x_2|^2} \leq 1$ ; this forms a circle of radius 1. Clearly, this surrounds a larger area than in  $p = 2$ .

A natural question that follows is what happens as  $p \rightarrow \infty$ ? Assuming  $|x_1| \geq |x_2|$ :

$$\begin{aligned} ||x||_p &= (|x_1|^p + |x_2|^p)^{\frac{1}{p}} \\ &= \left[ |x_1|^p \left( 1 + \left| \frac{x_2}{x_1} \right|^p \right) \right]^{\frac{1}{p}} \\ &= |x_1| \left( 1 + \left| \frac{x_2}{x_1} \right|^p \right)^{\frac{1}{p}} \end{aligned}$$

If  $|x_1| > |x_2|$ , this goes to  $|x_1|$ . If they are instead equal, then  $||x||_p = |x_1| \cdot 2^{\frac{1}{p}} \rightarrow |x_1| \cdot 1$  as well. Hence,  $\lim_{p \rightarrow \infty} ||x||_p = \max\{|x_1|, |x_2|\}$ . Thus, the unit ball will approach  $\max\{|x_1|, |x_2|\} \leq 1$ , that is, the unit square.

↪ **Proposition 1.2**

Let  $x \in \mathbb{R}^n$ . Then,  $||x||_p \rightarrow \max\{|x_1|, \dots, |x_n|\}$  as  $p \rightarrow \infty$ .

**Remark 1.2.** This is an extension of the previous example to arbitrary real space; the proof follows nearly identically.

↪ **Definition 1.4: Convex Set**

Let  $X$  be a normed space, and take  $x, y \in X$ . The line segment from  $x$  to  $y$  is the set

$$\{t \cdot x + (1 - t) \cdot y : 0 \leq t \leq 1\}.$$

Let  $A \subseteq X$ .  $A$  is *convex*  $\iff \forall x, y \in A$ , we have that

$$(t \cdot x + (1 - t) \cdot y) \in A \forall 0 \leq t \leq 1.$$

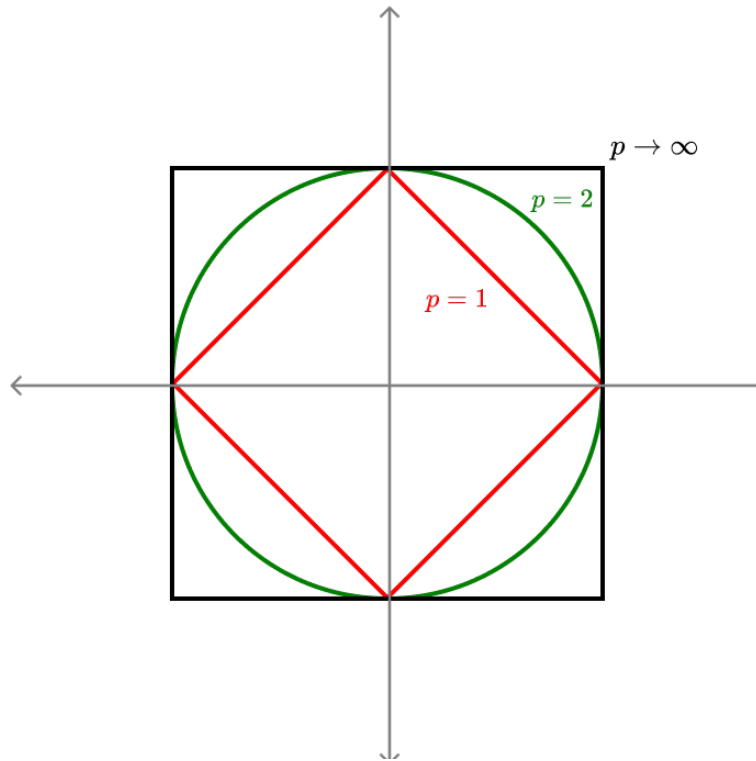


Figure 1: Regions of  $\mathbb{R}^2$  where  $\|x\|_p \leq 1$  for various values of  $p$ .

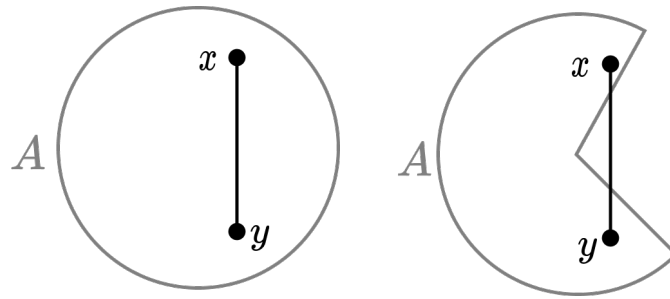


Figure 2: Convex (left) versus not convex (right) sets.

**Remark 1.3.** Think of this as saying “a set is convex iff every point on a line segment connected any two points is in the set”.

#### ↪ Definition 1.5: $\ell_p$

The space  $\ell_p$  of sequences is defined as

$$\{x = (x_1, x_2, \dots, x_n, \dots) : \sum_{n=1}^{\infty} |x_n|^p < +\infty\} \quad *.$$

Then,  $*$  defines the  $\ell^p$  norm on the space of sequences; that is,  $\|x\|_p := \left(\sum_{n=1}^{\infty} |x_n|^p\right)^{\frac{1}{p}}$ .

⊗ **Example 1.2:**  $\ell_p, x_n = \frac{1}{n}$

. Let  $x_n = \frac{1}{n}$ . For which  $p$  is  $x \in \ell_p$ ? We have, raising the norm to the power of  $p$  for ease:

$$\begin{aligned} \|x\|_p^p &= |x_1|^p + |x_2|^p + \cdots + |x_n|^p + \cdots \\ &= 1^p + \left(\frac{1}{2}\right)^p + \cdots < \infty \iff p > 1. \end{aligned}$$

In the case that  $p = 1$ , this becomes a harmonic sum, which diverges.

⊗ **Example 1.3:**  $L^p$  space of functions

Let  $f(x)$  be a continuous function. We define the norm of  $f$  over an interval  $[a, b]$

$$\|f\|_p = \left[ \int_a^b |f(x)|^p dx \right]^{\frac{1}{p}}.$$

**Remark 1.4.** Triangle inequality for  $\|x\|_p$  or  $\|f\|_p$  is called Minkowski inequality;  $\|x\|_p + \|y\|_p \geq \|x + y\|_p$ . This will be discussed further.

⊗ **Example 1.4:** Distances between sets in  $\mathbb{R}^2$

Let  $A, B$  be bounded, closed, “nice” sets in  $\mathbb{R}^2$ . We define

$$d(A, B) := \text{Area}(A \Delta B),$$

where

$$A \Delta B : (A \setminus B) \cup (B \setminus A) = (A \cup B) \setminus (A \cap B).$$

It can be shown that this is a “valid” distance.

**Remark 1.5.**  $\Delta$  denotes the “symmetric difference” of two sets.

⊗ **Example 1.5:**  $p$ -adic distance

Let  $p$  be a prime number. Let  $x = \frac{a}{b} \in \mathbb{Q}$ , and write  $x = p^k \cdot \left(\frac{c}{d}\right)$ , where  $c, d$  are not divisible by  $p$ . Then, the  $p$ -adic norm is defined  $\|x\|_p := p^{-k}$ . It can be shown that this is a norm.

Suppose  $p = 2, x = 28 = 4 \cdot 7 = 2^2 \cdot 7$ . Then,  $\|28\|_2 = 2^{-2} = \frac{1}{4}$ ; similarly,  $\|1024\|_2 = \|2^{10}\|_2 = 2^{-10}$ .

More generally, we have that  $\|2^k\|_2 = 2^{-k}$ ; conversely,  $\|2^{-k}\| = 2^k$ . That is, the closer to 0, the larger the distance, and vice versa, contrary to our notion of Euclidean distance.

↪ **Proposition 1.3**

$\|x\|_p$  as defined above is a well-defined norm over  $\mathbb{Q}$ .

Proof. Left as a (homework) exercise. ■

## 2 POINT-SET TOPOLOGY

### 2.1 Definitions

#### ↪ [Definition 2.1: Topological space](#)

A set  $X$  is a topological space if we have a collection of subsets  $\tau$  of  $X$  called *open sets* s.t.

1.  $\emptyset \in \tau, X \in \tau$
2. Consider  $\{A_\alpha\}_{\alpha \in I}$  where  $A_\alpha$  an open set for any  $\alpha$ ; then,  $\bigcup_{\alpha \in I} A_\alpha \in \tau$ , that is, it is also an open set.
3. If  $J$  is a finite set, and  $A_\beta$  open for all  $\beta \in J$ , then  $\bigcap_{\beta \in J} A_\beta \in \tau$  is also open.

In other words, 2.: arbitrary unions of open sets are open, and 3.: finite intersections of open sets are open.

#### ↪ [Definition 2.2: Closed sets](#)

Closed sets are complements of open sets; hence, axioms for closed sets follow appropriately;

- 1.\*  $X, \emptyset$  closed;
- 2.\*  $B_\alpha$  closed  $\forall \alpha \in I \implies \bigcap_{\alpha \in I} B_\alpha$  closed.
- 3.\*  $B_\beta$  closed  $\forall \beta \in J, J$  finite, then  $\bigcup_{\beta \in J} B_\beta$  also closed.

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### ↪ Definition 2.3: Equivalence of Metrics

Suppose we have a metric space  $X$  with two distances  $d_1, d_2$ ; will these necessarily admit the same topology?

A sufficient condition is that, if  $\forall x \neq y \in X, \exists 1 < C < +\infty$  s.t.

$$\frac{1}{C} < \frac{d_1(x, y)}{d_2(x, y)} < C.$$

That is, the distances are equivalent, up to multiplication by a constant.

Indeed, this condition gives that  $d_2 < C d_1$  and  $d_2 > \frac{d_1}{C}$ ; this gives

$$B_{d_1}(x, \frac{r}{C}) \subseteq B_{d_2}(x, r) \subseteq B_{d_1}(x, C \cdot r).$$

Hence,  $d_1, d_2$  define the same open/closed sets on  $X$  thus admitting the same topologies. We write  $d_1 \asymp d_2$ .

**Remark 2.1.** If  $d_1 \asymp d_2$  and  $d_2 \asymp d_3$ , then also  $d_1 \asymp d_3$ . Moreover, clearly,  $d_1 \asymp d_1$  and  $d_1 \asymp d_2 \implies d_2 \asymp d_1$ , hence this is a well-defined equivalence relation.

Hence, it's enough to show that  $\forall 1 < p < +\infty$ , we have  $\|x\|_p \asymp \|x\|_\infty$  to show that any  $\|x\|_q$  norm are equivalent for all  $q$  on  $\mathbb{R}^n$ .

### ↪ Definition 2.4: Interior, Boundary of a Topological Set

Let  $X$  be a topological space,  $A \subseteq X$  and let  $x \in X$ . We have the following possibilities

1.  $\exists U$ -open :  $x \in U \subseteq A$ . In this case, we say  $x \in$  the *interior* of  $A$ , denoted

$$x \in \text{Int}(A).$$

2.  $\exists V$ -open :  $x \in V \subseteq X \setminus A = A^C$ . In this case, we write

$$x \in \text{Int}(X^C).$$

3.  $\forall U$ -open :  $x \in U, U \cap A \neq \emptyset$  AND  $U \cap A^C \neq \emptyset$ . In this case, we say  $x$  is in the *boundary* of  $A$ , and denote

$$x \in \partial A.$$

### ↪ Definition 2.5: Closure

$x \in \text{Int}(A)$  or  $x \in \partial A$  (that is,  $x \in \text{Int}(A) \cup \partial A$ )  $\iff$  every open set  $U$  that contains  $x$  intersects  $A$ .<sup>1</sup> Such points are called *limit points* of  $A$ . The set of all limit points of  $A$  is called the *closure* of  $A$ , denoted  $\overline{A}$ .



**Remark 2.2.** We have that

$$\text{Int}(A) \subseteq A \subseteq \overline{A} = \text{Int}(A) \cup \partial A.$$

↪ **Proposition 2.1: Properties of  $\text{Int}(A)$**

$\text{Int}(A)$  is *open*, and it is the largest open set contained in  $A$ . It is the union of all  $U$ -open s.t.  $U \subseteq A$ . Moreover, we have that

$$\text{Int}(\text{Int}(A)) = \text{Int}(A).$$

↪ **Proposition 2.2: Properties of  $\overline{A}$**

$\overline{A}$  is *closed*;  $\overline{A}$  is the smallest closed set that contains  $A$ , that is,  $\overline{A} = \bigcap B$  where  $B$  closed and  $A \subseteq B$ . We have too that

$$\overline{(\overline{A})} = \overline{A}.$$

↪ **Proposition 2.3**

1.  $A$  is open  $\iff A = \text{Int}(A)$
2.  $A$  is closed  $\iff A = \overline{A}$

## 2.2 Basis

↪ **Definition 2.6: Basis for a Topology**

Let  $\tau$  be a topology on  $X$ . Let  $\mathcal{B} \subseteq \tau$  be a collection of open sets in  $X$  such that every open set is a union of open sets in  $\mathcal{B}$ .

⊗ **Example 2.1: Example Basis**

$X = \mathbb{R}$ , and  $\mathcal{B} = \{\text{all open intervals } (a, b) : -\infty < a < b < +\infty\}$ .

↪ **Proposition 2.4**

Let  $\mathcal{B}$  be a collection of open sets in  $X$ . Then,  $\mathcal{B}$  is a basis  $\iff$

1.  $\forall x \in X, \exists U\text{-open} \in \mathcal{B} \text{ s.t. } x \in U$ .
2. If  $U_1 \in \mathcal{B}$  and  $U_2 \in \mathcal{B}$ , and  $x \in U_1 \cap U_2$ , then  $\exists U_3 \in \mathcal{B} \text{ s.t. } x \in U_3 \subseteq U_1 \cap U_2$ .

---

<sup>1</sup>"Requires" proof.

### ⊗ Example 2.2

Consider  $X = \mathbb{R}$ . Requirement 1. follows from taking  $U = (x - \varepsilon, x + \varepsilon)$  for any  $\varepsilon > 0$ . For 2., suppose  $x \in (a, b) \cap (c, d) =: U_1 \cap U_2$ . Let  $U_3 = (\max\{a, c\}, \min\{b, d\})$ ; then, we have that  $U_3 \subseteq U_1 \cap U_2$ , while clearly  $x \in U_3$ .

### ↪ Proposition 2.5

In a metric space, a basis for a topology is a collection of open balls,

$$\{B(x, r) : x \in X, r > 0\} = \{\{y \in X : d(x, y) < r\} : x \in X, r > 0\}.$$

Proof. We prove via proposition 2.4. Property 1. holds clearly;  $x \in B(x, \varepsilon)$ -open  $\subseteq \mathcal{B}$ .

For property 2., let  $x \in B(y_1, r_1) \cap B(y_2, r_2)$ , that is,  $d(x, y_1) < r_1$  and  $d(x, y_2) < r_2$ . Let

$$\delta := \min\{r_1 - d(x, y_1), r_2 - d(x, y_2)\}.$$

We claim that  $B(x, \delta) \subseteq U_1 \cap U_2$ .

Let  $z \in B(x, \delta)$ . Then,

$$d(z, y_1) \stackrel{\Delta \neq}{\leq} d(z, x) + d(x, y_1) < \delta + d(x, y_1) \leq r_1 - d(x, y_1) + d(x, y_1) = r_1,$$

hence, as  $d(z, y_1) < r_1 \implies z \in B(y_1, r_1) = U_1$ . Replacing each occurrence of  $y_1, r_1$  with  $y_2, r_2$  respectively gives identically that  $z \in B(y_2, r_2) = U_2$ . Hence, we have that  $B(x, \delta) \subseteq U_1 \cap U_2$  and 2. holds. ■

## 2.3 Subspaces

### ↪ Definition 2.7

Let  $X$  be a topological space and let  $Y \subseteq X$ . We define the subspace topology on  $Y$ :

1. Open sets in  $Y = \{Y \cap \text{open sets in } X\}$

### ↪ Proposition 2.6: Consequences of Subspace Topologies

Suppose  $\mathcal{B}$  is a basis for a topology in  $X$ . Then,  $\{U \cap Y : U \in \mathcal{B}\}$  forms a basis for the subspace  $Y \subseteq X$ .

Suppose  $X$  a metric space. Then,  $Y$  is also a metric space, with the same distance.

### ↪ Proposition 2.7

Let  $Y \subseteq X$ - a metric space. Then, the metric space topology for  $(Y, d)$  is the same as the subspace topology.

Proof. (Sketch) A basis for the open sets in  $X$  can be written  $\bigcup_{\alpha \in I} B(x_\alpha, r_\alpha)$ ; hence

$$Y \cap \left( \bigcup_{\alpha \in I} B(x_\alpha, r_\alpha) \right) = \bigcup_{\alpha \in I} (Y \cap B(x_\alpha, r_\alpha))$$

is an open set topology for  $Y$ . ■

### ↪ **Lemma 2.1**

Let  $A \subseteq X$ -open,  $B \subseteq A$ ;  $B$ -open in subspace topology for  $A \iff B$ -open in  $X$ .

### ↪ **Lemma 2.2**

Let  $Y \subseteq X$ ,  $A \subseteq Y$ . Then,  $\overline{A}$  in  $Y = Y \cap \overline{A}$  in  $X$ . We can denote this

$$\overline{A}_Y = \overline{A}_X \cap Y.$$

## 2.4 Continuous Functions

### ↪ **Definition 2.8: Continuous Function**

Let  $X, Y$  be topological spaces. Let  $f : X \rightarrow Y$ .  $f$  is *continuous*  $\iff \forall$  open  $V \in Y$ ,  $f^{-1}(V)$ -open in  $X$ .

### ↪ **Proposition 2.8**

This definition is consistent with the normal  $\varepsilon$ - $\delta$  definition on the real line.

Proof. Let  $f : \mathbb{R} \rightarrow \mathbb{R}$ , continuous; that is,  $\forall \varepsilon > 0, \forall x \in \mathbb{R} \exists \delta > 0$  s.t.  $|x_1 - x| < \delta$ , then  $|f(x_1) - f(x)| < \varepsilon$ .

