

Metric Spaces Exam Notes

Made by Leon :) *Note: Any reference numbers are to the lecture notes*

1 Introduction to Metric Spaces

Definition 1: Definition of a Metric

Let X be a non-empty set. A function $d : X \times X \rightarrow \mathbb{R}$ is called a **metric** iff for all $x, y, z \in X$,

- $d(x, y) \geq 0$ and $d(x, y) = 0 \iff x = y$
- $d(x, y) = d(y, x)$
- $d(x, y) \leq d(x, z) + d(z, y)$ (Triangle Inequality)

A non-empty set X equipped with a metric d is a **metric space**

Definition A: Real Vector Spaces

A **real vector space** V is a set with two operations $(X, +, \cdot)$, where:

- $+$ is addition, and \cdot is scalar multiplication
- $(X, +)$ is an abelian group - i.e. for all (vectors) $x, y, z \in X$:
 - Closure:** $x + y \in X$
 - Commutativity:** $x + y = y + x$
 - Associativity:** $x + (y + z) = (x + y) + z$
 - Identity:** $\exists 0 \in X$ s.t. for all $x \in X$ we have $0 + x = x + 0 = x$
 - Inverse:** $\forall x \in X$ we have $-x$ s.t. $x + (-x) = (-x) + x = 0$
- Vector space axioms: for all $x, y, z \in X$ and $\mu, \lambda \in \mathbb{R}$ we have:
 - Closure-ish thing:** $\lambda x \in X$
 - Distributivity 1:** $\lambda(x + y) = \lambda x + \lambda y$
 - Distributivity 2:** $(\lambda + \mu)x = \lambda x + \mu x$
 - Associativity:** $\lambda(\mu x) = (\lambda\mu)x$
 - Identity:** $1x = x$

Definition B: Normed and Inner Product Spaces

Def 5: Normed Vector Spaces

A **normed vector space** is a real vector space X equipped with a **norm**, i.e. a function that assigns to every vector $x \in X$ a real number $\|x\|$ so that, for all vectors x and y in X and all real scalars a :

- $\|x\| \geq 0$ and $\|x\| = 0 \iff x = 0$
- $\|ax\| = |a|\|x\|$
- $\|x + y\| \leq \|x\| + \|y\|$

Remark: If $(X, \|\cdot\|)$ is a normed vector space then

$$d(x, y) = \|x - y\|$$

defines a metric in X

Def 6: Inner Product Spaces

Let X be a real vector space. An **inner product** on X is a function that assigns to every pair $(x, y) \in X \times X$ a real number denoted by $\langle x, y \rangle$ and has the following properties:

- $\langle x, x \rangle \geq 0$ and $\langle x, x \rangle = 0 \iff x = 0$
- $\langle x, y \rangle = \langle y, x \rangle$
- $ax + by, z = a\langle x, z \rangle + b\langle y, z \rangle$

A **real inner product space** is a real vector space equipped with an inner product. If $\langle \cdot, \cdot \rangle$ is an inner product on X , then

- $\|x\| = \sqrt{\langle x, x \rangle}$ defines a norm in X
- $d(x, y) = \|x - y\|$ defines a metric in X

Definition C: n -dimensional Euclidean space

Let $X = \mathbb{R}^n = \{(x_1, x_2, \dots, x_n) : x_1, x_2, \dots, x_n \in \mathbb{R}\}$

For $x = (x_1, x_2, \dots, x_n), y = (y_1, y_2, \dots, y_n)$ in \mathbb{R}^n , define




$$\langle x, y \rangle = x_1y_1 + x_2y_2 + \dots + x_ny_n \text{ (inner product)}$$

$$\|x\|_2 = \langle x, x \rangle^{1/2} = \sqrt{x_1^2 + x_2^2 + \dots + x_n^2} \text{ (norm)}$$

Example D: Examples of Metric Spaces

Unless stated otherwise let $X = \mathbb{R}^n$. The case $X = \mathbb{R}^2$ is listed in red