Let  $V \subseteq \mathbb{R}$  open. Let  $y \in V$ . Then,  $\exists \varepsilon : (y - \varepsilon, y + \varepsilon) \subseteq V$ . Let  $y = f(x)$ , hence  $y \in f^{-1}(V)$ . Now, if  $d(x, x_1) < \delta$ , we have that  $d(f(x_1), f(x)) < \varepsilon$  (by continuity of  $f$ ), hence  $f(x_1) \in (y - \varepsilon, y + \varepsilon) \subseteq V$ ; moreover,  $(x - \delta, x + \delta) \subseteq f^{-1}(V)$ , thus  $f^{-1}(V)$  is open as required.

The inverse of this proof follows identically. ■

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### ↪ **Proposition 2.9**

Suppose  $\mathcal{B}$  forms a basis of topology for  $Y$ . Then,  $f : X \rightarrow Y$  is continuous if  $f^{-1}(U)$  open  $\forall U \in \mathcal{B}$ .

Proof. If  $U$ -open set in  $Y$ , then  $\exists I$ -index set and a collection of open sets  $\{A_\alpha\}_{\alpha \in I}, A_\alpha \in \mathcal{B}$ , s.t.  $U = \bigcup_{\alpha \in I} A_\alpha$ . Then, we have

$$f^{-1}(U) = f^{-1}\left(\bigcup_{\alpha \in I} (A_\alpha)\right) = \bigcup_{\alpha \in I} \underbrace{f^{-1}(A_\alpha)}$$

Hence, if each  $f^{-1}(A_\alpha)$  open, then  $\cup_{\alpha \in I} f^{-1}(A_\alpha)$  open; hence it suffices to check if  $f^{-1}(U) \forall U$ -open in  $V$  is open to see if  $f$  continuous. ■

↪ **Theorem 2.1: Continuity of Composition**

If  $f : X \rightarrow Y$  continuous and  $g : Y \rightarrow Z$  continuous, then  $g \circ f$  continuous as well.

Proof. Let  $U$ -open in  $Z$ . Then

$$(g \circ f)^{-1}(U) = f^{-1}(\underbrace{g^{-1}(U)}_{\text{open in } Y})$$

$$\underbrace{\hspace{10em}}_{\text{open in } X}$$

↪ **Proposition 2.10**

If  $f : X \rightarrow Y$  continuous and  $A \subseteq X$ ,  $A$  has subspace topology, then  $f|_A : A \rightarrow Y$  is also continuous.<sup>2</sup>

Proof. Let  $U$ -open in  $Y$ . Then

$$(f|_A)^{-1}(U) = \underbrace{f^{-1}(U)}_{\text{open}} \cap \underbrace{A}_{\text{open}}$$

By the definition of subspace topology, this is an open set and hence  $f|_A$  is continuous. ■

## 2.5 Product Spaces

↪ **Definition 2.9: Finite Product Spaces**

Let  $X_1, \dots, X_n$  be topological spaces. We define

$$(X_1 \times X_2 \times \cdots \times X_n),$$

and aim to define a *product topology*; a basis of which consists of cylinder sets.

---

<sup>2</sup>We denote  $f|_A$  as the restriction of the domain of  $f$  to  $A$ .

↪ **Definition 2.10: Cylinder Set**

A *cylinder set* has the form

$$A_1 \times A_2 \times \cdots \times A_n$$

where each  $A_j$ -open in  $X_j$ .

⊗ **Example 2.3**

Given an open interval  $(a_1, b_1), (a_2, b_2) \subset \mathbb{R}$ , the set  $(a_1, b_1) \times (a_2, b_2) \subset \mathbb{R}^2$  is a basis for the topology on  $\mathbb{R}^2$ .

↪ **Definition 2.11: Projection**

Let  $X_1 \times X_2 \times \cdots \times X_n =: X$ . The *projection*  $\pi_j : X \rightarrow X_j$  maps  $(x_1, \dots, x_n) \rightarrow x_j \in X_j$ .

**Remark 2.3.** One can show  $\pi_j$  continuous.

↪ **Definition 2.12: Coordinate Function**

Given a function  $f : Y \rightarrow X_1 \times \cdots \times X_n = (x_1(y), x_2(y), \dots, x_n(y))$ . The *coordinate function* is

$$f_j = \pi_j \circ f; \quad f_j = x_j(y).$$

↪ **Proposition 2.11**

$f : Y \rightarrow X = X_1 \times \cdots \times X_n$  continuous  $\iff f_j : Y \rightarrow X_j$  continuous.

Proof. Its enough to show that  $\forall U \in \mathcal{B}$ -basis for  $X$ -product space,  $f^{-1}(U)$ -open in  $Y$ . Take  $U = A_1 \times \cdots \times A_n$ -open. Then, we claim that

$$f^{-1}(U) = f^{-1}(A_1 \times \cdots \times A_n) = f_1^{-1}(A_1) \cap f_2^{-1}(A_2) \cap \cdots \cap f_n^{-1}(A_n). \quad \star$$

If this holds, then as each  $f_i$  continuous (being a composition of continuous functions) and each  $A_i$  open in  $X_i$ , then each  $f_i^{-1}(A_i)$  open in  $Y$  and hence  $\star$ , being the finite intersection of open sets in  $Y$ , is itself open in  $Y$ . ■

⊗ **Example 2.4: Fourier Transform: Motivation for Infinite Product Topologies**

Let  $f \in C([0, 2\pi])$  is real-valued. We write the  $n$ th Fourier coefficients

$$\begin{aligned}\hat{f}(n) &= \frac{1}{2\pi} \int_0^{2\pi} f(x) e^{-inx} dx \\ &= \frac{1}{2\pi} \int_0^{2\pi} f(x) \cos(nx) dx - i \frac{1}{2\pi} \int_0^{2\pi} f(x) \sin(nx) dx.\end{aligned}$$

And the Fourier transform of  $f$  as the infinite product

$$f(x) \mapsto (\dots, \hat{f}(-n), \hat{f}(-n+1), \dots, \hat{f}(-1), \hat{f}(0), \hat{f}(1), \dots, \hat{f}(n), \dots) \in \prod_{n \in \mathbb{Z}} (\mathbb{C})_n.$$

Hence, this is an (countably, as indexed by integers) infinite product space.

Now, let  $f : \mathbb{R} \rightarrow \mathbb{R}$ . Suppose  $f(x) \rightarrow 0$  “fast enough” as  $|x| \rightarrow \infty$  and  $f$  continuous. Then, we can define the Fourier coefficients

$$\hat{f}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(x) e^{-itx} dx,$$

where  $t \in \mathbb{R}$ . We then have the transform

$$f \mapsto \{\hat{f}(t)\}_{t \in \mathbb{R}}.$$

In this case, our index set is  $\mathbb{R}$  is (uncountably) infinite.

↪ **Definition 2.13: Product Topology/Cylinder Sets for  $\infty$  Products**

Let  $X = \prod_{\alpha \in I} X_\alpha$ . Then, a basis for  $X$  is given by cylinder sets of the form  $A = \prod_{\alpha \in I} A_\alpha$  where  $A_\alpha$ -open in  $X_\alpha$ , AND  $A_\alpha = X_\alpha$  except for finitely many indices  $\alpha$ .

That is, there exists a finite set  $J = (\alpha_1, \dots, \alpha_k) \subseteq I$ , such that we can write  $A = \prod_{\alpha \in J} A_\alpha \times \prod_{\alpha \notin J} X_\alpha$  (where  $A_\alpha$  open in  $X_\alpha$ ).

↪ **Proposition 2.12**

Given  $f : Y \rightarrow \prod_{\alpha \in I} X_\alpha = X$ , then (taking  $f_\alpha = \pi_\alpha \circ f$  as before) we have that  $f$  is continuous in  $X \iff f_\alpha : Y \rightarrow X_\alpha$  continuous in  $X_\alpha \forall \alpha \in I$ .

**Remark 2.4.** Extension of proposition 2.11 to infinite product space.

Proof. Write  $U = \prod_{\alpha \in J} A_\alpha \times \prod_{\alpha \notin J} X_\alpha$ . Then,

$$f^{-1}(U) = \bigcap_{\alpha \in J} f_\alpha^{-1}(A_\alpha)$$

which is open in  $Y$ , hence  $f$  continuous. ■

**Remark 2.5.** The intersection of the entire spaces give no restriction.

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## 2.6 Metrizable

### ↪ Proposition 2.13

Different metrics can define the same topology.

#### ⊗ Example 2.5

1. Different  $\ell_p$  metrics in  $\mathbb{R}^n$  (PSET 1)
2. Let  $(X, d)$  be a metric space. Then,

$$\tilde{d}(x, y) := \frac{d(x, y)}{d(x, y) + 1}$$

is also a metric (the first two axioms are trivial), and defines the same topology. Note, moreover, that  $\tilde{d}(x, y) \leq 1 \forall x, y$ ; this distance is bounded, and can often be more convenient to work with in particular contexts.

### ↪ Question 2.1

Suppose  $(X_k, d_k)$  are metric spaces  $\forall k \geq 1$ . Then, we can define the product topology  $\tau$  on

$$X := \prod_{k=1}^{\infty} X_k.$$

Does the product topology  $\tau$  come from a metric? That is, is  $\tau$  metrizable?

**Remark 2.6.** There do indeed exist examples of non-metrizable topological spaces; this question is indeed well-founded.

*Answer.* Let  $\underline{x} = (x_1, x_2, \dots, x_n, \dots)$ ,  $\underline{y} = (y_1, y_2, \dots, y_n, \dots) \in \prod_{k=1}^{\infty} X_k$  (where  $x_i, y_i \in X_i$ ) be infinite sequences of elements. Then, for each metric space  $X_k$  take the metric

$$\tilde{d}_k(x_k, y_k) = \frac{d_k(x_k, y_k)}{1 + d_k(x_k, y_k)}$$

(as in the example above). Then, we define

$$D(\underline{x}, \underline{y}) = \sum_{k=1}^{\infty} \frac{\tilde{d}_k(x_k, y_k)}{2^k},$$

noting that  $D(\underline{x}, \underline{y}) \leq \sum_{k=1}^{\infty} \frac{1}{2^k} = 1$  (by our construction, “normalizing” each metric), hence this is a valid, *converging* metric (which wouldn’t otherwise be guaranteed if we didn’t normalize the metrics). It remains to show whether this metric omits the same topology as  $\tau$ . ■

## 2.7 Compactness, Connectedness

### ↪ Definition 2.14: Compact

A set  $A$  in a topological space is said to be *compact* if every cover has a finite subcover. That is, if

$$A \subseteq \bigcup_{\alpha \in I} U_{\alpha} - \text{open},$$

then  $\exists \{\alpha_1, \dots, \alpha_n \in I\}$  such that  $A \subseteq \bigcup_{i=1}^n U_{\alpha_i}$ .

### ↪ Proposition 2.14

A closed interval  $[a, b]$  is compact.

*Proof.* If<sup>3</sup>  $a = b$ , this is clear. Suppose  $a < b$ , and let  $[a, b] \subseteq \bigcup_{i \in I} U_i =: \mathcal{U}$  be an arbitrary cover. Then, we proceed in the following steps:

1. **Claim:** Given  $x \in [a, b]$ ,  $x \neq b$ ,  $\exists y \in [a, b]$  s.t.  $[x, y]$  has a finite subcover.

Let  $x \in [a, b]$ ,  $x \neq b$ . Then,  $\exists U_{\alpha} \in \mathcal{U} : x \in U_{\alpha}$ . Since  $U_{\alpha}$  open, and  $x \neq b$ , we further have that  $\exists c \in [a, b]$  s.t.  $[x, c] \subseteq U_{\alpha}$ .

Now, let  $y \in (x, c)$ ; then, the interval  $[x, y] \subseteq [x, c] \subseteq U_{\alpha}$ , that is,  $[x, y]$  has a finite subcover.

2. Define  $C := \{y \in [a, b] : y > a, [a, y] \text{ has a finite subcover}\}$ . We note that

- $C \neq \emptyset$ ; taking  $x = a$  in Step 1. above, we have that  $\exists y \in [a, b]$  such that  $[a, y]$  has a finite step cover, so this  $y \in C$ .
- $C$  bounded; by construction,  $\forall y \in C, a < y \leq c$ .

Thus, we can validly define  $c := \sup C$ , noting that  $a < c \leq b$ . Ultimately, we wish to prove that  $c = b$ , completing the proof that  $[a, b]$  has a finite subcover.

3. **Claim:**  $c \in C$ .

Let  $U_{\beta} \in \mathcal{U} : c \in U_{\beta}$ . Then, by the openness of  $U_{\beta}$ ,  $\exists d \in [a, b]$  s.t.  $(d, c] \subseteq U_{\beta}$ .

<sup>3</sup>This proof is adapted from that of Theorem 27.1 in Munkre’s Topology, an identical theorem but applied to more general ordered topologies.



Supposing  $c \notin C$ , then  $\exists z \in C$  such that  $z \in (d, c)$ ; if one did not exist, then this would imply that  $d$  was a smaller upper bound than  $c$ , a contradiction. Thus,  $[z, c] \subseteq (d, c] \subseteq U_\beta$ .

Moreover, we have that, given  $z \in C$ ,  $[a, z]$  has a finite subcover; call it  $U_z \subseteq \mathcal{U}$ . This gives, then:

$$[a, c] = [a, z] \cup [z, c] \subseteq U_z \cup U_\beta.$$

But this is a finite subcover of  $[a, c]$ , contradicting the fact that  $c \notin C$ . We conclude, then, that  $c \in C$  after all.

4. **Claim:**  $c = b$ .

Suppose not; then, since we have  $c \leq b$ , then assume  $c < b$ . Then, applying Step 1. with  $x = c$  (which we can do, by our assumption of  $c \neq b$ !), then we have that  $\exists y > c$  s.t.  $[c, y]$  has a finite subcover, call this  $U_y \subseteq \mathcal{U}$ .

Moreover, we had  $c \in C$ , hence  $[a, c]$  has a finite subcover, call this  $U_c \subseteq \mathcal{U}$ .

Then, this gives us that

$$[a, y] = [a, c] \cup [c, y] \subseteq U_c \cup U_y,$$

that is,  $[a, y]$  has a finite subcover, and so  $y \in C$ . But recall that  $y > c$ ; hence, this a contradiction to  $c$  being the least upper bound of  $C$ . We conclude that  $c = b$ , and thus  $[a, b]$  has a finite subcover, and is thus compact. ■

**Remark 2.7.** A similar proof shows that  $[a, b]$  is connected; we cannot cover it by two disjoint open sets.

↪ **Theorem 2.2: On Compactness**

Let  $A \subseteq \mathbb{R}^n$ . Then,  $A$  compact  $\iff A$  closed and bounded.

↪ **Proposition 2.15**

If  $X, Y$  are compact topological spaces, then  $X \times Y$  is compact.

**Remark 2.8.** By induction, if  $X_1, \dots, X_n$  compact, so is  $\prod_{i=1}^n X_i$ .

↪ **Proposition 2.16**

A closed subset of a compact topological space is compact in the subspace topology.

Proof. (Of theorem 2.2)

( $\Leftarrow$ ) If  $A \subseteq \mathbb{R}^n$  closed and bounded, then  $A \subseteq [-R, +R]^n$  for some  $R > 0$  (it is contained in some “ $n$ -cube”). Then, we have that  $[-R, R]$  is compact, by proposition 2.14, proposition 2.15, and proposition 2.16,  $A$  itself compact.

( $\Rightarrow$ ) Suppose  $A \subseteq \mathbb{R}^n$  is compact. Then,  $\bigcup_{x \in A} B(x, \varepsilon)$  for some  $\varepsilon > 0$  is an open cover of  $A$ . As  $A$  compact, there must exist a finite subcover of this cover,  $A \subseteq \bigcup_{i=1}^N B(x_i, r_i)$ . Let  $R := \max_{i=1}^N (||x_i|| + r_i)$ . Then,  $A \subseteq \overline{B(0, R)}$ , that is,  $A$  is bounded.

Now, suppose  $x$  is a limit point of  $A$ . Then, any neighborhood of  $x$  contains a point in  $A$ , so  $\forall r > 0, B(x, r) \cap A \neq \emptyset$ , and so  $\overline{B}(x, r)$  also contains a point of  $A$  for any  $r > 0$ .

Now, suppose  $x \notin A$  (looking for a contradiction). Then,

$$U := \bigcup_{r>0} U_r := \bigcup_{r>0} (\mathbb{R}^n \setminus \overline{B}(x, r)) = \mathbb{R}^n \setminus \{x\}$$

is an open cover for the set  $A$ .  $A$  being compact implies that  $U$  has a finite subcover such that  $A \subset U_{r_1} \cup U_{r_2} \cup \dots \cup U_{r_N}$ . Let  $r_0 = \min_{i=1}^N r_i$ . Then,  $A \subseteq U_{r_0}$ , and  $A \cap B(x, r_0) = \emptyset$ ; but this is a contradiction to the definition of a limit point, hence any limit point  $x$  is contained in  $A$  and  $A$  is thus closed by definition. ■

### ↪ **Proposition 2.17**

Compact  $\implies$  sequentially compact; that is, every sequence in a compact set has a convergent subsequence.

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### ↪ **Definition 2.15: Connected**

A topological space  $X$  is *not connected* if  $X = U \cup V$  for two open, nonempty, disjoint sets  $U, V$ .

If this does not hold,  $X$  is said to be *connected*.

A set  $A \subseteq X$  is not connected if  $A$  is not connected in the subspace topology  $\iff A = U \cup V$ , for  $U, V$ -open in  $X$ ,  $(U \cap A) \neq \emptyset$ ,  $(V \cap A) \neq \emptyset$  and  $U \cap V = \emptyset$ .

### ↪ **Theorem 2.3**

Let  $X$  be a connected topological space. Let  $f : X \rightarrow Y$  be a continuous function. Then,  $f(X)$  is also connected.

*Proof.* Suppose, seeking a contradiction, that  $X$  is connected, but  $f(X)$  is not. Then, we can write  $f(X) \subseteq Y$  as  $f(X) \subseteq U \cup V$ , such that  $U, V$  open in  $Y$  and  $U \cap V = \emptyset$ . Then,

$$(U \cap f(X)) \cap (V \cap f(X)) = \emptyset.$$

We also have that

$$X \subseteq \underbrace{f^{-1}(U)}_{\text{open in } X, \neq \emptyset} \cup \underbrace{f^{-1}(V)}_{\text{open in } X, \neq \emptyset}.$$

$f^{-1}(U) \cap f^{-1}(V) = \emptyset$  (that is, they are disjoint) by our assumption; this is a contradiction to the connectedness of  $X$ , as we are able to write it as a subset of two disjoint open sets. Hence,  $f(X)$  is indeed connected. ■

↪ **Lemma 2.3**

Any interval  $(a, b), [a, b], [a, b), \dots, \subseteq \mathbb{R}$  is connected.

Proof.

↪ **Theorem 2.4: “Intermediate Value Theorem”**

Suppose  $X$  is connected and  $f : X \rightarrow \mathbb{R}$  is a continuous function. Then,  $f$  takes intermediate values.

More precisely, let  $a = f(x), b = f(y)$  for  $x, y \in X$ . Assume  $a < b$ . Then,  $\forall a < c < b, \exists z \in X$  s.t.  $f(z) = c$ .

Proof. Suppose, seeking a contradiction, that  $\exists c : a < c < b$  s.t.  $c \notin f(X)$  (that is, there exists an intermediate value that is “not reached” by the function).

Let  $U = (-\infty, c)$  and  $V = (c, +\infty)$ ; note that these are disjoint open sets. Then, we have that

$$X = f^{-1}(U) \cup f^{-1}(V),$$

by our assumption of  $c \notin f(X)$ . But this gives that  $X$  is not connected, as the union of two open (by continuity), disjoint, nonempty ( $f(x) = a \in U \implies x \in f^{-1}(U)$ , and  $f(y) = b \in V \implies y \in f^{-1}(V)$ ) sets, a contradiction. ■

↪ **Theorem 2.5**

Suppose  $X$  is compact,  $Y$ -topological space,  $f : X \rightarrow Y$  is a continuous function. Then,  $f(X)$  is also compact.

Proof. Let  $\{U_\alpha\}_{\alpha \in I}$  be an open cover of  $f(X) \subseteq Y$ , that is,

$$f(X) \subseteq \bigcup_{\alpha \in I} U_\alpha \implies X \subseteq f^{-1}\left(\bigcup_{\alpha \in I} U_\alpha\right) = \bigcup_{\alpha \in I} f^{-1}(U_\alpha) =: \bigcup_{\alpha \in I} V_\alpha - \text{open}.$$

Then, this is an open cover of  $X$ ;  $X$  is compact, thus there exists a finite subcover, that is, indices  $\{\alpha_1, \dots, \alpha_n\} \subseteq I$  such that  $X = \bigcup_{i=1}^n V_{\alpha_i}$ . Thus,

$$f(X) \subseteq \bigcup_{i=1}^n U_{\alpha_i},$$

which is a finite subcover of  $f(X)$ . Thus,  $f(X)$  is compact. ■

**Remark 2.9.** Recall the “extreme value theorem”: let  $f : [a, b] \rightarrow \mathbb{R}$  a continuous function; then, a minimum and maximum is obtained for  $f(x)$  on this interval for values in this interval.

↪ **Theorem 2.6**

Let  $X$  compact, and  $f : X \rightarrow \mathbb{R}$  a continuous function. Then,

$$\max_{x \in X} f(x) \text{ and } \min_{x \in X} f(x)$$

are both attained.

*Proof.*  $f(X) \subseteq \mathbb{R}$  is compact by theorem 2.5, and so by theorem 2.2,  $f(X)$  is closed and bounded. Let, then,  $m = \inf f(X)$  and  $M = \sup f(X)$ ; these necessarily exist, since  $f(X)$  is bounded. Both  $m$  and  $M$  are limit points of  $f(X)$ . But  $f(X)$  is closed, and hence contains all of its limit points, and thus  $m \in f(X)$  and  $M \in f(X)$ , and thus  $\exists y_m : f(y_m) = m$  and  $y_M : f(y_M) = M$ . ■

↪ **Definition 2.16: Path Connected**

A set  $A \subseteq X$  is called *path connected* if  $\forall x, y \in A, \exists f : [a, b] \rightarrow X$ , continuous, s.t.  $f(a) = x, f(b) = y$  and  $f([a, b]) \subseteq A$ .

The set  $\{f(t) : a \leq t \leq b\}$  is called a *path* from  $x$  to  $y$ .

↪ **Theorem 2.7: Path connected  $\implies$  connected**

If  $A \subseteq X$  is path connected, then  $A$  is connected.

*Proof.* Suppose, seeking a contradiction, that  $A$  is path connected, but not connected. Then, we can write  $\overline{A} \subseteq U \cup V$ , for open, disjoint, nonempty subsets  $U, V \subseteq X$ .

Let  $x \in U \cap A$  and  $y \in V \cap A$ . Then,  $\exists f : [a, b] \rightarrow A$  s.t.  $f(a) = x, f(b) = y$ , and  $f([a, b]) \subseteq A$ , by the path connectedness of  $A$ . Then,

$$[a, b] \subseteq f^{-1}(A) \subseteq \underbrace{f^{-1}(U \cap A)}_{\text{open}} \cup \underbrace{f^{-1}(V \cap A)}_{\text{open}} =: \underbrace{U_1}_{a \in} \cup \underbrace{U_2}_{b \in},$$

that is,  $[a, b]$  is contained in a union of open, nonempty, disjoint sets, contradicting  $[a, b]$  the connectedness of  $[a, b]$  by lemma 2.3. Thus,  $A$  is connected. ■

**Remark 2.10.** A counterexample to the opposite side of the implication is the Topologist's sine curve, the set

$$\{(x, \sin\left(\frac{1}{x}\right)) : x \in (0, 1]\} \cup \{0\} \times [-1, 1].$$

This set is connected in  $\mathbb{R}^2$ , but is not path connected.

↪ **Proposition 2.18**

For open sets in  $\mathbb{R}^n$ , path connected  $\iff$  connected.

## 2.8 Path Components, Connected Components

**Remark 2.11.** Remark that if a metric space  $X$  is not connected, then we can write  $X = U \cup V$  where  $U, V$  are open, nonempty and disjoint. It follows, then, that  $U = V^c$  (and vice versa) and hence  $U, V$  are both open and closed.

### ↪ Definition 2.17: Connected Component

A connected component of  $x \in X$  is the largest connected subset of  $X$  that contains  $x$ .

#### ⊗ Example 2.6

Let  $X = (0, 1) \cup (1, 2)$ . Here, we have two connected components,  $(0, 1)$  and  $(1, 2)$

#### ⊗ Example 2.7: Middle Thirds Cantor Set

Let  $C_0 := [0, 1]$ , and given  $C_n$ , define  $C_{n+1} := \frac{1}{3} (C_n \cup (2 + C_n))$  for  $n \geq 0$ .  $C_\infty$  is totally disconnected.

### ↪ Definition 2.18: Path Component

A path component  $P(x)$  of  $x \in X$  is the largest path connected subset of  $X$  that contains  $x$ .

### ↪ Proposition 2.19

$P(x) = \{x \in X : \exists \text{ continuous path } \gamma : [0, 1] \rightarrow X : \gamma(0) = x, \gamma(1) = y\}$ .

**Remark 2.12.** Where we “start” a path does not matter. We write  $x \sim y$  if  $\exists \gamma$  from  $x$  to  $y$ ; this is an equivalence relation on the elements of  $X$ .

**Remark 2.13.** The choice of  $[0, 1]$  here is arbitrary; any closed interval is homeomorphic.

### ↪ Lemma 2.4

If  $P(x) \cap P(y) \neq \emptyset$ , then  $P(x) = P(y)$ .

Proof.  $P(x) \cap P(y) \neq \emptyset \implies \exists z : x \sim z \wedge y \sim z \implies x \sim y$ . ■

### ↪ Lemma 2.5

If  $A \subseteq X$  is connected, then  $\overline{A}$  is also connected.

### ↪ Lemma 2.6

Suppose  $A \subseteq X$  is both open and closed. Then, if  $C \subseteq X$  is connected and  $C \cap A \neq \emptyset$ , then  $C \subseteq A$ .

Proof. If  $A$  is both open and closed, then  $C \cap A$  is both open and closed in  $C$ . If  $C \cap A^C \neq \emptyset$ , then this is also open and closed in  $C$ . Hence, we can write  $C = (C \cap A) \cup (C \cap A^C)$ , that is, a disjoint union of two nonempty open sets, contradicting the connectedness of  $C$ . Hence,  $C \cap A^C = \emptyset$ , and so  $C \subseteq A$ . ■

### ↪ Proposition 2.20

Let  $\{C_\alpha\}_{\alpha \in I}$  be a collection of nonempty connected subspaces of  $X$  s.t.  $\forall \alpha, \beta \in I, C_\alpha \cap C_\beta \neq \emptyset$ . Then,  $\bigcup_{\alpha \in I} C_\alpha$  is connected.

### ↪ Proposition 2.21

Suppose each  $x \in X$  has a path-connected neighborhood. Then, the path components in  $X$  are the same as the connected components in  $X$ .

## 2.8.1 Cantor Staircase Function

### ↪ Definition 2.19: An Explicit Definition

Let  $x \in C : x = 0.a_1a_2a_3 \dots$  (base 3), ie  $a_j = \begin{cases} 0 \\ 2 \end{cases}$ . Define

$$f(x) = \begin{cases} \sum \frac{a_j/2}{2^j} & x \in C \\ \text{extend by continuity} & x \notin C. \end{cases}$$

That is, if  $x \notin C$ , set  $f(y) = \sup_{x \in C, x < y} f(x) = \inf_{x \in C, x > y} f(x)$ .

### ↪ Definition 2.20: Complement Definition

To construct the complement of the Cantor set, begin with  $[0, 1]$  and at a step  $n$ , we remove  $2^n$  open intervals from this interval.  $f(x)$  will be constant on each of these intervals with values  $\frac{k}{2^n}$  where  $k$  odd and  $0 < k < 2^n$ . Extend by continuity to all  $x \in C$ .

**Remark 2.14.** *Wikipedia's explanation of this is far better than whatever this definition is trying to say.*

### 3 $L^p$ SPACES

#### 3.1 Review of $\ell^p$ Norms

**Remark 3.1.** Recall that for  $1 \leq p \leq +\infty$ , we define for  $x = (x_1, \dots, x_n) \in \mathbb{R}^n$  the norm

$$\|x\|_p = (|x_1|^p + \dots + |x_n|^p)^{\frac{1}{p}}, \quad \|x\|_\infty = \max_{i=1}^n |x_i|.$$

Similarly, for infinite vector spaces, we had, for  $x = (x_1, \dots, x_n, \dots)$ , the norm

$$\|x\|_p = \left( \sum_{i=1}^{\infty} |x_i|^p \right)^{\frac{1}{p}}, \quad \|x\|_\infty = \sup_{i \geq 1} |x_i|.$$

Here, we define

$$\ell_p := \{x = (x_1, \dots, x_n) : \|x\|_p < +\infty\}.$$

#### 3.2 $\ell^p$ Norms, Hölder-Minkowski Inequalities

##### ↪ **Definition 3.1:** Hölder Conjugates

For  $1 \leq p, q \leq +\infty$ , we say that  $p, q$  are said to be *Hölder conjugates* if

$$\frac{1}{p} + \frac{1}{q} = 1.$$

**Remark 3.2.** We refer to these simply as “conjugates” throughout as no other conception of conjugate numbers will be discussed.

Further, we take by convention  $\frac{1}{\infty} = 0$ .

##### ↪ **Proposition 3.1:** Hölder’s Inequality

Let  $x = (x_1, \dots, x_n), y = (y_1, \dots, y_n) \in \mathbb{R}^n$ . Suppose  $p, q : 1 \leq p, q \leq +\infty$  are conjugate. Then,

$$\langle x, y \rangle_{\mathbb{R}^n} := \left| \sum_{i=1}^n x_i y_i \right| \leq \|x\|_p \cdot \|y\|_q$$

##### ⊗ **Example 3.1**

For the case  $p = 1$  or  $\infty$  (functionally, the same case):

↪ **Lemma 3.1**

Let  $p, q$  be conjugates, and  $x, y \geq 0$ . Then,

$$xy \leq \frac{x^p}{p} + \frac{y^q}{q}.$$

**Remark 3.3.** If the inequality holds, then, for some  $t > 0$ , let  $\tilde{x} = t^{\frac{1}{p}} \cdot x$ ,  $\tilde{y} = t^{\frac{1}{q}} y$ . Substituting  $x$  for  $\tilde{x}$  and  $y$  for  $\tilde{y}$ , we have

$$\text{LHS: } \tilde{x}\tilde{y} = t^{\frac{1}{p}}x \cdot t^{\frac{1}{q}}y = t^{\frac{1}{p}+\frac{1}{q}} \cdot xy = xy$$

$$\text{RHS: } \dots = t\left(\frac{x^p}{p} + \frac{y^q}{q}\right).$$

That is, we have

$$t \cdot xy \leq t\left(\frac{x^p}{p} + \frac{y^q}{q}\right),$$

hence, the inequality is preserved under multiplication by a positive scalar; moreover, the original inequality holds iff this “scaled” version holds. Hence, choosing  $t$  such that  $\tilde{y} = 1$  (let  $t = \left(\frac{1}{y}\right)^q$ ), it suffices to prove the lemma for  $y = 1$ .

Proof. If  $x = 0$  or  $y = 0$ , then the entire LHS becomes 0 and we are done; assume  $x, y > 0$ ; by the previous remark, assume wlog  $y = 1$ . Then, we have

$$\begin{aligned} x \cdot y \leq \frac{x^p}{p} + \frac{y^q}{q} &\iff x \cdot 1 \leq \frac{x^p}{p} + \frac{1}{q} \\ &\iff \frac{x^p}{p} - x + \frac{1}{q} =: f(x) \geq 0. \end{aligned}$$

Taking the derivative, we have

$$\begin{aligned} f'(x) &= \frac{px^{p-1}}{p} - 1 = x^{p-1} - 1 \\ p > 1 &\implies p - 1 > 0 \implies \begin{cases} f'(x) > 0 & \forall x > 1 \\ f'(x) = 0 & x = 0 \\ f'(x) < 0 & \forall 0 < x < 1 \end{cases} \end{aligned}$$

Hence,  $x = 1$  is a local minimum of the function, and thus  $f(x) \geq f(1) \forall 0 < x \leq 1$ . But  $f(1) = \frac{1^p}{p} - 1 + \frac{1}{q} = 1 - 1 = 0$ , hence  $f(x) \geq 0 \forall x \geq 0$ , as desired, and the inequality holds. ■



Proof. Assume  $\|x\|_p = \|y\|_q = 1$ . Then,

$$\begin{aligned}
\left| \sum_{i=1}^n x_i y_i \right| &\leq \sum_{i=1}^n |x_i y_i| && \text{(by triangle inequality)} \\
&\leq \sum_{i=1}^n \left| \frac{x_i^p}{p} + \frac{y_i^q}{q} \right| && \text{(by lemma 3.1)} \\
&= \frac{1}{p} \left( \sum_{i=1}^n |x_i|^p \right) + \frac{1}{q} \left( \sum_{i=1}^n |y_i|^q \right) \\
&= \frac{1}{p} \|x\|_p^p + \frac{1}{q} \|y\|_q^q && \text{(by staring)} \\
&= \frac{1}{p} \cdot 1^p + \frac{1}{q} \cdot 1^q = \frac{1}{p} + \frac{1}{q} = 1 && \text{(by assumption)} \\
&= \|x\|_p \cdot \|y\|_q,
\end{aligned}$$

and the proposition holds, in the special case  $\|x\|_p = \|y\|_q = 1$ .

If  $\|x\|_p = 0$  or  $\|y\|_q = 0$ , then  $x_1 = \dots = x_n = 0$  or  $y_1 = \dots = y_n = 0$ , resp, then we'd have ( $\|x\|_p = 0$  case)

$$0 \cdot y_1 + \dots + 0 \cdot y_n \leq 0,$$

which clearly holds.

Assume, then,  $\|x\|_p > 0, \|y\|_q > 0$ . Let  $\tilde{x} := \frac{x}{\|x\|_p}, \tilde{y} := \frac{y}{\|y\|_q}$ . Then,

$$\|\tilde{x}\|_p^p = \frac{(\sum_{i=1}^n |x_i|^p)}{\|x\|_p^p} = \frac{\|x\|_p^p}{\|x\|_p^p} = 1 \implies \|\tilde{x}\|_p = 1.$$

The same case holds for  $\tilde{y}$ , hence  $\|\tilde{y}\|_q = 1$ ; that is, we have “rescaled” both vectors. Hence, we can use the case we proved above for when the norms were identically 1 on  $\tilde{x}, \tilde{y}$ . We have:

$$\left| \sum_{i=1}^n \tilde{x}_i \tilde{y}_i \right| \leq 1$$

But by definition of  $\tilde{x}, \tilde{y}$ , we have

$$\left| \sum_{i=1}^n \tilde{x}_i \tilde{y}_i \right| = \left| \frac{1}{\|x\|_p \|y\|_q} \sum_{i=1}^n x_i y_i \right| \leq 1 \implies \left| \sum_{i=1}^n x_i y_i \right| \leq \|x\|_p \cdot \|y\|_q,$$

and the proof is complete. ■

↪ **Proposition 3.2: Minkowski Inequality**

Let  $1 \leq p \leq \infty$ ,  $x, y \in \mathbb{R}^n$ . Then,

$$\|x + y\|_p \leq \|x\|_p + \|y\|_p.$$

**Remark 3.4.** This is just the triangle inequality for  $\ell_p$  norms.

Proof. The cases  $p = 1, \infty$  are left as an exercise.