Name	Norm and Metric
Standard	$X = \mathbb{R}$ and $ x $ = Absolute Value $d(x, y) = x - y $
Taxicab	$\ x\ _1 = x_1 + x_2 + \dots + x_n $ $d_1(x, y) = x_1 - y_1 + x_2 - y_2 + \dots + x_n - y_n $
Euclidean	$\ x\ _2 = \sqrt{ x_1 ^2 + x_2 ^2 + \dots + x_n ^2}$ $d_2(x, y) = \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2 + \dots + (x_n - y_n)^2}$
p -metric	$\ x\ _p = \left(\sum_{k=1}^n x_k ^p \right)^{1/p}$ $d_p(x, y) = \left(\sum_{k=1}^n x_k - y_k ^p \right)^{1/p}$
Chebyshev	$\ x\ _\infty = \max\{ x_1 , x_2 , \dots, x_n \}$ $d(x, y) = \max\{ x_1 - y_1 , x_2 - y_2 , \dots, x_n - y_n \}$
Discrete	$d(x, y) = \begin{cases} 0 & x = y \\ 1 & x \neq y \end{cases}$
Post Office	$d(x, y) = \begin{cases} \ x\ _2 + \ y\ _2 & x = y \\ 1 & x \neq y \end{cases}$

1	1	1	$\sqrt{2}$	1	$\sqrt{2}$	2	1	2
1		1	1		1	1		1
1	1	1	$\sqrt{2}$	1	$\sqrt{2}$	2	1	2
Chebyshev			Euclidean			Taxicab		

The complex plane

Let $X = \mathbb{C}, d : \mathbb{C} \times \mathbb{C} \rightarrow \mathbb{R}$

$$d(z, w) = |z - w|$$

If $z = a + ib, w = c + id, a, b, c, d \in \mathbb{R}$, then

$$z - w = (a - c) + i(b - d)$$

therefore,

$$d(z, w) = \sqrt{(a - c)^2 + (b - d)^2}$$

Example E: Sequence Spaces

The space ℓ^1

ℓ^1 is the set of real sequences $(x_n)_{n \in \mathbb{N}}$ where $\sum_{n=1}^\infty |x_n|$ converges.

For $x = (x_1, \dots, x_n, \dots) \in \ell^1, y = (y_1, \dots, y_n, \dots) \in \ell^1$ we define

- Norm:** $\|x\|_1 = \sum_{n=1}^\infty |x_n|$
- Metric:** $d_1(x, y) = \|x - y\|_1 = \sum_{n=1}^\infty |x_n - y_n|$

The space ℓ^2

ℓ^2 is the set of real seqs $(x_n)_{n \in \mathbb{N}}$ where $\sum_{n=1}^\infty |x_n|^2$ converges

For $x = (x_1, \dots, x_n, \dots) \in \ell^2, y = (y_1, \dots, y_n, \dots) \in \ell^2$ we define

- Inner product:** $\langle x, y \rangle = \sum_{n=1}^\infty x_n y_n$
- Norm:** $\|x\|_2 = \left(\sum_{n=1}^\infty |x_n|^2 \right)^{1/2}$
- Metric:** $d_2(x, y) = \|x - y\|_2 = \left(\sum_{n=1}^\infty |x_n - y_n|^2 \right)^{1/2}$

Thm: ℓ^2 is a real vector space

The space ℓ^∞

ℓ^∞ is the set of all bounded sequences of real numbers For $x = (x_1, \dots, x_n, \dots), y = (y_1, \dots, y_n, \dots) \in \ell^\infty$

- Norm:** $\|x\|_\infty = \sup\{|x_1|, \dots, |x_n|, \dots\}$
- Metric:** $\|x - y\|_\infty = \sup\{|x_1 - y_1|, \dots, |x_n - y_n|, \dots\}$

The space $C([a, b])$

$X = C([a, b])$ is the set of all continuous functions $f : [a, b] \rightarrow \mathbb{R}$

- Norm:** $\|f\|_\infty = \max\{|f(x)| : a \leq x \leq b\}$
- Metric:** $d_\infty(f, g) = \|f - g\|_\infty = \max\{|f(x) - g(x)| : a \leq x \leq b\}$

The L^1 metric

X is the set of all continuous functions $f : [a, b] \rightarrow \mathbb{R}$

- Norm:** $\|f\|_1 = \int_a^b |f(x)| dx$
- Metric:** $d_2(f, g) = \|f - g\|_1 = \int_a^b |f(x) - g(x)| dx$

The L^2 metric

X is the set of all continuous functions $f : [a, b] \rightarrow \mathbb{R}$

- Inner Product:** $\langle f, g \rangle = \int_a^b f(x)g(x)dx$
- Norm:** $\|f\|_2 = \langle f, f \rangle^{1/2} = \left(\int_a^b |f(x)|^2 dx \right)^{1/2}$
- Metric:** $d_1(f, g) = \left(\int_a^b |f(x) - g(x)|^2 dx \right)^{1/2}$

Definition F: Metric Subspaces

Ex 7: Let (X, d) be a metric space and Y a non-empty subset of X . Define

- $d_Y : Y \times Y \rightarrow \mathbb{R}$
- $d_Y(y, y') = d(y, y')$

Then d_Y is a metric on Y . d_Y is called the **induced** or **inherited** metric, and (Y, d_Y) is said to be a metric subspace of the metric space (X, d)

Theorem G: a lack of equality or fair treatment in t...

Good old fashioned Triangle Inequality

If it ain't broke...

$$|x + y| \leq |x| + |y| \quad \text{and} \quad |x - y| \geq ||x| - |y||$$

Cauchy-Schwarz Inequality

For all x and y of an inner product space:

$$|\langle x, y \rangle| \leq \|x\| \|y\|$$

Minkowski's Inequality

Let $p \geq 1$, and real numbers x_i, y_i , ($i = 1, \dots, n$). Then

$$\|x + y\|_p \leq \|x\|_p + \|y\|_p$$
$$\left(\sum_{i=1}^n |x_i + y_i|^p \right)^{\frac{1}{p}} \leq \left(\sum_{i=1}^n |x_i|^p \right)^{\frac{1}{p}} + \left(\sum_{i=1}^n |y_i|^p \right)^{\frac{1}{p}}$$

Ex 56 (Young's Inequality)

Let $1 \leq p, q \leq \infty$ s.t. $\frac{1}{p} + \frac{1}{q} = 1$, and $a, b \geq 0$. Then

$$ab \leq \frac{a^p}{p} + \frac{b^q}{q}$$

Thm 169 (Hölder Inequality)

Let $1 \leq p, q \leq \infty$ s.t. $\frac{1}{p} + \frac{1}{q} = 1$ and $x, y \in \mathbb{R}^n$. Then

$$\sum_{i=1}^n |x_i y_i| \leq \|x\|_p \|y\|_q$$

Definition 166: Equivalent Norms

Two norms on the same real vector space are said to be equivalent iff their corresponding metrics are equivalent

Thm 167: If $\|\cdot\|_1$ and $\|\cdot\|_2$ are norms on the same real vector space X and there exist positive constants C and C' s.t., for all $x \in X$,

$$D\|x\|_1 \leq \|x\|_2 \leq C'\|x\|_1$$

then they are equivalent

Equivalence Theorems of p -metrics

171: Any of the following norms are equivalent:

$$\|x\|_p = (|x_1|^p + \dots + |x_n|^p)^{1/p}, \quad x \in \mathbb{R}^n, \quad 1 \leq p < \infty$$
$$\|x\|_\infty = \max\{|x_1|, \dots, |x_n|\}, \quad x \in \mathbb{R}^n$$

172: Let $1 \leq p \leq q < \infty$. For all $x \in \mathbb{R}^n$:

$$\|x\|_q \leq \|x\|_p$$

As a consequence,

$$\|x\|_\infty \leq \|x\|_q \leq \|x\|_p \leq \|x\|_1$$

173: All norms in \mathbb{R}^n are equivalent

Definition 8: Open Ball

Let (X, d) be a metric space, c be a point in X , and $r > 0$. The **open ball** with center c and radius r is defined by

$$B(c, r) = \{x \in X : d(c, x) < r\}$$

2 Convergence

Definition 15: Convergent Sequence

Let (X, d) be a metric space, $(x_n)_{n=1}^\infty$ be a sequence in X , and $x \in X$. We say that $(x_n)_{n=1}^\infty$ converges to x iff for every $\epsilon > 0$, there exists an index N s.t. for all $n \geq N$ we have $d(x_n, x) < \epsilon$.