Assume  $1 < p < \infty$ . Then,

$$\begin{aligned} \|x + y\|_p^p &= \sum_{j=1}^n |x_j + y_j|^p = \sum_{j=1}^n |x_j + y_j| |x_j + y_j|^{p-1} \\ &\leq \sum_{j=1}^n (|x_j| + |y_j|) \cdot |x_j + y_j|^{p-1} \\ &= \underbrace{\sum_{j=1}^n |x_j| \cdot |x_j + y_j|^{p-1}}_{:=A} + \overbrace{\sum_{j=1}^n |y_j| \cdot |x_j + y_j|^{p-1}}^{:=B} \quad \circledast \end{aligned}$$

Let  $\vec{u} = (|x_1|, \dots, |x_n|)$  and  $\vec{v} = (|x_1 + y_1|^{p-1}, \dots, |x_n + y_n|^{p-1})$ , then,  $A = \vec{u} \cdot \vec{v} = \langle \vec{u}, \vec{v} \rangle_{\mathbb{R}^n}$ . We have

$$\begin{aligned} \|\vec{u}\|_p &= \left( \sum_{i=1}^n (|x_i|^p) \right)^{\frac{1}{p}} = \|x\|_p \\ \|\vec{v}\|_q &= \left( \sum_{i=1}^n (|x_i + y_i|^{p-1})^q \right)^{\frac{1}{q}} \\ &= \left[ \sum_{i=1}^n (|x_i + y_i|^{p-1})^{\frac{p}{p-1}} \right]^{\frac{p-1}{p}} \\ &= \left[ \sum_{i=1}^n |x_i + y_i|^p \right]^{\frac{p-1}{p}} \\ &= \|x + y\|_p^{p-1} \end{aligned}$$

where the second-to-last line follows from  $p, q$  being conjugate, hence  $q = \frac{p}{p-1}$ . Thus, by Hölder's Inequality, we have that

$$A = \langle \vec{u}, \vec{v} \rangle \leq \|\vec{u}\|_p \cdot \|\vec{v}\|_q = \|x\|_p \cdot \|x + y\|_p^{p-1}.$$

By a similar construction, we can show that

$$B \leq \|y\|_p \cdot \|x + y\|_p^{p-1}.$$

Thus, returning to our original inequality in  $\circledast$ , we have

$$\begin{aligned} \|x + y\|_p^p &\leq A + B \\ &\leq \|x\|_p \cdot \|x + y\|_p^{p-1} + \|y\|_p \cdot \|x + y\|_p^{p-1} \\ &\implies \|x + y\|_p \leq \|x\|_p + \|y\|_p, \end{aligned}$$

and the proof is complete. ■

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### 3.3 Complete Metric Spaces, Completeness of $\ell_p$

#### ↪ **Theorem 3.1**

The sequence of centers of balls with monotonically decreasing radii is a Cauchy sequence in  $X$ .

Proof. Let  $\varepsilon > 0$  and let  $N : \forall j > N, r_j < \varepsilon$ . Then,

$$d(x_j, x_k) < r_{\min(j,k)} = r_j$$
■

#### ↪ **Definition 3.2: Complete Metric Space**

A metric space is complete if every Cauchy sequence converges to a limit in that space.

#### $\circledast$ **Example 3.2: Examples of Complete Metric Spaces**

1.  $\mathbb{R}$ ,  $p$ -adic integers  $(\mathbb{Z}_p)/\text{rationals}(\mathbb{Q}_p)$ .
2.  $\ell_p = \{x = (x_i)_{i=1}^\infty : \sum_{i=1}^\infty |x_i|^p < +\infty\}, 1 \leq p \leq +\infty$
3.  $\ell_\infty = \{x = (x_i) : \sup_{i=1}^\infty |x_i| < +\infty\}$ .

#### ↪ **Proposition 3.3**

Hölder's Inequality and Minkowski Inequality inequalities hold for infinite sequences. that is,

1. if  $x = (x_i) \in \ell_p$  and  $y = (y_i) \in \ell_q$  with  $\frac{1}{p} + \frac{1}{q} = 1$ , then

$$\left| \sum_{i=1}^\infty x_i y_i \right| \leq \|x\|_{\ell_p} \|y\|_{\ell_q}.$$

2. if  $x, y \in \ell_p$ , then

$$\|x + y\|_p \leq \|x\|_p + \|y\|_p.$$

**Remark 3.5.** 2. gives the triangle inequality for the  $\|x\|_p$  norm on  $\ell_p$ .

Moreover,

$$\begin{aligned}\|c \cdot x\|_p &= \|(c_1 x_1, \dots, c_n x_n, \dots)\|_p \\ &= \left( \sum_{i=1}^{\infty} |c x_i|^p \right)^{\frac{1}{p}} = \left( \sum_{i=1}^{\infty} |c|^p |x_i|^p \right)^{\frac{1}{p}} \\ &= (|c|^p)^{\frac{1}{p}} \|x\|_p = c \cdot \|x\|_p\end{aligned}$$

Proof. (of 2.) If  $x, y \in \ell_p$ , we have that  $\sum_{i=1}^{\infty} |x_i|^p < +\infty$ ,  $\sum_{i=1}^{\infty} |y_i|^p < +\infty$ , so  $\exists N > 0 : \sum_{i=N+1}^{\infty} |x_i|^p < \varepsilon$ ,  $\sum_{i=N+1}^{\infty} |y_i|^p < \varepsilon$ . Let  $x_i^{(n)} = (x_1, \dots, x_n, 0, 0, \dots)$  be  $(x)$  truncated after  $n$  (finite) coordinates. This gives

$$\|(x_i + y_i)^{(n)}\|_p \leq \|x_i^{(n)}\|_p + \|y_i^{(n)}\|_p \leq \|x\|_p + \|y\|_p$$

by Minkowski on finite spaces. Taking  $n \rightarrow \infty$  (ie, “detruncating”), we have  $(x + y) \in \ell_p$ , and thus  $\|x + y\|_p \leq \|x\|_p + \|y\|_p$ .

1. left as an exercise. ■

#### ↪ Proposition 3.4

Let  $1 \leq p \leq +\infty$ , and  $\|x\|_{\infty} = \sup_{i=1}^{\infty} |x_i| = A < +\infty$ ,  $\|y\|_{\infty} = \sup_{i=1}^{\infty} |y_i| = B < +\infty$ . Then, the triangle inequality  $\|x + y\|_{\infty} \leq \|x\|_{\infty} + \|y\|_{\infty}$  holds.

Proof. We have

$$\sup_{i=1}^{\infty} |x_i + y_i| \leq \sup_{i=1}^{\infty} (|x_i| + |y_i|) \leq \sup_{i=1}^{\infty} |x_i| + \sup_{i=1}^{\infty} |y_i| = \|x\|_{\infty} + \|y\|_{\infty}.$$

#### ↪ Proposition 3.5

$\|x\|_{\infty} := \sup_{i=1}^{\infty} |x_i|$  is a well-defined norm on  $\ell_{\infty}$ .

Proof. The triangle inequality is prove in proposition 3.4. The remainder of the requirements are left as an exercise. ■

#### ↪ Proposition 3.6

$\ell_p \subseteq \ell_q$  if  $p < q$ .

Proof. Let  $x \in \ell_p$ . If  $\sum_{i=1}^{\infty} |x_i|^p < +\infty$ , then  $\exists N : \forall i \geq N, |x_i| \leq 1$ . Then,

$$\begin{aligned} \sum_{i \geq N} |x_i|^q &\leq \sum_{i \geq N} |x_i|^p < \infty \\ \Rightarrow \sum_{i=1}^{\infty} |x_i|^q < +\infty &\Rightarrow x \in \ell_q \\ &\Rightarrow \ell_p \subseteq \ell_q \end{aligned}$$

■

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### 3.4 Contraction Mapping Theorem

#### ↪ Definition 3.3: Contraction Mapping

Let  $(X, d)$  be a metric space. A *contraction mapping* on  $X$  is a function  $f : X \rightarrow X$  for which  $\exists$  a constant  $0 < c < 1$  such that

$$d(f(x), f(y)) \leq c \cdot d(x, y) \quad \forall x, y \in X.$$

#### ↪ Theorem 3.2: Contraction Mapping Theorem

Let  $(X, d)$  be a complete metric space, and let  $f : X \rightarrow X$  be a contraction. Then, there exists a unique fixed point  $z$  of  $f$  such that  $f(z) = z$ .

Moreover,  $f^{[n]}(x) := f \circ f \circ \dots \circ f(x) \rightarrow z$  as  $n \rightarrow \infty$  for any  $x \in X$ .

**Remark 3.6.** The “functional construction” of the Cantor set is an example of a contraction mapping, with  $f_1(x) = \frac{x}{3}$ ,  $f_2(x) = \frac{x+2}{3}$ . The first has a fixed point of 0, and the second a fixed point of 1.

**Remark 3.7.** This is a generalization of [this proof](#) done in Analysis I, an equivalent claim over the reals.

Proof. Fix  $x \in X$ . Consider the sequence  $\{x_0, x_1, x_2, \dots, x_n, \dots\} := \{x, f(x), f \circ f(x), \dots, f^{[n]}(x), \dots\}$  (we call  $f^{[n]}$  the *orbit* of  $x$  under iterations of  $f$ ). We claim that this is a Cauchy sequence. Let  $n \in \mathbb{N}$  arbitrary, then we have, by the property of the contraction mapping,

$$d(f^{[n+1]}(x) - f^{[n]}(x)) \leq c \cdot d(f^{[n]}(x) - f^{[n-1]}(x)) \leq c^2 d(f^{[n-1]}(x) - f^{[n-2]}(x)).$$

Arguing inductively, it follows that

$$d(f^{[n+1]}(x) - f^{[n]}(x)) \leq c^n d(f(x), x). \quad \star$$

Let now  $m, k \in \mathbb{N}, m, k > 0$ . It follows that

$$\begin{aligned} d(f^{[m]}, f^{[m+k]})(x) &\leq d(f^{[m]}(x), f^{[m+1]}(x)) + d(f^{[m+1]}(x), f^{[m]}(x)) + \dots + d(f^{[m+k-1]}(x), f^{[m+k]}(x)) \\ &\stackrel{\star}{\leq} d(x, f(x)) [c^m + c^{m+1} + \dots + c^{m+k-1}] \\ &\leq c^m d(x, f(x)) [1 + c + \dots + c^k + c^{k+1} + \dots] = \frac{c^m d(x, f(x))}{1 - c} \end{aligned}$$

Now, given  $\varepsilon > 0$ , choose  $N$  such that  $\frac{c^N d(x, f(x))}{1 - c} < \varepsilon$ . It follows, then, that  $\{f^{[n]}(x)\}_{n \in \mathbb{N}}$  a Cauchy sequence, and thus converges,  $f^{[n]}(x) \rightarrow z$  as  $n \rightarrow \infty$  for some  $z$ .

We further have to show that  $f(z) = z$ . It is easy to show that  $f$  continuous due to the contraction mapping (it is clearly Lipschitz with constant  $c$ ), and it thus follows that

$$\lim_{n \rightarrow \infty} f(f^{[n]}(x)) = \lim_{n \rightarrow \infty} f^{[n+1]}(x) \implies f(z) = z,$$

by sequential characterization of continuous functions.

Finally, we need to show that this limit is unique. Suppose  $\exists y_1 \neq y_2$ , ie two fixed points with  $f(y_1) = y_1$  and  $f(y_2) = y_2$ . Then, by the property of the contraction mapping,

$$d(f(y_1), f(y_2)) \leq c \cdot d(y_1, y_2),$$

but by assumption of being fixed points,

$$d(f(y_1), f(y_2)) = d(y_1, y_2),$$

implying  $d(y_1, y_2) \leq c \cdot d(y_1, y_2)$ . This is only possible if  $d(y_1, y_2) = 0$ , and thus  $y_1 = y_2$  and the fixed point is indeed unique. ■

### ↪ **Theorem 3.3:** $\ell_p$ complete

The space  $\ell_p$  is complete for all  $1 \leq p \leq +\infty$ .

Equivalently, if  $(x^1), (x^2), \dots, (x^n)$  is a Cauchy sequence in  $\ell^p$ ,  $\exists y \in \ell^p$  s.t.  $x^n \rightarrow y$  as  $n \rightarrow \infty$ .

Proof. (Sketch) We suppose first  $p < +\infty$ . Consider an arbitrary number of Cauchy sequences in  $\ell_p$ :

$$\begin{aligned} x^{(1)} &= (x_1^{(1)}, \dots, x_n^{(1)}, \dots) \\ x^{(2)} &= (x_1^{(2)}, \dots, x_n^{(2)}, \dots) \\ &\vdots \quad \vdots \quad \vdots \\ x^{(k)} &= (x_1^{(k)}, \dots, x_n^{(k)}, \dots) \in \ell_p \end{aligned}$$

We claim that, for any  $k \in \mathbb{N}$ , the  $(x_k^{(n)})_{n \in \mathbb{N}}$  is a Cauchy sequence; note that in this definition we are taking a *fixed-index* (namely, the  $k$ th) element from different sequences (namely, the  $n$ th sequence).

Since  $x^{(1)}, x^{(2)}, \dots, x^{(n)}, \dots$  are Cauchy sequences in  $\ell^p$ , we have for a fixed  $\varepsilon > 0$ ,  $\exists N \in \mathbb{N} : \forall m, n > N$ ,  $d_p(x^{(m)}, x^{(n)}) < \varepsilon$ :

$$\begin{aligned} d_p(x^{(m)}, x^{(n)})^p &= \|x^{(m)} - x^{(n)}\|_p^p = \sum_{i=1}^{\infty} |x_i^{(m)} - x_i^{(n)}|^p < \varepsilon^p \\ |x_k^{(m)} - x_k^{(n)}|^p &\leq \sum_{i=1}^{\infty} |x_i^{(m)} - x_i^{(n)}|^p \implies |x_k^{(m)} - x_k^{(n)}|^p < \varepsilon^p \\ &\implies |x_k^{(m)} - x_k^{(n)}| < \varepsilon, \end{aligned}$$

since we are taking “less of the summands in the second line”. It follows, then, that for each  $k$ ,  $\exists z_k : x_k^{(n)} \rightarrow z_k$  as  $n \rightarrow \infty$ . Let  $z = (z_1, \dots, z_n, \dots)$ . We claim that  $x^{(n)} \rightarrow z \in \ell_p$  as  $n \rightarrow \infty$ .

First, we show that  $d_p(x^{(n)}, z) \rightarrow 0$  as  $n \rightarrow \infty$  (that is,  $x^{(n)} \rightarrow z$  as  $n \rightarrow \infty$ ). Fix  $\varepsilon > 0$ , and choose  $N \in \mathbb{N}$  for which  $d_p(x^{(m)}, x^{(n)}) < \varepsilon \forall m, n \geq N$  (by Cauchy). Fix  $K \in \mathbb{N}, K > 0$ .

$$\begin{aligned} d_p^p(x^{(n)}, z) &= \|x^{(n)} - z\|_p^p = \sum_{i=1}^{\infty} |x_i^{(n)} - z_i|^p \\ \|x^{(m)} - x^{(n)}\|_p^p < \varepsilon^p &\implies \sum_{i=1}^K |x_i^{(m)} - x_i^{(n)}|^p \leq \varepsilon^p \end{aligned}$$

Let  $m \rightarrow \infty$ ; then  $x_i^{(m)} \rightarrow z_i$  (note that  $i$  fixed!), and we have

$$\sum_{i=1}^K |z_i - x_i^{(n)}|^p \leq \varepsilon^p.$$

Let  $K \rightarrow \infty$ ; then,

$$\sum_{i=1}^{\infty} |z_i - x_i^{(n)}|^p \leq \varepsilon^p \implies \|z - x^{(n)}\|_p \leq \varepsilon \implies d_p(z, x^{(n)}) \leq \varepsilon,$$

and thus  $x^{(n)} \rightarrow z$  as  $n \rightarrow \infty$ .

It remains to show that  $z \in \ell_p$ , ie  $\|z\|_p < +\infty$ . We have:

$$\|z\|_p \leq \underbrace{\|z - x^{(n)}\|_p}_{\rightarrow 0} + \|x^{(n)}\|_p.$$

For sufficiently large  $n$ ,  $\|z - x^{(n)}\| \leq 1$  (for instance);  $x^{(n)} \in \ell_p$ , hence  $\|x^{(n)}\|_p < +\infty$  (say,  $\|x^{(n)}\|_p \leq M$ ). Thus:

$$\|z\|_p \leq 1 + M < +\infty \implies z \in \ell_p,$$

and the proof is complete. ■

### 3.5 Equivalent Notions of Compactness in Metric Spaces

#### ↪ Definition 3.4: Totally Bounded

Let  $(X, d)$  be a metric space. If for every  $\varepsilon > 0$ ,  $\exists x_1, \dots, x_n \in X, n = n(\varepsilon) : \bigcup_{i=1}^n B(x_i, \varepsilon) = X$ , we say  $X$  is *totally bounded*.

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#### ↪ Theorem 3.4

Let  $(X, d)$  be a metric space. TFAE:

1.  $X$  is complete and totally bounded;
2.  $X$  is compact;
3.  $X$  is sequentially compact (every sequence has a convergent subsequence).

Proof. (1.  $\implies$  2.) Suppose  $X$  complete and totally bounded. Assume towards a contradiction that  $X$  not compact, ie there exists an open cover  $\{U_\alpha\}_{\alpha \in I}$  of  $X$  with no finite subcover.

$X$  being totally bounded gives that it can be covered by finitely many open balls of radius  $\frac{1}{2}$ . It must be that at least one of these open balls cannot be finitely covered, otherwise we would have a finite subcover. Let  $F_1$  be the closure of this ball.  $F_1$  closed, with diameter  $\text{diam}(F_1) \leq 1$ .  $X$ .

We also have that  $X$  can be covered by finitely many balls of radius  $\frac{1}{4}$ ; again, there must be at least one ball  $B_1$  such that  $B_1 \cap F_1$  cannot be covered by finitely many open sets from the cover. Let  $F_2 = \overline{B_1} \cap F_1$ -closed, with  $\text{diam}(F_2) \leq \frac{1}{4} + \frac{1}{4} = \frac{1}{2}$ .<sup>4</sup>

Arguing inductively, at some step  $n$ ,  $X$  can be covered by finitely many balls of radius  $\frac{1}{2^n}$ ; at least one of these balls  $B$  cannot be covered by a finite subcover hence  $B \cap F_{n-1}$  cannot be covered by finitely many  $U_\alpha$ 's. Let  $F_n = \overline{B} \cap F_{n-1}$ -closed, with  $\text{diam}(F_n) \leq \frac{1}{2^{n-1}}$ .

As such, we have a nested sequence  $F_1 \supseteq F_2 \supseteq \dots \supseteq F_n \supseteq \dots$  of closed sets, where  $\text{diam}(F_k) \leq \frac{1}{2^{k-1}} \rightarrow 0$  as  $k \rightarrow \infty$ .

#### ↪ Lemma 3.1 (Cantor Intersection Theorem). $\bigcap_{k=1}^{\infty} F_k \neq \emptyset$ .

Proof. (Of Lemma) Let  $x_k \in F_k$ . Then,  $\{x_k\}_{k \in \mathbb{N}}$  is a Cauchy sequence, since

$$d(x_n, x_{n+k}) \leq \text{diam}(F_n) + \dots + \text{diam}(F_{n+k}) \leq \frac{1}{2^{n-1}},$$

by the nested property, which can be made arbitrarily small for sufficiently large  $n, k$ . Hence,  $x_n \rightarrow y \in X$  for some  $y$ , as  $X$  complete. The tail of  $x_n$  lies in  $F_n$  for all sufficiently large  $n$ , and as each  $F_n$  closed, the limit must lie in  $F_n$  for all sufficiently large  $n$ . We conclude the intersection nonempty. ■

<sup>4</sup> $B_1$  has radius  $\frac{1}{4}$  and hence diameter  $\frac{1}{2}$ . The intersection of  $B_1$  with a set with a larger diameter must have diameter  $\leq \frac{1}{2}$



This  $y$  from the lemma is covered by some  $U_{\alpha_0}$ -open for some  $\alpha_0 \in I$ . Being open,  $\exists \varepsilon > 0 : B(y, \varepsilon) \subseteq U_{\alpha_0}$ . Let  $n : \frac{1}{2^{n-1}} < \varepsilon$ . Then,  $y \in F_n$ , and as  $\text{diam}(F_n) \leq \frac{1}{2^{n-1}}$ , we have that  $F_n \subseteq B(y, \frac{1}{2^{n-1}}) \subseteq B(y, \varepsilon) \subseteq U_{\alpha_0}$ . But then, we have that  $F_n$  covered by a single open set  $U_{\alpha_0}$ , a contradiction to our inductive construction of  $F_n$ . We conclude  $X$  compact.

(2.  $\implies$  3.) Suppose  $X$  compact. Let  $\{x_n\}_{n \in \mathbb{N}} \in X$ . Let  $F_n = \overline{\bigcup_{k \geq n} \{x_k\}}$ -closed; we have too that  $F_1 \supseteq F_2 \supseteq \dots \supseteq F_n \supseteq \dots$ .

### ↪ Definition 3.5: Finite Intersection Property

$\mathcal{F}$  has finite intersection property provided any finite subcollection of sets in  $\mathcal{F}$  has a non-empty intersection.

↪ Lemma 3.2 (Finite Intersection Formulation of Compactness).  $X$ -compact  $\iff$  every collection  $\mathcal{F}$  of closed subsets of  $X$  with finite intersection property has non-empty intersection.

Proof. ■

This lemma directly gives that  $\bigcap_{n=1}^{\infty} F_n \neq \emptyset$ ,  $\{F_n\}_{n \in \mathbb{N}}$  being a collection of closed subsets with any subset having nonempty intersection (by the nestedness). Let  $y \in \bigcap_{n=1}^{\infty} F_n$ . Take  $B(y, \frac{1}{k})$ , which thus has nonempty intersection with  $\{x_k\}_{k \geq n} \forall n$ , ie  $\exists n_1 : d(y, x_{n_1}) < 1$  and  $\exists n_2 > n_1 : d(y, x_{n_2}) < \frac{1}{2}$ . Arguing inductively,  $\exists n_j > n_{j-1} : d(y, x_{n_j}) < \frac{1}{j}$  for any given  $n_{j-1}$ . It follows that  $\lim_{j \rightarrow \infty} x_{n_j} = y$ , and thus  $\{x_{n_j}\}$  is a convergent subsequence of  $\{x_n\}$  that converges within  $X$ , and thus  $X$  is sequentially compact.

(3.  $\implies$  1.) Suppose  $X$  sequentially compact. Let  $\{x_n\} \in X$  be a Cauchy sequence in  $X$ , which thus have a convergent subsequence  $\{x_{n_k}\} \rightarrow y$ .

↪ Lemma 3.3. Let  $\{x_n\}$  be a Cauchy sequence in  $X$  where  $X$  sequentially compact. Then, if  $\{x_{n_k}\} \rightarrow y$ , so does  $\{x_n\} \rightarrow y$

Proof. ■

Then,  $\{x_n\}_n \rightarrow y$  and so  $X$  complete.

Suppose  $X$  not totally bounded, ie  $\exists \varepsilon > 0 : X$  cannot be covered by a finite union of balls of  $B(x_j, \varepsilon)$ . Let  $x_1 \in X$  s.t.  $B(x_1, \varepsilon) \not\supseteq X$ ;  $\exists x_2 \in X \setminus B(x_1, \varepsilon)$ , and so  $X \not\subseteq B(x_1, \varepsilon) \cup B(x_2, \varepsilon)$  by assumption. Then, choose  $x_3 \in X \setminus (B(x_1, \varepsilon) \cup B(x_2, \varepsilon))$ . Arguing inductively, we have that  $\exists x_n \in X \setminus (\bigcup_{i=1}^n B(x_i, \varepsilon))$ , noting that  $d(x_n, x_j) \geq \varepsilon \forall 1 \leq j \leq n$ .

Consider the sequence  $\{x_j\}_{j \in \mathbb{N}}$ :

↪ Lemma 3.4.  $\{x_j\}$  cannot have a convergent subsequence.

Proof. Follows by  $d(x_m, x_n) \geq \varepsilon \forall m, n$ . ■

This contradicts our assumption that  $X$  sequentially compact, and we conclude  $X$  must be totally bounded. ■

⊗ **Example 3.3: Complete Metric Space Example:  $L^p$  norm**

Let  $f \in C([a, b])$ . We define the norm

$$\|f\|_p := \left( \int_a^b |f(x)|^p dx \right)^{\frac{1}{p}}.$$

As desired,  $\|f\|_p \geq 0$ ;  $\|f\|_p = 0 \iff f \equiv 0$ ;  $\|c \cdot f\|_p = c \cdot \|f\|_p$ .

Hölder's and Minkowski's inequalities for functions also hold; for  $\frac{1}{p} + \frac{1}{q} = 1$ ,  $1 \leq p, q \leq \infty$ ,

$$\int |fg| \leq \|f\|_p \cdot \|g\|_q; \quad \|f + g\|_p \leq \|f\|_p + \|g\|_p,$$

respectively.

We similarly have the  $L^\infty$  norm, namely, for a function  $f : [a, b] \rightarrow \mathbb{R}$ ,

$$\|f\|_\infty = \sup_{x \in [a, b]} |f(x)|,$$

which obeys all the necessary properties as well.

Let  $f_n \rightarrow f$  in  $C([a, b])$ , wrt  $\|\cdots\|_\infty$ , where  $\{f_n\}_{n \in \mathbb{N}}$  a sequence of functions. Namely, we say that

$$\forall \varepsilon > 0, \exists N \in \mathbb{N} : \forall n \geq N, \sup_{x \in [a, b]} |f_n(x) - f(x)| < \varepsilon.$$

If this holds, we say that  $f_n$  *uniformly converges*.

We say that  $f_n(x) \rightarrow f(x)$  *pointwise* on  $[a, b]$  if  $\forall x \in [a, b], f_n(x) \rightarrow f(x)$ . Note that uniform convergence implies pointwise convergence, but not the converse.

↪ **Theorem 3.5**

Suppose  $f_n(x)$  continuous, and  $f_n(x) \rightarrow f(x)$  uniformly on  $[a, b]$ . Then,  $f(x)$  also continuous on  $[a, b]$ .

Proof. Fix  $\varepsilon > 0, x_0 \in [a, b]$ . We have that  $\exists N : n \geq N, |f_n(x) - f(x)| < \frac{\varepsilon}{3}, \forall x \in [a, b]$ .

Let  $n \geq N$ .  $f_n(x)$  continuous at  $x_0$ , hence  $\exists \delta(x_0) > 0 : |y - x_0| \implies |f_n(y) - f_n(x_0)| < \frac{\varepsilon}{3}$ . We have

$$\begin{aligned} |f(x_0) - f(y)| &\leq |f(x_0) - f_n(x_0)| + |f_n(x_0) - f_n(y)| + |f_n(y) - f(y)| \\ &\leq \frac{\varepsilon}{3} + \frac{\varepsilon}{3} + \frac{\varepsilon}{3} = \varepsilon, \end{aligned}$$

completing the proof. ■

**Remark 3.8.** This does not hold with pointwise convergence.

**Remark 3.9.** We will prove later that  $C([a, b])$  is complete for  $\|f\|_\infty$ , but not for arbitrary  $\|f\|_p$ ,  $1 \leq p < +\infty$ . To “complete”  $C([a, b])$  for  $p \neq \infty$ , we will need to consider measurable functions and redefine our notion of integration.

↪ Lecture 11; Last Updated: Thu Feb 8 09:51:13 EST 2024

## 4 DERIVATIVES

### 4.1 Introduction

#### ↪ Definition 4.1: Differentiable

We say  $f(x)$  differentiable at  $c$  if  $\exists \lim_{x \rightarrow c} \frac{f(x) - f(c)}{x - c}$ . If so, we denote the limit  $f'(c)$ .

**Remark 4.1.** For  $x$  close to  $c$ , then  $f(x) \approx f(c) + f'(c)(x - c)$ ; this is a linear approximation of  $f$  at  $c$ .

#### ⊗ Example 4.1: Weierstrass

$f(x) = \sum_{n=1}^{\infty} \frac{\cos(3^n)x}{2^n}$  is continuous in  $\mathbb{R}$ , but nowhere differentiable.

#### ↪ Definition 4.2

The derivative,  $dx$ , is a linear map  $C([a, b]) \rightarrow C^0([a, b])$ .

### 4.2 Chain Rule

**Remark 4.2.** See [Analysis I notes](#) as well.

#### ↪ Theorem 4.1: Caratheodory's Theorem

Let  $f : I \rightarrow \mathbb{R}$ ,  $c \in I$ .  $f$  is differentiable at  $x = c$  iff  $\exists \varphi(x) : I \rightarrow \mathbb{R}$  s.t.  $\varphi$  continuous at  $c$  and  $f(x) - f(c) = \varphi(x)(x - c)$ .<sup>5</sup>

Proof. If  $f'(c)$  exists, let

$$\varphi(x) = \begin{cases} \frac{f(x) - f(c)}{x - c} & x \neq c \\ f'(c) & x = c. \end{cases},$$

which is well defined. Moreover, for  $x \neq c$ ,  $\varphi(x)(x - c) = \frac{f(x) - f(c)}{x - c}(x - c) = f(x) - f(c)$  as desired; the case for  $x = c$  is clear. Continuity at  $c$ :

$$\lim_{x \rightarrow c} \varphi(x) = \lim_{x \rightarrow c} \frac{f(x) - f(c)}{x - c} = f'(c) = \varphi(c).$$

<sup>5</sup>If not stated otherwise, sets named  $I$  or  $J$  are intervals.

Conversely, suppose such a  $\varphi$  exists. Then, by continuity,

$$\exists \varphi(c) = \lim_{x \rightarrow c} \varphi(x) = \lim_{x \rightarrow c} \frac{f(x) - f(c)}{x - c}$$

which gives directly that  $f$  differentiable at  $c$ . ■

#### ↪ **Theorem 4.2: Chain Rule**

Let  $f : J \rightarrow \mathbb{R}, g : I \rightarrow \mathbb{R}, f(J) \subseteq I$ . If  $f(x)$  differentiable at  $c$  and  $g(y)$  is differentiable at  $y = f(c)$ , then  $g \circ f(x)$  is also differentiable at  $c$ , and

$$(g \circ f)'(c) = g'(f(c))f'(c).$$

*Proof.* Using Caratheodory's Theorem,  $\exists \varphi : f(x) - f(c) = \varphi(x)(x - c)$  with  $\varphi(c) = f'(c)$ . Let  $d = f(c)$ , then similarly  $\exists \psi : g(y) - g(d) = \psi(y)(y - d)$  with  $\psi(d) = g'(d)$ , with  $\varphi, \psi$  continuous at  $c, d$  resp. Then,

$$g(f(x)) - g(f(c)) = \psi(f(x))(f(x) - f(c)) = (\psi \circ f)(x) \cdot (\phi(x)(x - c))$$

$\psi \circ f$  is continuous at  $c$ , as a composition of continuous functions ( $\psi, \phi$  continuous by construction,  $f$  differentiable and thus continuous). It follows, then, that

$$\lim_{x \rightarrow c} \frac{g(f(x)) - g(f(c))}{x - c} = \lim_{x \rightarrow c} (\psi \circ f)(x) \cdot \varphi(x) = \psi(f(c))\varphi(c) = g'(f(c)) \cdot f'(c),$$

by construction. ■

## 4.3 Critical Points

#### ↪ **Definition 4.3**

$f : I \rightarrow \mathbb{R}$  has a max/min  $c$  if  $\exists J \subseteq I : x \in J$  s.t.  $\max_{x \in J} f(x)/\min_{x \in J} f(x) = f(c)$ .

#### ↪ **Theorem 4.3: Rolle's**

Let  $f : [a, b] \rightarrow \mathbb{R}$  continuous. Suppose  $f'(x)$  exists for all  $x \in (a, b)$  and  $f(a) = f(b) = 0$ . Then,  $\exists c \in (a, b) : f'(c) = 0$ .

**Remark 4.3.** A “complex-version” of Rolle's:

#### ↪ **Theorem 4.4: Gauss-Lucas**

Let  $P(z)$  be a complex-valued polynomial. Then, the roots of  $P'(z)$  lie inside the convex hull of roots of  $P(z)$ , where a convex hull is the smallest polygon with vertices at the roots of  $P(z)$ .

#### ↪ Definition 4.4

Consider  $P(z) = z^n - 1$  for some  $n \in \mathbb{N}$ . If  $z$  a root, we can show that  $(|z|)^n = 1$ , hence all roots lie on the unit circle in the complex plane at multiples of the same angle. This gives us a regular  $n$ -gon in the complex plane. We then have that  $P'(z) = nz^{n-1}$ , with has root  $z = 0$ , which clearly lies within the  $n$ -gon hull.

#### ↪ Theorem 4.5: Mean Value

Let  $f$  be continuous on  $[a, b]$  and differentiable on  $(a, b)$ . Then,  $\exists c \in (a, b)$  s.t.  $f(b) - f(a) = f'(c)(b - a)$ .

*Proof.* Let  $\varphi(x) = f(x) - f(a) = \frac{f(b)-f(a)}{(b-a)}(x - a)$ , where  $\varphi(a) = 0 = \varphi(b)$ . By Rolle's theorem,  $\exists c \in (a, b) : \varphi'(c) = 0 = f'(c) - \frac{f(b)-f(a)}{(b-a)}$ , as desired. ■

↪ Lecture 12; Last Updated: Thu Feb 15 09:47:18 EST 2024

## 4.4 Aside: Continued Fractions

We have that, for any  $x \in \mathbb{R}$ ,  $x = \lfloor x \rfloor + \{x\}$ , with  $\{x\} \in (0, 1)$ ;  $\lfloor x \rfloor$  and  $\{x\}$  are the integral and fractional parts of  $x$  respectively.

Fix  $x \in \mathbb{R}$ , assuming  $x \neq 0$ .

Let  $x_1 := \frac{1}{\{x\}}$ . We can write

$$x = \lfloor x \rfloor + \frac{1}{x_1}.$$

If  $\{x_1\} \neq 0$ , let  $x_2 := \frac{1}{\{x_1\}}$  and write

$$x = \lfloor x \rfloor + \frac{1}{\lfloor x_1 \rfloor + \frac{1}{x_2}}.$$

Continuing in this manner, this process stops if  $\{x_i\} = 0$  for some  $i$ ; if  $x \in \mathbb{Q}$ , this process will stop, else, it will continue infinitely. For instance, the Golden Ratio  $x = \frac{\sqrt{5}+1}{2}$  has continued fraction expansion

$$x = \frac{1}{1 + \frac{1}{1 + \frac{1}{\ddots}}}$$

More succinctly, we can denote  $a_0 := \lfloor x \rfloor$  and  $a_i = \lfloor x_i \rfloor, i \geq 1$ , and write

$$x = a_0 + \frac{1}{a_1 + \frac{1}{a_2 + \frac{1}{a_3 + \ddots}}}$$

We notate, accordingly,  $x := (a_1, a_2, a_3, \dots)$ ; in this case, the Golden Ratio can be notated  $(1, 1, 1, \dots)$ .

We denote  $\frac{p_n}{q_n}$  as the  $n$ th continued fraction of a given  $x$ . It turns out that this is the best possible rational approximation for  $x \notin \mathbb{Q}$ .

## 4.5 Back To Derivatives

### ↪ Theorem 4.6

$f : I \rightarrow \mathbb{R}$ , differentiable.  $f$  is increasing (resp decreasing) iff  $f'(x) \geq 0 \forall x \in I$  (resp  $f'(x) \leq 0 \forall x \in I$ ).

### ↪ Proposition 4.1

Let  $f$  continuous on  $I = [a, b]$ . Let  $a < c < b$  and suppose  $f$  differentiable on  $(a, c)$  and  $(c, b)$ . Suppose  $f'(x) \geq 0$  on  $(c - \delta, c)$  and  $f'(x) \leq 0$  on  $(c, c + \delta)$  for some  $\delta > 0$ . Then,  $f$  has local max at  $x = c$ .