Observe that:

- $d(x_n, x) < \epsilon$ is equivalent to $x_n \in B(x, \epsilon)$.
- $x_n \rightarrow x$ in (X, d) iff $d(x_n, x) \rightarrow 0$ on the real line

Theorem 16: Uniqueness of metric limit

- Let (X, d) be a metric space, and $x, x' \in X$, $x \neq x'$. Then there exists a positive radius r s.t. $B(x, r) \cap B(x', r) = \emptyset$
- A sequence in a metric space can have at most one limit

Definition 19: Bounded Sequence

A sequence in a metric space is said to be **bounded** iff there exists an open ball that contains all of its terms

Note: this is the same definition as “sequence is bounded if there is upper and lower bound”, as open ball implies the same thing

Thm 20: Every convergent sequence is bounded

Definition 21: Cauchy Sequence

A sequence $(x_n)_{n=1}^\infty$ in a metric space (X, d) is said to be a **Cauchy sequence** iff for every positive ϵ , there exists an index N , s.t. for all indices n, m with $n, m \geq N$,

$$d(x_n, x_m) < \epsilon$$

Thm 22: If a sequence in a metric space converges, then it is a Cauchy sequence. **Note:** the converse is not true

Definition 24: Complete Metric Spaces

A metric space is said to be **complete** if and only if every Cauchy Sequence is convergent

Example 25: Examples of Complete Metric Spaces

- \mathbb{R} with the standard metric is complete
- \mathbb{Q} with the standard metric is not complete
- $(0, 1)$ with the standard metric is not complete
- $[0, 1]$ with the standard metric is complete
- $\mathbb{R}^n, \ell^p, C([a, b])$ is complete (proof later)

Definition 26: Open Sets and Closed Sets

Let (X, d) be a metric space.

- A subset G of X is said to be **open** iff for every point x in G there exists a positive radius r such that $B(x, r) \subseteq G$.
- A subset F of X is said to be **closed** iff F^c is open

Definition 31: Discrete Spaces and Clopens

A metric space is called **discrete** iff all its subsets are open (equiv. all subsets are closed)

Example: $[0, 1] \cap (2, 3)$

Def 33: A set that is both open and closed is called **clopen**

Theorem 34: Properties of open and closed sets

Let (X, d) be a metric space

1. The union of **any family** of open sets is an open set
2. The intersection of **finitely many** open sets is an open set
3. The intersection of **any family** of closed sets is a closed set
4. The union of **finitely many** closed sets is a closed set

Remark 35: Infinite open sets

The intersection of infinitely many open sets isn't always an open set e.g., let $G_n = (-\frac{1}{n}, \frac{1}{n})$, $n = 1, 2, \dots$ on \mathbb{R} with the standard metric. Each G_n is open but

$$\bigcap_{n=1}^{\infty} G_n = \{0\}$$

Theorem 18: Relatively open sets

Let (X, d) be a metric space and A a nonempty subset of X equipped with the induced metric d_A . Let $G \subseteq A$. Then G is open in (A, d_A) iff there exists a subset O of X , open in (X, d) , s.t. $G = A \cap O$. The open sets of (A, d_A) are referred to as **relatively open**

Theorem 36

Let (X, d) be a metric space, $(x_n)_{n=1}^\infty$ be a sequence in X and x be a point in X .

$x_n \rightarrow x$ iff every open set that contains x contains eventually all terms of the sequence

Definition H: Neighbourhoods of points

An **open neighbourhood** of a point x is any open set that has x . $x_n \rightarrow x$ iff every open neighbourhood of x contains eventually all terms of the sequence.

A **neighbourhood** of a point x is a set that contains an open neighbourhood of x .

$x_n \rightarrow x$ iff every neighbourhood of x contains eventually all terms of the sequence.

Remark 38: Infinite closed sets

The union of infinitely many closed sets is not always a closed set. For example, let $F_n = [\frac{1}{n}, 1]$, $n = 1, 2, \dots$, on the real line with the standard metric. Each F_n is closed but

$$\bigcup_{n=1}^{\infty} F_n = (0, 1]$$

is not closed.