### ↪ Lemma 4.1

Let  $I \subseteq \mathbb{R}$ , and assume  $f : I \rightarrow \mathbb{R}$  is differentiable at  $x = c \in I$ .

1. If  $f'(c) > 0$ , then  $\exists \delta > 0 : f(x) > f(c) \forall x \in I, x \in (c, c + \delta)$ .
2. (Reverse statement for  $f'(c) < 0$ )

### ↪ Theorem 4.7: Darboux

Suppose  $f$  differentiable on  $I := [a, b]$  and  $f'(a) < k < f'(b)$ . Then,  $\exists c \in (a, b)$  such that  $f'(c) = k$ .

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## 4.6 L'Hopital's Rules

### ↪ Proposition 4.2

Suppose  $f(x), g(x) : [a, b] \rightarrow \mathbb{R}$  with  $f(a) = g(a) = 0$ , and  $g(x) \neq 0 \forall a < x < b$ . Suppose  $f, g$  are differentiable at  $x = a$  and  $g'(a) \neq 0$ . Then,  $\lim_{x \rightarrow a^+} \frac{f(x)}{g(x)}$  exists, and moreover, it is equal to  $f'(a)g'(a)$ .

Proof.

$$\lim_{x \rightarrow a^+} \left( \frac{f(x) - f(a)}{x - a} \right) / \left( \frac{g(x) - g(a)}{x - a} \right) = \lim_{x \rightarrow a^+} \frac{f(x)}{x - a} \frac{x - a}{g(x)} = \lim_{x \rightarrow a^+} \frac{f(x)}{g(x)},$$

but the original line is simply  $\frac{f'(a)}{g'(a)}$ . ■

### ⊗ Example 4.2

$$\lim_{x \rightarrow 0} \frac{\sin x}{x} = \frac{\cos(0)}{1} = 1.$$

### ↪ **Theorem 4.8: Cauchy Mean Value**

Let  $f(x), g(x) : [a, b] \rightarrow \mathbb{R}$  where  $f, g$  continuous on  $[a, b]$  and differentiable on  $(a, b)$ . Assuming  $g'(x) \neq 0, \forall x \in (a, b)$ , then  $\exists c \in (a, b)$  such that

$$\frac{f(b) - f(a)}{g(b) - g(a)} = \frac{f'(c)}{g'(c)}.$$

### ↪ **Proposition 4.3: More General L'Hopital**

let  $-\infty \leq a < b \leq +\infty$  and  $f, g$  differentiable on  $(a, b)$ . Suppose  $\lim_{x \rightarrow a^+} f(x) = 0 = \lim_{x \rightarrow a^+} g(x)$ .

1. If  $\exists L := \lim_{x \rightarrow a^+} \frac{f'(x)}{g'(x)}$  where  $L$  some real number, then  $\lim_{x \rightarrow a^+} \frac{f(x)}{g(x)} = L$  as well.
2. If  $\exists L := \lim_{x \rightarrow a^+} \frac{f'(x)}{g'(x)}$  where  $L = +\infty$  or  $-\infty$ , then  $\lim_{x \rightarrow a^+} \frac{f(x)}{g(x)} = L$  as well.

### ↪ **Proposition 4.4**

Let  $-\infty \leq a < b \leq +\infty, f, g$  differentiable on  $(a, b)$  and  $g'(x) \neq 0 \forall x \in (a, b)$ . Suppose  $\lim_{x \rightarrow a^+} g(x) = \pm\infty$ .

1. If  $\lim_{x \rightarrow a^+} \frac{f'(x)}{g'(x)} =: L$  exists and is some finite real number, then  $\lim_{x \rightarrow a^+} \frac{f(x)}{g(x)} = L$  as well.
2. If  $\lim_{x \rightarrow a^+} \frac{f'(x)}{g'(x)} =: L$  exists and is  $\pm\infty$ , then  $\lim_{x \rightarrow a^+} \frac{f(x)}{g(x)} = L$  as well.

## 4.7 Taylor's Theorem

### ↪ **Theorem 4.9: Taylor's Theorem**

Let  $I = [a, b] \subseteq \mathbb{R}, f : I \rightarrow \mathbb{R}, f \in C^n(I)$  and suppose  $f^{(n+1)}(x)$  exists on  $(a, b)$ . Let  $x_0 \in [a, b]$ . Then, for any  $x \in [a, b], \exists c$  between  $x, x_0$  such that

$$f(x) = f(x_0) + f'(x_0)(x - x_0) + \frac{f''(x_0)}{2}(x - x_0)^2 + \cdots + \frac{f^{(n)}(x_0)}{n!}(x - x_0)^n + \frac{f^{(n+1)}(c)}{(n+1)!}(x - x_0)^{n+1}$$

### ↪ **Theorem 4.10: Relative Extrema**

<sup>6</sup>Let  $I \subseteq \mathbb{R}$  be an open interval,  $x_0 \in I$ , and  $n \geq 2$ . Suppose  $f', f'', \dots, f^{(n)}$  are continuous in a neighborhood of  $x_0$ , and  $f'(x_0) = f''(x_0) = \dots = f^{(n-1)}(x_0) = 0$  and  $f^{(n)}(x_0) \neq 0$ . Then:

1. if  $n$  is even and  $f^{(n)}(x_0) > 0$ , then  $f$  has a local minimum at  $x_0$ ;
2. if  $n$  is even and  $f^{(n)}(x_0) < 0$ , then  $f$  has a local maximum at  $x_0$ ;
3. if  $n$  is odd, then  $f$  has neither a local minimum nor maximum at  $x_0$ .

Proof. If  $n := 2m$ -even and  $f^{(2m)}(x_0) > 0$ , then  $f^{(n)}(c) > 0$  so  $f(x) - f(x_0) = f^{(2m)}(c)(x - x_0) > 0$ . ■

## 4.8 Convex Sets

### ↪ **Definition 4.5: Convex Set**

$A \subseteq V$ -vector space over  $\mathbb{R}$  is *convex* if for any  $x, y \in A$  and any  $0 \leq t \leq 1$ ,  $t \cdot x + (1 - t) \cdot y \in A$ .

### ↪ **Definition 4.6: Convex Function**

Let  $f : I \rightarrow \mathbb{R}$ .  $f$  is *convex* if  $\forall x_1, x_2 \in I$  and  $0 \leq t \leq 1$ ,

$$f((1 - t)x_1 + tx_2) \leq (1 - t)f(x_1) + tf(x_2).$$

↪ Lecture 15; Last Updated: Thu Feb 22 21:53:23 EST 2024

## 5 RIEMANN INTEGRAL

### 5.1 Introduction

#### ↪ **Definition 5.1: Partitions**

A *partition* is a division of an interval  $(a, b)$ , denoted

$$\mathcal{P} = \{a = x_0, x_1, \dots, x_{n-1}, x_n = b\}.$$

We define  $\text{diam}(\mathcal{P}) := \max_n |x_i - x_{i-1}|$ .

A *marked partition*, denoted  $\dot{\mathcal{P}}$ , is one in which, for each interval we choose some  $t_i \in (x_i, x_{i+1}]$ .

<sup>6</sup>Bartle-Sherbert, Theorem 6.4.4



↪ **Definition 5.2: Riemann Sum**

We denote

$$S(f, \dot{\mathcal{P}}) = \sum_{i=1}^n f(t_i)(x_i - x_{i-1}).$$

↪ **Definition 5.3: Riemann Integrable**

A function  $f$  is *Riemann Integrable* if  $[a, b]$  if  $S(f, \dot{\mathcal{P}}) \rightarrow L$  as  $\text{diam}(\dot{\mathcal{P}}) \rightarrow 0$  for any choice of  $t_i \in [x_i, x_{i+1}]$ .

That is,  $\forall \varepsilon > 0, \exists \delta : \text{if } \text{diam}(\mathcal{P}) < \delta, \text{ then for any choice of } t_i \in [x_i, x_{i+1}] \text{ we have } |L - S(f, \dot{\mathcal{P}})| < \varepsilon$ .

↪ **Proposition 5.1**

1. If  $L$  exists, it is unique.
2. The integral is linear in  $f(x)$ ; if  $\int_a^b f(x) dx$  and  $\int_a^b g(x) dx$  exist, then  $\int_a^b (c_1 f + c_2 g) dx = c_1 \int_a^b f dx + c_2 \int_a^b g dx$ .
3. If  $f \leq g$  are Riemann integrable on  $[a, b]$ , then  $\int_a^b f(x) dx \leq \int_a^b g(x) dx$ .

↪ **Proposition 5.2**

If  $f(x)$  integrable on  $[a, b]$ , the  $f(x)$  is bounded on  $[a, b]$ .

*Proof.* Suppose  $\int_a^b f$  exists. Let  $\varepsilon > 0$ , and  $\delta$  such that if  $\text{diam}(\dot{\mathcal{P}}) < \delta$  then  $|L - S(f, \dot{\mathcal{P}})| < \varepsilon$ . Let  $\varepsilon = 1$ . Then,  $S(f, \dot{\mathcal{P}}) \leq |L| + 1$ .

Let  $Q = \{a = x_0, \dots, x_n = b\}$  be a partition of  $[a, b]$  such that  $\text{diam}(Q) < \delta$ . Suppose towards a contradiction that  $f$  is not bounded on  $[a, b]$ . Then,  $f$  is unbounded on at least one interval  $[x_i, x_{i+1}]$ , say, on  $[x_k, x_{k+1}]$ . Let  $t_i = x_i$  for  $i \neq k$  and choose  $t_k \in [x_k, x_{k+1}]$  such that  $|f(t_k)|(x_{k+1} - x_k) > |L| + 1 + |\sum_{i \neq k} f(t_i)(x_{i+1} - x_i)|$  (which we can do by assumption of  $f$  being unbounded).

By assumption,  $|S(f, \dot{Q})| \leq |L| + 1$ , but we have that

$$S(f, \dot{Q}) = \underbrace{\sum_{i \neq k} f(t_i)(x_{i+1} - x_i)}_{:=N} + |f(t_k)|(x_{k+1} - x_k) > 2N + |L| + 1,$$

contradiction. ■

## 5.2 Cauchy Criterion

↪ **Proposition 5.3: Cauchy Criterion for Integrability**

$f \in \mathcal{R}[a, b] \iff \forall \varepsilon > 0, \exists \delta > 0$  : if  $\dot{P}$  and  $\dot{Q}$  are tagged partitions of  $[a, b]$  s.t.  $\text{diam } \dot{P} < \delta$  and  $\text{diam } \dot{Q} < \delta$ , then  $|S(f, \dot{P}) - S(f, \dot{Q})| < \varepsilon$ .<sup>7</sup>

## 5.3 Squeeze Theorem

↪ **Theorem 5.1**

Let  $f : [a, b] \rightarrow \mathbb{R}$ . Then  $\int_a^b f$  exists  $\iff \forall \varepsilon > 0, \exists \alpha_\varepsilon(x), \omega_\varepsilon(x) \in \mathcal{R}[a, b], \alpha_\varepsilon \leq f \leq \omega_\varepsilon$ , and

$$\int_a^b (\omega_\varepsilon - \alpha_\varepsilon) < \varepsilon$$

Proof. If  $f \in \mathcal{R}[a, b]$  then take  $\alpha_\varepsilon = f = \omega_\varepsilon$ .

Conversely, let  $\varepsilon > 0$ . Since  $\alpha_\varepsilon, \omega_\varepsilon \in \mathcal{R}[a, b]$ , then,  $\exists \delta > 0$  such that for any tagged partition with  $\text{diam } \dot{P} < \delta$ , then  $|S(\alpha_\varepsilon, \dot{P}) - \int_a^b \alpha_\varepsilon| < \varepsilon$  and  $|S(\omega_\varepsilon, \dot{P}) - \int_a^b \omega_\varepsilon| < \varepsilon$ , thus

$$\int_a^b \alpha_\varepsilon - \varepsilon < S(\alpha_\varepsilon, \dot{P}) \leq S(f, \dot{P}) \leq S(\omega_\varepsilon, \dot{P}) < \int_a^b \omega_\varepsilon + \varepsilon.$$

Let  $\dot{Q}$  be any other tagged partition with  $\text{diam } \dot{Q} < \delta$ ; then, the same inequality holds ie  $\int_a^b \alpha_\varepsilon - \varepsilon < S(f, \dot{Q}) < \int_a^b \omega_\varepsilon + \varepsilon$ . Subtracting one from the other, we see that

$$|S(f, \dot{P}) - S(f, \dot{Q})| < \int_a^b \omega_\varepsilon - \int_a^b \alpha_\varepsilon + 2\varepsilon < 3\varepsilon,$$

and thus  $f \in \mathcal{R}[a, b]$  by Cauchy Criterion. ■

↪ Lecture 16; Last Updated: Tue Feb 27 13:18:19 EST 2024

↪ **Lemma 5.1: BS-7.2.4**

Let  $J \subseteq [a, b]$  an interval with endpoints  $c < d$ . If

$$\varphi_J(x) := \begin{cases} 1 & x \in J \\ 0 & x \notin J \end{cases}.$$

Then,  $\varphi_J \in \mathcal{R}[a, b]$  and  $\int_a^b \varphi_J = d - c$ .

<sup>7</sup>Note that  $\mathcal{R}[a, b]$  is the set of all real-valued functions integrable on the interval  $[a, b]$ .

↪ **Theorem 5.2**

Let  $\varphi : [a, b] \rightarrow \mathbb{R}$ ,  $\varphi \in \mathcal{R}[a, b]$ ; that is, step functions are integrable.

↪ **Theorem 5.3**

$f$  continuous on  $[a, b]$  implies  $f \in \mathcal{R}[a, b]$ .

*Proof.* (Sketch)  $f$  uniform continuous; use this to construct step functions that “bound”  $f$  from above and below. Apply the squeeze theorem. ■

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↪ **Theorem 5.4: BS-7.2.7**

Monotone functions on  $[a, b]$  are integrable.

*Proof.* We show only for increasing. Let  $f : [a, b] \rightarrow \mathbb{R}$  be monotone increasing. If  $f$  constant, then it is a step function and we are done.

Otherwise,  $f(b) - f(a) > 0$ . Let  $\varepsilon > 0$  and  $q \in \mathbb{N}$  such that  $h := \frac{f(b)-f(a)}{q} < \frac{\varepsilon}{b-a}$ , effectively subdividing the  $y$ -axis into  $q$  equal-sized parts. Then, let

$$y_i := f(a) + ih, \quad 0 \leq i \leq q,$$

and take

$$A_k := f^{-1}([y_{k+1}, y_k)) = \begin{cases} \emptyset \\ \{x\} \\ I_i \end{cases}.$$

We disregard each  $A_k : A_k = \emptyset$ , and adjoin the isolated points  $\{x\}$  to the  $I_i$ 's, and hence have a partition  $\cup_k A_k = [a, b]$ . Letting  $\alpha(x) = y_{k-1}$  and  $\omega(x) = y_k$  for  $x \in A_k$ , then  $\alpha(x) \leq f(x) \leq \omega(x) \forall x \in [a, b]$  (effectively, we are created a “series of squeezes”). Then,

$$\int_a^b \omega(x) - \alpha(x) dx = \sum_{k=1}^q (y_k - y_{k-1})(x_k - x_{k-1}) = h(b - a) < \varepsilon,$$

and the proof is completed by applying the squeeze theorem. ■

↪ **Theorem 5.5: Additivity; BS-7.2.8**

Let  $f : [a, b] \rightarrow \mathbb{R}$  and  $a < c < b$ . Then,  $f \in \mathcal{R}[a, b] \iff f \in \mathcal{R}[a, c]$  and  $f \in \mathcal{R}[c, b]$ . Moreover,  $\int_a^b f(x) dx = \int_a^c f(x) dx + \int_c^b f(x) dx$ .

*Proof.* See book. Remark that this holds for finite summations of integrals as such by induction. ■

## 5.4 Fundamental Theorem of Calculus

### ↪ Definition 5.4

Call  $F(x)$  a *primitive* of  $f(x)$  if  $F$  differential and  $F'(x) = f(x)$ .

### ↪ Theorem 5.6: Fundamental Theorem of Calculus

Let  $F, f : [a, b] \rightarrow \mathbb{R}$  and  $E \subseteq [a, b]$  a finite set s.t.

1.  $F$  continuous on  $[a, b]$
2.  $F'(x) = f(x) \forall x \in [a, b] \setminus E$ ; ie they agree for all but finitely many points
3.  $f \in \mathcal{R}[a, b]$

Then,  $\int_a^b f(x) = F(b) - F(a)$ .

Proof. (Sketch) Remark first that it suffices to prove for  $E := \{a, b\}$ ; using additivity, we can subdivide any other such  $E$  into such subsets of 1 or 2 elements.

Fix  $\varepsilon > 0$  and take  $\delta > 0$  such that for any  $\dot{P}$  of  $[a, b]$  s.t.  $\text{diam } \dot{P} < \delta$ ,  $\left| S(f, \dot{P}) - \int_a^b f(x) \right| < \varepsilon$ . Applying the mean value theorem to  $F$  on each  $[x_{i-1}, x_i]$  of  $\dot{P}$ :

$$\begin{aligned} F(x_i) - F(x_{i-1}) &= F'(u_i)(x_i - x_{i-1}), \quad u_i \in [x_{i-1}, x_i] \\ &= f(u_i)(x_i - x_{i-1}) \end{aligned}$$

Hence, summing over each of these,

$$\begin{aligned} F(x_1) - \cancel{F(x_0)} + \cancel{F(x_2)} - F(x_1) + \cdots + \cancel{F(x_n)} - F(x_{n-1}) &= f(u_1)(x_1 - a) + \cdots + f(u_n)(x_n - x_{n-1}) \\ \implies F(b) - F(a) &= \sum_{i=1}^n f(u_i)(x_i - x_{i+1}) =: S(f, \dot{P}_1) \end{aligned}$$

by construction,  $\text{diam}(\dot{P}_1) < \delta$  since the only change we have made from  $\dot{P}$  is the tags, hence  $\left| S(f, \dot{P}_1) - \int_a^b f(x) \right| < \varepsilon$ . Thus,

$$\begin{aligned} \left| S(f, \dot{P}_1) - \int_a^b f(x) \right| &= \left| F(b) - F(a) - \int_a^b f(x) \right| < \varepsilon \\ \implies F(b) - F(a) &= \int_a^b f(x) \quad \text{as } \varepsilon \rightarrow 0. \end{aligned}$$

■

## 5.5 Upper and Lower Riemann Sums

### ↪ Definition 5.5: Upper/Lower Riemann Sums

For a partition  $P$ ,

- $\bar{S}(f, P) := \sum_{i=1}^n (\sup_{t \in [x_{i-1}, x_i]} f(t)) \cdot (x_i - x_{i-1})$
- $\underline{S}(f, P) := \sum_{i=1}^n (\inf_{t \in [x_{i-1}, x_i]} f(t)) \cdot (x_i - x_{i-1})$

### ↪ Proposition 5.4

For any tagged partition  $\dot{P}$ ,

$$\underline{S}(f, P) \leq S(f, \dot{P}) \leq \bar{S}(f, P).$$

Moreover,  $f \in \mathcal{R}[a, b]$  if  $\forall \varepsilon > 0, \exists \delta > 0$  s.t.  $\text{diam}(P) < \delta \implies \left| \bar{S}(f, P) - \underline{S}(f, P) \right| < \varepsilon$ .

Proof. (Sketch) Remark that this is a similar idea to saying that  $\inf = \sup \implies$  limit exists. ■

### ↪ Proposition 5.5

Let  $P_1, P_2$  be partitions of  $[a, b]$ , and let  $P_3$  be the *common refinement* of  $P_1, P_2$ . Then

$$\underline{S}(f, P_i) \leq \underline{S}(f, P_3) \leq \bar{S}(f, P_3) \leq \bar{S}(f, P_i), \quad i = 1, 2,$$

that is, the finer refinement always gives a better approximation.

## 5.6 Indefinite Integral

### ↪ Definition 5.6

For  $f \in \mathcal{R}[a, b]$  and any  $z \in [a, b]$ , define

$$F(z) := \int_a^z f(x) \, dx.$$

### ↪ Theorem 5.7

$F(z)$  continuous on  $[a, b]$ .

Proof.  $f \in \mathcal{R}[a, b] \implies f$  bounded  $\implies \exists M$  s.t.  $|f(x)| \leq M \, \forall x \in [a, b]$ , so (assuming  $z < w$ ),

$$|F(z) - F(w)| = \left| \int_a^z f(x) \, dx - \int_a^w f(x) \, dx \right| = \left| \int_z^w f(x) \, dx \right| \leq M \cdot |z - w|,$$

so taking  $w \rightarrow z$ ,  $|F(z) - F(w)| \rightarrow 0$ . ■

↪ **Theorem 5.8: Another Fundamental Theorem of Calculus**

Let  $f \in \mathcal{R}[a, b]$ ,  $f$ -continuous at  $c \in [a, b]$ . Then  $F(z)$  differentiable at  $c$  and  $F'(c) = f(c)$ .

↪ **Corollary 5.1**

If  $f(x)$  continuous on  $[a, b]$   $F'(x) = f(x) \forall x \in [a, b]$ .

↪ **Theorem 5.9: Substitution/Change of Variables**

Let  $J := [\alpha, \beta]$ ,  $\varphi : J \rightarrow \mathbb{R}$ ,  $\varphi \in C^1([a, b])$ . Suppose  $\varphi(J) \subseteq I \subseteq \mathbb{R}$ , and let  $f : I \rightarrow \mathbb{R}$  be continuous on  $I$ . Then,

$$\int_{\varphi(\alpha)}^{\varphi(\beta)} f(x) dx = \int_{\alpha}^{\beta} f(\varphi(t)) \cdot \varphi'(t) dt.$$

Proof. Left as a (homework) exercise; make use of the chain rule! ■

⊗ **Example 5.1**

Compute  $\int_1^4 \frac{\sin(\sqrt{t})}{\sqrt{t}} dt$  using the previous theorem.

## 5.7 Lebesgue Integrability Criterion

↪ **Definition 5.7: Lebesgue Measure 0**

$A \subseteq \mathbb{R}$  has *Lebesgue measure 0* iff  $\forall \varepsilon > 0$ ,  $A$  can be covered by a countable union of intervals  $J_k := [a_k, b_k]$  such that  $\sum_{k=1}^{\infty} |J_k| \leq \varepsilon$ . We also call such an  $A$  a null set.

For some set  $S \subseteq \mathbb{R}$  and statement  $P$ , we say “ $P$  holds for almost every  $x \in S$ ” if  $\{x \in S : P \text{ false}\}$  has Lebesgue measure 0.

⊗ **Example 5.2**

1. Any countable set is a null set.
2. The Cantor set is a null set.

↪ **Theorem 5.10: Lebesgue Integrability Criterion**

Let  $f : [a, b] \rightarrow \mathbb{R}$  be a bounded function. Then

$$\begin{aligned} f \in \mathcal{R}[a, b] &\iff f \text{ -- continuous for almost every } x \in [a, b] \\ &\iff \{z \in [a, b] : f \text{ discontinuous}\} \text{ has Lebesgue measure } 0. \end{aligned}$$

**Remark 5.1.** The proof is rather involved, but is in the appendix of Bartle. Its important to remark that this is a necessary and sufficient condition.

⊗ **Example 5.3**

1. Let  $f : [0, 1] \rightarrow \mathbb{R}, f(x) := \begin{cases} 1 & x \in \mathbb{Q} \\ 0 & x \notin \mathbb{Q} \end{cases}$ .  $f$  discontinuous everywhere, so  $f \notin \mathcal{R}[a, b]$ .
2. Let  $f(x) := \begin{cases} \frac{1}{b} & x = \frac{a}{b} \in \mathbb{Q} \text{ s.t. } (a, b) = 1 \\ 0 & x \notin \mathbb{Q} \end{cases}$ . One can show that  $f$  continuous on  $x \in \mathbb{R} \setminus \mathbb{Q}$  and only discontinuous on  $\mathbb{Q}$ . But this is a countable set so certainly has Lebesgue measure 0 and so  $f \in \mathcal{R}[0, 1]$ .

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↪ **Theorem 5.11: Composition**

$f \in \mathcal{R}[a, b], f([a, b]) \subseteq [c, d], \varphi : [c, d] \rightarrow \mathbb{R}$  continuous, then  $\varphi \circ f \in \mathcal{R}[a, b]$ .

Proof.

$$\{x \text{ s.t. } \varphi \circ f \text{ discontinuous at } x\} \subseteq \{x : f \text{ discontinuous at } x\}$$

since  $\varphi$  continuous. The RHS has Lebesgue measure 0, and thus so does the LHS, hence the proof. ■

↪ **Theorem 5.12: Product Theorem**

$f, g \in \mathcal{R}[a, b] \implies f \cdot g \in \mathcal{R}[a, b]$ .

Proof.  $f \cdot g = \frac{1}{4} [(f + g)^2 - (f - g)^2]$ .  $f \pm g \in \mathcal{R}[a, b]$  and so so is  $(f \pm g)^2$  by taking  $\varphi(x) := x^2$  as in the previous theorem. It follows that  $f \cdot g \in \mathcal{R}[a, b]$ . ■

## 5.8 Integration by Parts

↪ **Theorem 5.13**

Let  $F, G$  be differentiable on  $[a, b]$ , with  $f := F', g := G'$ . Suppose  $f, g \in \mathcal{R}[a, b]$ , then

$$\int_a^b f(x)G(x) \, dx = F(x)G(x)|_a^b - \int_a^b F(x)g(x) \, dx.$$

Proof. Remark that  $(FG)' = F'G + FG' = fG + Fg$ , so on the one hand

$$\int_a^b (FG)' \, dx = \int_a^b (fG + Fg) \, dx = \int_a^b fG \, dx + \int_a^b Fg \, dx,$$

but on the other hand, by the fundamental theorem of calculus,

$$\int_a^b (FG)' \, dx = [F \cdot G](a) - [F \cdot G](b) = F(x)G(x)|_a^b,$$

and so

$$\begin{aligned} F(x)G(x)|_a^b &= \int_a^b fG \, dx + \int_a^b Fg \, dx \\ \Rightarrow \int_a^b f(x)G(x) \, dx &= F(x)G(x)|_a^b - \int_a^b F(x)g(x) \, dx, \end{aligned}$$

and hence the result. ■

↪ **Theorem 5.14: Taylor's Theorem, Remainder's Version**

Suppose  $f', f'', \dots, f^{(n)}$  exist on  $[a, b]$  and  $f^{(n+1)} \in \mathcal{R}[a, b]$ .<sup>8</sup> Then,

$$f(b) = f(a) + \frac{f'(a)}{1!}(b-a) + \frac{f''(a)}{2!} + \dots + \frac{f^{(n)}(a)}{n!}(b-a)^n + R_n,$$

with  $R_n := \frac{1}{n!} \int_a^b f^{(n+1)}(t)(b-t)^n \, dt$ .

Proof. See Bartle; makes use of integration by parts. ■

## 6 FUNCTION SEQUENCES, SERIES

### 6.1 Pointwise and Uniform Convergence

<sup>8</sup>Remark that this is a weaker condition than continuity as was used in our previous statement of Taylor's theorem.



### ↪ Definition 6.1: Pointwise vs Uniform Convergence

We say a sequence of functions  $f_n \rightarrow f$  *pointwise* on a set  $E$  if  $\forall x \in E, f_n(x) \rightarrow f(x)$  as  $n \rightarrow \infty$ .

On the other hand,  $f_n \rightarrow f$  *uniformly* on  $E$  if  $\forall \varepsilon > 0, \exists N \in \mathbb{N}$  such that  $\forall n \geq N$  and  $x \in E$ ,  $|f_n(x) - f(x)| < \varepsilon$ .

**Remark 6.1.** Notice that uniformly implies pointwise convergence.

#### ⊗ Example 6.1

Let  $f_n := \begin{cases} 2nx & 0 \leq x \leq \frac{1}{2n} \\ 0 & x > \frac{1}{2n} \end{cases}$ . Show that  $f_n \rightarrow 0$  pointwise but not uniformly (hint:  $f_n(\frac{1}{2n}) = 1 \forall n$ ).

### ↪ Theorem 6.1

Suppose  $\lim_{n \rightarrow \infty} f_n$  continuous on  $[a, b]$  where each  $f_n$  also continuous on  $[a, b]$ . Then, the space of function  $C([a, b])$  equipped with the sup norm is complete.

Proof. Proven in tutorials. ■

### ↪ Theorem 6.2: Interchange of Limits

Let  $J \subseteq \mathbb{R}$  be a bounded interval such that  $\exists x_0 \in J : f_n(x_0) \rightarrow f(x_0)$ . Suppose  $f'_n(x) \rightarrow g(x)$  uniformly  $\forall x \in J$ . Then,  $\exists f : f_n(x) \rightarrow f(x)$  uniformly on  $J$ ,  $f(x)$  differentiable on  $J$ , and  $f'(x) = g(x) \forall x \in J$ .

Proof. This is a rather painful proof; one needs to make use of the “multiple epsilons” from each given continuity/convergence/differentiability statement. ■

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### ↪ Theorem 6.3

Let  $f_n \in \mathcal{R}[a, b]$ ,  $f_n \rightarrow f$  uniformly on  $[a, b]$ . Then,  $f \in \mathcal{R}[a, b]$  and  $\int_a^b f_n(x) dx \rightarrow \int_a^b f(x) dx$ .

### ↪ Theorem 6.4: Bounded Convergence Theorem

$f_n \in \mathcal{R}[a, b]$ ,  $f_n \rightarrow f \in \mathcal{R}[a, b]$ , not necessarily uniformly. Suppose  $\exists B > 0$  s.t.  $|f_n(x)| \leq B \forall x \in [a, b]$ . Then,  $\int_a^b f_n \rightarrow \int_a^b f$  as  $n \rightarrow \infty$ .

↪ **Theorem 6.5: Dimi's Theorem/Monotone Convergence**

$f_n \in C([a, b])$ ,  $f_n(x)$  monotone (as a sequence). Suppose  $f_n \rightarrow f \in C([a, b])$ . Then,  $f_n \rightarrow f$  uniformly on  $[a, b]$ .

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## 6.2 Series

↪ **Definition 6.2: Absolute Convergence**

Let  $\{x_j\} \in X$  where  $X$  a normed vector space (say,  $\mathbb{R}$ ). We say

$$\sum_{j=1}^{\infty} x_j \text{ converges absolutely} \iff \sum_{j=1}^{\infty} \|x_j\| < +\infty.$$

↪ **Theorem 6.6**

Any rearrangement of absolutely convergent series given the same sum.

↪ **Definition 6.3: Conditional Convergence**

$\sum_{j=1}^{\infty} \vec{x}^{(j)}$  conditionally convergent if  $\sum_{j=1}^{\infty} x^{(j)}$  converges (ie each component converges) but  $\sum_{j=1}^{\infty} \|\vec{x}^{(j)}\| = \infty$ .

↪ **Theorem 6.7**

If  $\sum_{i=1}^{\infty} a_i \in \mathbb{R}$  conditionally convergent, you can change the order of summation such that  $\forall x \in \mathbb{R}$ ,  $\exists \sigma$ -permutation such that  $\sum_{i=1}^{\infty} a_{\pi(i)} = x$ .

*Proof.* (Sketch) Separate  $a_i$  into positive, negative parts. Since conditionally convergent,  $\sum_{a_j > 0} a_j = +\infty$  and  $\sum_{a_j < 0} a_j = -\infty$ . Add positive  $a_i$ 's until the partial sum  $\geq x$ , then add negative  $a_i$ 's until the partial sum  $\leq x$ , and repeat. The final rearrangement will converge as desired. ■

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↪ **Theorem 6.8**

Suppose  $\sum_{i=1}^{\infty} \vec{v}_i$ ,  $\vec{v}_i \in \mathbb{R}^n$ , converges, but  $\sum_{i=1}^{\infty} \|\vec{v}_i\| = +\infty$ . Then, the set of rearranged sums  $\sum_{i=1}^{\infty} \vec{v}_{\sigma(i)}$  for each  $\sigma : \mathbb{N} \leftrightarrow \mathbb{N}$  permutation form an *affine subspace* of  $\mathbb{R}^n$ .

## 6.3 Tests for Absolute Convergence

### ↪ Proposition 6.1

Let  $x_n, y_n$  be sequences and  $r := \lim_{n \rightarrow \infty} \left| \frac{x_n}{y_n} \right|$ .

1. If  $r \neq 0$ ,  $\sum_{n=1}^{\infty} x_n$  converges absolutely iff  $\sum_{n=1}^{\infty} y_n$  converges absolutely. In addition, if  $0 < r_1 := \liminf \left| \frac{x_n}{y_n} \right| \leq \limsup \left| \frac{x_n}{y_n} \right| =: r_2 < +\infty$ , this still holds.
2. If  $r = 0$ , and if  $\sum y_n$  converges absolutely, so does  $\sum x_n$ .

### ↪ Proposition 6.2: Root Test

If there  $\exists r < 1$  such that  $|x_n|^{1/n} \leq r$  for sufficiently large  $n \geq K$ , then  $\sum_{n=K}^{\infty} |x_n| \leq \sum_{n=K}^{\infty} r^{-n}$  converges.

If  $|x_n|^{1/n} \geq n$  for  $n \geq K$ ,  $\sum x_n$  does not converge absolutely.

### ↪ Proposition 6.3: Ratio Test

Let  $x_n \neq 0$ . If  $\exists 0 < r < 1$ ,  $\left| \frac{x_{n+1}}{x_n} \right| \leq r$  for sufficiently large  $n$ ,  $\sum x_n$  absolutely convergent.

If  $\left| \frac{x_{n+1}}{x_n} \right| \geq 1$  for  $n \geq K$ ,  $\sum x_n$  diverges.

### ↪ Proposition 6.4: Integral Test

Let  $f(x) \geq 0$  be non-increasing/non-decreasing function of  $x \geq 1$ . Then  $\sum_{k=1}^{\infty} f(k)$  converges  $\iff \lim_{k \rightarrow \infty} \int_1^k f(x) dx$  finite.

### ↪ Proposition 6.5: Raabe's Test

Let  $x_n \neq 0$ .

1. Suppose  $\exists a > 1$  s.t.  $\left| \frac{x_{n+1}}{x_n} \right| \leq 1 - \frac{1}{n}, n \geq K$ . Then  $\sum x_n$  converges absolutely.
2. If  $\exists a \leq 1$  s.t.  $\left| \frac{x_{n+1}}{x_n} \right| \geq 1 - \frac{1}{n}, n \geq K$ . Then  $\sum x_n$  does not converge absolutely.

### ↪ Corollary 6.1

Let  $a := \lim_{n \rightarrow \infty} n(1 - \left| \frac{x_{n+1}}{x_n} \right|)$ , if such a limit exists. Then, if  $a > 1$ ,  $\sum x_n$  converges absolutely, and if  $a < 1$ ,  $\sum x_n$  does not.

## 6.4 Tests for Non-Absolute Convergence

### ↪ **Proposition 6.6: Alternating Series**

If  $x_n > 0$ ,  $x_{n+1} \leq x_n$ ,  $\lim_{n \rightarrow \infty} x_n = 0 \implies \sum (-1)^n x_n$  converges.

### ↪ **Lemma 6.1: Abel's Lemma**

Let  $x_n, y_n \in \mathbb{R}$ . Let  $s_0 := 0$ ,  $s_n := \sum_{k=1}^n y_k$ . Then, for  $m > n$ ,

$$\sum_{k=n+1}^m x_k y_k = x_m s_m - x_{n+1} s_{n+1} + \sum_{k=n+1}^m (x_k - x_{k+1}) s_k$$

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## 7 APPENDIX

### 7.1 Notes from Tutorials

#### ↪ **Theorem 7.1**

Let  $(X, d)$  be a compact metric space.<sup>9</sup> Let  $C(X) := \{f : X \rightarrow \mathbb{R} : f \text{ continuous}\}$  be a vector space. Take the uniform norm  $\|f\| := \sup_{x \in X} |f(x)|$  on  $C(X)$ . Then,  $(C(X), \|\cdot\|)$  is complete.<sup>10</sup>

*Proof.* Denote the “canonical norm”  $\rho(f, g) := \|f - g\|$ .