Theorem 41

A subset F of a metric space is closed iff the limit of every convergent sequence of elements of F belongs to F

- In any metric space (X, d) , singletons $F = \{x\}$ are closed.
- In any metric space, any finite set is closed because

$$\{x_1, \dots, x_n\} = \{x_1\} \cup \dots \cup \{x_n\}$$

Definition 43: Closure

Let (X, d) be a metric space and $A \subseteq X$. The **closure** of A , denoted by \overline{A} , is the smallest closed subset of X that contains A

There exists at least one closed subset of X that contains A , namely X itself. The smallest closed subset of X that contains A is

$$\bigcap_{\substack{A \subseteq F \subseteq X \\ F \text{ closed}}} F$$

Theorem 44: Properties of Closure

Let (X, d) be a metric space and $A, B \subseteq X$.

1. $\overline{\emptyset} = \emptyset$ and $\overline{X} = X$
2. $A \subseteq \overline{A}$ and \overline{A} is closed
3. A is closed iff $A = \overline{A}$
4. $\overline{\overline{A}} = \overline{A}$
5. If $A \subseteq B$, then $\overline{A} \subseteq \overline{B}$
6. $\overline{A \cup B} = \overline{A} \cup \overline{B}$

Example 2.1.1: Examples of closure

- On the real line with the standard metric, $\overline{(a, b)} = [a, b]$
- In \mathbb{R}^n with the Euclidean metric d_2 , the closure of the open ball $B(c, r)$ is the closed ball $\{x \in \mathbb{R}^n : d_2(x, c) \leq r\}$
- On the complex plane with its standard metric, the closure of an open disc is the corresponding closed disc

- Let X be a non-empty set with the discrete metric, $c \in X$ and $r = 1$. Then $B(c, 1) = \{c\}$, therefore $\overline{B(c, 1)} - \{c\} = \{c\}$, while

$$\{x \in X : d(x, c) \leq 1\} = X$$

The closure of an open ball is not always equal to the corresponding closed ball

- $X = \mathbb{R}$, $d(x, y) = |x - y|$. $\overline{\mathbb{Q}} = \mathbb{R}$

Definition 49: Dense Subset of a Metric Space

Let (X, d) be a metric space. A subset $D \subseteq X$ is **dense** iff $\overline{D} = X$

Random Fact: In \mathbb{R}^n with the Euclidean metric d_2 , \mathbb{Q}^n is dense.

Theorem 50: Adherent Points

Let (X, d) be a metric space, $A \subseteq X, x \in X$. The following are equiv.

1. $x \in \overline{A}$
2. For every positive r , $B(x, r) \cap A \neq \emptyset$
3. There exists a sequence $(a_n)_{n \in \mathbb{N}}$ with $a_n \in A$ for all n , such that $a_n \rightarrow x$

A point x with any of these properties is called an **adherent point** of A . So, \overline{A} is the set of all adherent points of A .

Definition 52: Limit points of sets

Let (X, d) be a metric space, $A \subseteq X$ and $x \in X$. We say that x is a **limit point** or an **accumulation point** of A iff every open ball centered at x contains an element of A distinct from x , i.e.

$$\forall r > 0 \quad (B(x, r) \setminus \{x\}) \cap A \neq \emptyset$$

The set of all limit points of A is called the **derived set** of A and is denoted by A' or \dot{A} .

Definition 54: Continuity at a point

Let $(X, d_X), (Y, d_Y)$ be metric spaces and $f : X \rightarrow Y$ be a function. We say that f is **continuous at a point** x_0 in X iff...