Let  $(f_n) \in C(X)$  be a Cauchy sequence. Then,  $\forall \varepsilon > 0, \exists N \in \mathbb{N} : \forall m, n \geq N, \rho(f_n, f_m) < \varepsilon$ .

Fix  $x \in X$ , noting that

$$|f_n(x) - f_m(x)| \leq \sup_{y \in X} |f_n(y) - f_m(y)| = \rho(f_n, f_m) < \varepsilon. \quad *^1$$

Define, for this fixed  $x$ , a sequence in  $\mathbb{R} \{f_n(x)\}_{n \in \mathbb{N}}$ . By  $*^1$ , we have that this sequence is Cauchy in  $\mathbb{R}$ , but as  $\mathbb{R}$  complete,  $f_n(x)$  hence converges, to some limit we call  $f(x) := \lim_{n \rightarrow \infty} f_n(x)$ . Note that  $x$  is still fixed at this point; these are but real numbers we are working with here.

Now, as  $x$  was completely arbitrary, we can repeat this process for all of  $X$ , and define a function  $f : X \rightarrow \mathbb{R}$  where  $f(x) := \lim_{n \rightarrow \infty} f_n(x)$ .

For a fixed  $x$ , we have that  $f_m(x) \rightarrow f(x)$  as  $m \rightarrow \infty$ . This implies:

$$\begin{aligned} 0 &\leq \lim_{m \rightarrow \infty} |f_n(x) - f_m(x)| \leq \lim_{m \rightarrow \infty} \varepsilon = \varepsilon \\ &\implies |f_n(x) - f(x)| \leq \varepsilon \quad \forall n \geq N \\ &\implies \rho(f_n, f) = \sup_{x \in X} |f_n(x) - f(x)| \leq \varepsilon \implies f_n \rightarrow f \end{aligned}$$

It remains to show that  $f \in C(X)$ . Let  $c \in X$  and  $\varepsilon > 0$ , and the corresponding  $N \in \mathbb{N} : \rho(f_n, f) < \frac{\varepsilon}{3} \quad \forall n \geq N$ . By construction,  $f_N \in C(X)$ , and is thus continuous at  $c$ . This gives that  $\exists \delta > 0 : |f_N(x) - f_N(c)| < \frac{\varepsilon}{3}$  whenever  $d(x, c) < \delta$ .<sup>11</sup>

Hence, if  $d(x, c) < \delta$ , we have

$$\begin{aligned} |f(x) - f(c)| &\leq |f(x) - f_N(x)| + |f_N(x) - f_N(c)| + |f_N(c) - f(c)| \\ &\leq \rho(f, f_N) + \frac{\varepsilon}{3} + \frac{\varepsilon}{3} \\ &< \frac{\varepsilon}{3} + \frac{\varepsilon}{3} + \frac{\varepsilon}{3} = \varepsilon, \end{aligned}$$

<sup>10</sup>In this proof, the compactness is necessary for the norm to be well-defined.

<sup>10</sup>In this way, this becomes a Banach Space: a complete, normed vector space.

<sup>11</sup>Be careful here, there are three different metrics going on;  $\rho$  from the vector space,  $d$  from the underlying metric space, and  $|\cdot|$  from  $\mathbb{R}$ .

hence  $f$  continuous at  $c$ , which was completely arbitrary, and thus  $f \in C(X)$ . ■

↪ **Theorem 7.2**

Let  $(X, d)$ -complete. Let  $\{F_n\}$  be a decreasing family of non-empty closed sets with  $\lim_{n \rightarrow \infty} \text{diam}(F_n) = 0$ . Then,  $\exists z : \bigcap_{n \in \mathbb{N}} F_n = \{z\}$ .

↪ **Theorem 7.3**

Let  $(X, d)$ -complete, and  $f : X \rightarrow X$  an “expanding map”, such that  $d(x, y) \leq d(f(x), f(y)) \forall x, y \in X$ . Then,  $f$  is a surjective isometry, ie,  $f(X) = X$  and  $d(f(x), f(y)) = d(x, y) \forall x, y \in X$ .

↪ **Lemma 7.1**

Differentiable  $\implies$  Continuous.

Proof. Let  $f : I \rightarrow \mathbb{R}$ , and  $c \in I$  arbitrary. Notice that  $\forall x \neq c \in I, f(x) - f(c) = (x - c) \frac{f(x) - f(c)}{x - c}$ . Hence,

$$\begin{aligned} \lim_{x \rightarrow c} (f(x) - f(c)) &= \lim_{x \rightarrow c} (x - c) \frac{f(x) - f(c)}{x - c} \\ &= \lim_{x \rightarrow c} (x - c) \cdot \lim_{x \rightarrow c} \frac{f(x) - f(c)}{x - c} \\ &= 0 \cdot f'(c) = 0 \\ &\implies \lim_{x \rightarrow c} f(x) = f(c), \end{aligned}$$

hence  $f$  continuous, noting that the splitting of the limits is valid as both are defined. ■

⊗ **Example 7.1**

$$\text{Let } f : \mathbb{R} \rightarrow \mathbb{R}, f(x) := \begin{cases} x^2 & x \in \mathbb{Q} \\ 0 & x \notin \mathbb{Q} \end{cases}$$

Claim:  $f$  discontinuous at all  $x \neq 0$ .

Proof. Let  $x \neq 0 \in \mathbb{R}$ . By density of  $\mathbb{Q} \subseteq \mathbb{R}$ , there exist sequences  $(r_n) \in \mathbb{Q}$  s.t.  $r_n \rightarrow x$  and  $(z_n) \in \mathbb{R} \setminus \mathbb{Q}$  s.t.  $z_n \rightarrow x$ . Then:

$$\begin{aligned} \lim_{n \rightarrow \infty} f(r_n) &= \lim_{n \rightarrow \infty} r_n^2 = x^2 \\ \lim_{n \rightarrow \infty} f(z_n) &= \lim_{n \rightarrow \infty} 0 = 0, \end{aligned}$$

hence  $f$  discontinuous by the sequential criterion at  $x \neq 0$ . ■

Claim:  $f'(0) = 0$ .

Proof. Let  $\varepsilon > 0$  and  $\delta = \varepsilon$ . Notice that  $f(x) \leq x^2 \forall x$ . Then, we have that  $\forall |x| < \delta$ ,

$$\begin{aligned} \left| \frac{f(x) - f(0)}{x - 0} - 0 \right| &= \left| \frac{f(x)}{x} \right| \\ &\leq \left| \frac{x^2}{x} \right| = |x| < \delta = \varepsilon \end{aligned}$$

■

↪ **Definition 7.1**

Let  $f : I \rightarrow \mathbb{R}$ . A point  $c \in I$  is a local max (resp min) if  $\exists \delta > 0$  s.t.  $f(x) \leq f(c)$  (resp  $f(x) \geq f(c)$ )  $\forall x \in (c - \delta, c + \delta) \cap I$ .

↪ **Lemma 7.2**

Let  $f : I \rightarrow \mathbb{R}$  be differentiable at  $c \in I^\circ$ . If  $c$  a local extrema of  $f$ , then  $f'(c) = 0$ .

Proof. Assume wlog that  $c$  a local max; if a local min, take  $\tilde{f} := -f$  and continue.

Since  $I^\circ$  open,  $\exists \delta_1 > 0 : (c - \delta_1, c + \delta_1) \subseteq I^\circ \subseteq I$ . We also have that  $\exists \delta_2 > 0 : f(x) \leq f(c) \forall x \in (c - \delta_2, c + \delta_2) \cap I$ , by  $c$  an extrema.

Let  $\delta := \min\{\delta_1, \delta_2\}$ . Then, we have both  $(c - \delta, c + \delta) \subseteq I$  and  $f(x) \leq f(c) \forall x \in (c - \delta, c + \delta)$ .

Since  $f'(c)$  exists,  $\lim_{x \rightarrow c^+} \frac{f(x) - f(c)}{x - c} = \lim_{x \rightarrow c^-} \frac{f(x) - f(c)}{x - c}$ . But we have from the property of being a maximum

that

$$\lim_{x \rightarrow c^+} \frac{f(x) - f(c)}{x - c} \geq 0, \quad \lim_{x \rightarrow c^-} \frac{f(x) - f(c)}{x - c} \leq 0,$$

hence, as these two limits must agree, they must equal 0 and thus  $f'(c) = 0$ . ■

## 7.2 Miscellaneous

### ⊗ Example 7.2: Rudin, Chapter 7: Differentiability

1. Let  $f$  be defined  $\forall x \in \mathbb{R}$ , and suppose that  $|f(x) - f(y)| \leq (x - y)^2$ ,  $\forall x, y \in \mathbb{R}$ . Prove that  $f$  is constant.<sup>12</sup>

Proof. Let  $x > y \in \mathbb{R}$ . Then, as  $|x - y| = x - y$ , we have

$$\begin{aligned} |f(x) - f(y)| \leq (x - y)^2 &\implies \left| \frac{f(x) - f(y)}{x - y} \right| \leq x - y = |x - y| \rightarrow 0 \text{ as } y \rightarrow x \\ &\implies \left| \frac{f(x) - f(y)}{x - y} \right| \rightarrow 0 \end{aligned}$$

This implies, then, that  $f'(x)$  is defined  $\forall x \in \mathbb{R}$ , and moreover, that  $f'(x) = 0 \forall x \in \mathbb{R}$ . We conclude, then, that  $f(x)$  constant  $\forall x \in \mathbb{R}$ . ■

2. Suppose  $f'(x) > 0$  in  $(a, b)$ . Prove that  $f$  is strictly increasing in  $(a, b)$ , and let  $g$  be its inverse function. Prove that  $g$  is differentiable, and that

$$g'(f(x)) = \frac{1}{f'(x)} \quad (a < x < b).$$

Proof. Fix  $x > y \in (a, b)$ . Then, by the mean value theorem,  $\exists z \in (x, y) : f'(z) = \frac{f(x) - f(y)}{x - y}$ . Since  $f'(z) > 0$ , it follows that

$$\frac{f(x) - f(y)}{x - y} > 0 \implies f(x) - f(y) > x - y > 0 \implies f(x) > f(y),$$

hence,  $f$  increasing, as  $x > y$  arbitrary.

Let now  $g := f^{-1}$ . ■

<sup>12</sup>Note that this means that  $f$  Hölder continuous with constant  $\alpha = 2$ . Indeed, Hölder continuous functions with  $\alpha > 1$  are always constant by a similar proof. For  $0 < \alpha \leq 1$ , we have the inclusion continuously differentiable  $\implies$  Lipschitz  $\implies \alpha$ -Hölder  $\implies$  uniformly continuous  $\implies$  continuous.



## 7.3 Class Midterm Solutions

### ↪ Question 7.1

Let  $X$  be a topological space, and let  $f, g : X \rightarrow \mathbb{R}$  be two continuous functions. Show that the set  $\{x \in X : f(x) > g(x)\}$  is an open subset of  $X$ .

*Proof.* Let  $A := \{x \in X : f(x) > g(x)\}$ . Letting  $\varphi(x) := f(x) - g(x) = (f - g)(x)$ , then remark that  $A \equiv \{x \in X : \varphi(x) > 0\}$ , and since differences of continuous functions are continuous,  $\varphi$  continuous. Letting  $B := (0, \infty) \subseteq \mathbb{R}$ , then, we have that  $A = \varphi^{-1}(B)$ . But  $B$  an open set, and the inverse images of open sets by continuous functions are open, hence  $A$  open. ■

### ↪ Question 7.2

- (a) List three equivalent properties (definitions) of compact sets in metric spaces; you don't need to prove anything.
- (b) Is the unit ball<sup>13</sup> in the space  $\ell^2$  of infinite sequences compact? Prove or disprove. You may use any of the properties from (a).

*Proof.* (a) Every open cover admits a finite subcover  $\iff$  sequentially compact  $\iff$  complete and totally bounded.

- (b) Denote the closed unit ball centered at  $(0, 0, \dots)$  in  $\ell^2$ ,  $B := \{x \in \ell^2 : d_2^2(0, x) = \sum_{i=1}^{\infty} |x_i|^2 \leq 1\}$ . Consider the sequence of “unit sequences”

$$\{e^n\}_{n \in \mathbb{N}} \in B, \quad e_i^n := \delta_{in}.$$

Then, for any  $i \neq j$ ,  $d_2(e^n, e^m) = \sqrt{2} > 1$ . It follows that, although  $e^n \in B$  for any  $n$ , there cannot exist a subsequence of  $x^n$  that converges within  $B$  (verify why this is!). Thus,  $B$  cannot be sequentially compact and thus not compact. ■

<sup>13</sup>Jakobson said in class this is supposed to be a closed ball.

↪ **Question 7.3**

- (a) Define a complete metric space.
- (b) State (without proof) the contraction mapping theorem.
- (c) Let  $f : (0, 1) \rightarrow (0, 1)$  be defined by  $f(x) = x/2$ . Is  $f$  a contraction?
- (d) Does  $f$  have a fixed point in the open interval  $I = (0, 1)$ ? Does that contradict the contraction mapping theorem?

Proof. (a) A complete metric space is a metric space in which every Cauchy sequence converges within that space.

(b) Let  $(X, d)$  be a complete metric space, and let  $f : X \rightarrow X$  be a contraction mapping, ie for any  $x, y \in X$ ,  $d(f(x), f(y)) \leq c \cdot d(x, y)$  for some  $c \in (0, 1)$ . Then, the contraction mapping states that  $f$  has a unique fixed point  $z \in X$ , ie  $f(z) = z$  and  $\lim_{n \rightarrow \infty} f^{(n)}(x) = z$  for any  $x$ .

(c) For any  $x, y \in (0, 1)$ , we have

$$d(f(x), f(y)) = |f(x) - f(y)| = \left| \frac{x - y}{2} \right| = \frac{1}{2} |x - y| = c \cdot d(x, y),$$

so  $f$  indeed a contraction mapping with  $c := \frac{1}{2}$ .

(d) We have that for any  $x \in I$ ,  $f^{(n)}(x) = \frac{x}{2^n}$  so  $x$  a fixed point iff  $\frac{x}{2^n} = \frac{x}{2^{n-1}}$  for some  $n$ , which is only possible if  $x = 0$ , but  $0 \notin I$ , so indeed  $f$  has no fixed point in  $I$ . This is not a contradiction to the contraction mapping theorem since  $I := (0, 1)$  not complete (indeed,  $\frac{1}{n} \in I \forall n$  but  $\frac{1}{n} \rightarrow 0 \notin I$ ).

■

↪ **Question 7.4**

Let  $x = (x_1, x_2, \dots)$  and  $y = (y_1, y_2, \dots)$  be infinite real sequences satisfying  $\|x\|_2 \leq 2$  and  $\|y\|_2 \leq 3$ , where  $\|\cdots\|_2$  the  $\ell^2$  norm.

(a) State Holder's inequality and Minkowski inequality for sequences.

(b) Give an upper bound for  $x \cdot y = \sum_i x_i y_i$ , and for  $\|x + y\|$ .

Proof. (a) Holder's inequality: for  $p, q$  Holder conjugates and  $x \in \ell^p, y \in \ell^q$  we have

$$\left| \sum_{i=1} x_i y_i \right| \leq \|x\|_p \|y\|_q.$$

Minkowski inequality: for  $x, y \in \ell^p$ ,

$$\|x + y\|_p \leq \|x\|_p + \|y\|_p.$$

(b) For  $x, y$  as given; by Holders,  $x \cdot y \leq \|x\|_p \|y\|_q = 2 \cdot 3 = 6$ , and by Minkowski's,  $\|x + y\| \leq \|x\| + \|y\| = 2 + 3 = 5$ , so 6, 5 are upper bounds for  $x \cdot y, \|x + y\|$  respectively.

■

→ **Question 7.5**

(a) State (without proof) Taylor's theorem.

(b) Let  $f \in C^4([0, 2])$ , and let  $f'(1) = f''(1) = f'''(1) = 0$  while  $f^{(4)}(1) = 2$ . Use (a) to show that  $f(x)$  has a local extremum at  $x = 1$ , and determine its type.

Proof. (a) Let  $I := [a, b] \subseteq \mathbb{R}$  and let  $f : I \rightarrow \mathbb{R}$  such that  $f \in C^n(I)$ , and  $f^{(n+1)}(x)$  exists on  $(a, b)$ . Then, for  $x_0 \in [a, b]$ , there exists some  $c \in (\min(x, x_0), \max(x, x_0))$  such that

$$f(x) = f(x_0) + f'(x_0)(x - x_0) + \cdots + \frac{f^{(n)}(x_0)}{n!}(x - x_0)^n + \frac{f^{(n+1)}(c)}{(n+1)!}(x - x_0)^{n+1}.$$

(b) By Taylor's, for any  $x \in [0, 2]$ , there exists some  $c$  between  $x$  and 1 such that

$$\begin{aligned} f(x) &= f(1) + \underbrace{f'(1)(\cdots) + f''(1)(\cdots) + f'''(1)(\cdots)}_{=0} + \frac{f^{(4)}(c)}{4!}(x - 1)^4 \\ &= f(1) + \frac{f^{(4)}(c)}{4!}(x - 1)^4 \\ \implies f(x) - f(1) &\geq \frac{f^{(4)}(c)}{4!}(x - 1)^4 \forall x \in [0, 2] \end{aligned}$$

By continuity of  $f^{(4)}$ , there exists some neighborhood  $V$  of  $x_0 = 1$  such that  $f^{(4)}(c)$  has the same sign of  $f^{(4)}(1)$ . So, for any  $x \in V$ ,  $\frac{f^{(4)}(c)}{4!} \geq 0$ , since  $\frac{f^{(4)}(1)}{4!} = \frac{2}{4!} \geq 0$ . Thus, since  $(x - 1)^4 \geq 0$ , we have that for such  $x$  in  $V$ ,

$$f(x) - f(1) \geq 0 \implies f(x) \geq f(1).$$

Hence, we have a neighborhood of 1 such that for all  $x$  in the neighborhood  $f(x) \geq f(1)$ . It follows that 1 a local minimum of  $f$ .

■