- for every $\epsilon > 0$, there exists a $\delta > 0$, such that, for all $x \in X$ with $d_X(x, x_0) < \delta$ we have

$$d_Y(f(x), f(x_0)) < \epsilon$$

- for every $\epsilon > 0$, there exists a $\delta > 0$, such that, for all $x \in B_X(x_0, \delta)$ we have

$$f(x) \in B_Y(f(x_0), \epsilon)$$

- **Thm 57:** for every open nbhd G of $f(x_0)$, there exists an open nbhd O of x_0 such that, for all $x \in O$, we have $f(x) \in G$

Def 55: Continuity of a Function

Let $(X, d_X), (Y, d_Y)$ be metric spaces. A function $f : X \rightarrow Y$ is said to be **continuous** iff it is continuous at every point in X

Theorem 58: Continuity and Convergence

Let $(X, d_X), (Y, d_Y)$ be metric spaces, x_0 be a point in X , and $f : X \rightarrow Y$ be a function. The following are equivalent:

1. f is continuous at x_0
2. For every sequence $(x_n)_{n=1}^\infty$ in X , if $x_n \xrightarrow{n \rightarrow +\infty}$ in (X, d_X) ,

$$\text{then } f(x_n) \xrightarrow{n \rightarrow +\infty} f(x_0) \text{ in } (Y, d_Y)$$

Theorem 59: Continuity and Open Sets

Let $(X, d_X), (Y, d_Y)$ be metric spaces. A function $f : X \rightarrow Y$ is continuous iff the inverse image $f^{-1}(G)$ of any open subset G of Y is an open subset of X

Definition 60: Topological Space

A **topological space** is a set X together with a family \mathcal{T} of subsets of X that has the following properties:

- $\emptyset, X \in \mathcal{T}$
- Any union of elements of \mathcal{T} is an element of \mathcal{T}
- Any finite intersection of elements of \mathcal{T} is an element of \mathcal{T}

\mathcal{T} is called a **topology** and the elements of \mathcal{T} are called **open sets**

Definition 61: Continuity of Topological Spaces

- Let (X, \mathcal{T}_X) and (Y, \mathcal{T}_Y) be two topological spaces. A function $f : X \rightarrow Y$ is said to be **continuous** iff for every G in \mathcal{T}_Y the pre-image $f^{-1}(G)$ is an element of \mathcal{T}_X .
- f is said to be a **homeomorphism** iff it is a continuous bijection and its inverse is continuous.
- If such a homeomorphism exists then (X, \mathcal{T}_X) and (Y, \mathcal{T}_Y) are said to be **homeomorphic**

Theorem 2.1.2: $d : X \times X \rightarrow \mathbb{R}$ is continuous

Let (X, d) be a metric space. The function $f : X \times X \rightarrow \mathbb{R}$ is continuous.

\mathbb{R} is equipped with the standard metric. $X \times X$ is equipped with the product metric

Let $(X, \|\cdot\|_X), (Y, \|\cdot\|_Y)$ be normed vector spaces. Recall that $d_X : X \times X \rightarrow \mathbb{R}$, $d(x, x') = \|x - x'\|_X$, and $d_Y : Y \times Y \rightarrow \mathbb{R}$, $d_Y(y, y') = \|y - y'\|_Y$ are metrics

Definition 2.1.3: Bounded Linear Operators

A linear operator $T : X \rightarrow Y$ is said to be **bounded** iff there exists a positive constant C such that, for all $x \in X$,

$$\|T(x)\|_Y \leq C\|x\|_X$$

Theorem 2.1.4: Linear Operator Equivalence

Let $T : X \rightarrow Y$ be a linear operator. The following are equivalent:

1. T is continuous
2. T is continuous at 0
3. T is bounded

- Let $(X, \|\cdot\|)$ be a normed vector space and define $f : \mathbb{R} \times X \rightarrow X$ by $f(\lambda, x) = \lambda x$. Define $g : X \times X \rightarrow X$ by $g(x, y) = x + y$. f and g are continuous

2.2 Fixed Points and Lipschitz

Definition 2.2.1: Lipschitz Functions

Let $(X, d_X), (Y, d_Y)$ be metric spaces. A function $f : X \rightarrow Y$ is said to be a **Lipschitz** function iff there exists a constant L such that for all $x, x' \in X$,

$$d_Y(f(x), f(x')) \leq L d_X(x, x')$$

If $L < 1$, f is said to be a **contraction**

Note: Magnus uses non-standard terminology here:

- When the equation is satisfied and $L < 1$, Magnus calls f a **strict contraction**
- He uses **contraction** for a functino f that satisfies the weaker condition: for all $x, x' \in X$ with $x \neq x'$

$$d_Y(f(x), f(x')) < d_X(x, x')$$

Theorem 2.2.2: Lipschitz Continuity

Every Lipschitz function is continuous

Definition 2.2.3: Fixed Points

A **fixed point** of a function $f : S \rightarrow S$ where S is a non-empty set, is any element x of S such that $f(x) = x$
Solving equations can sometimes be reduced to finding fixed points

Watch lecture recording 06/03 for more in-depth examples

- Newton’s Method for solving $f(x) = 0$
- Picard’s Method for solving the Initial Value Problem

Theorem 2.2.4: Banach’s Fixed Point Theorem

Let (X, d) be a complete metric space and let $f : X \rightarrow X$ be a contraction. Then f has a unique fixed point

2.3 Equivalent Metrics

Definition 2.3.1: Equivalent Metrics

Two metrics on the same non-empty set X are said to be **equivalent** iff they have the same open sets

Theorem 2.3.2: Equivalent Metrics Theorem

Let d_1 and d_2 be metrics on the same non-empty set X . If there exist positive constants C and C' such that for all x, y in X ,

$$Cd_1(x, y) \leq d_2(x, y) \leq C'd_1(x, y)$$

then d_1 and d_2 are equivalent

Definition 2.3.3: Limits of functions between metric spaces

Let (X, d_X) and (Y, d_Y) be metric spaces, x_0 be a limit point of X , $y_0 \in Y$ and $f : X \rightarrow Y$ be a function. We say that $\lim_{x \rightarrow x_0} f(x) = y_0$ iff

$$\forall \epsilon > 0 \quad \exists \delta > 0 \quad \forall x \in B_X(x_0, \delta) \setminus \{x_0\} \quad f(x) \in B_Y(y_0, \epsilon)$$

Theorem 2.3.4: Completeness of the Classical Spaces

Some examples of complete metric spaces:

- (\mathbb{R}^n, d_2)
- ℓ^2
- $C([a, b])$
- ℓ^∞

Let (X, d_X) and (Y, d_Y) be two metric spaces and assume that (Y, d_Y) is complete.
Let $C(X, Y)$ be the set of all continuous and bounded functions from X to Y . For $f, g \in C(X, Y)$ define

$$D(f, g) = \sup\{d_Y(f(x), g(x)) : x \in X\}$$

D is a metric and the metric space $(C(X, Y), D)$ is complete

Definition 2.3.5: The product space X^n

Let (X, d) be a metric space and $n \in \mathbb{N}$. Define $D : X^n \rightarrow \mathbb{R}$ by

$$D(x_1, x_2) = d(x_{11}, x_{21}) + d(x_{12}, x_{22}) + \cdots + d(x_{1n}, x_{2n})$$

Lemma: D is a metric and a sequence converges in (X^n, D) iff it converges componentwise

Lemma: If (X, d) is complete then (X^n, D) is complete

Definition 2.3.6: The product space $X^{\mathbb{N}}$

Let B^A , where A, B are sets, be the set of all functions from A to B
Def: Let (X, d) be a metric space. Define a metric $D : X^{\mathbb{N}} \times X^{\mathbb{N}} \rightarrow \mathbb{R}$ by

$$D(x_1, x_2) = \sum_{n=1}^{\infty} \frac{1}{2^n} \frac{d(x_{1n}, x_{2n})}{1 + d(x_{1n}, x_{2n})}$$

where $x_1 = (x_{11}, \dots, x_{1n}, \dots)$, $x_2 = (x_{21}, \dots, x_{2n}, \dots)$
 $(X^{\mathbb{N}}, D)$ is called a **product space**

Theorem 2.3.7: Convergence of Product spaces

Let (X, d) be a metric space, let $(x_k)_{k=1}^\infty$ be a sequence in $X^{\mathbb{N}}$ and let $x \in X^{\mathbb{N}}$. Write $x_k = (x_{k1}, \dots, x_{kn}, \dots)$ and $x = (l_1, \dots, l_n, \dots)$.

Then, $x_k \xrightarrow[k \rightarrow +\infty]{(X^{\mathbb{N}}, D)} x$ if and only if, for all n , $x_{kn} \xrightarrow[k \rightarrow +\infty]{(X^{\mathbb{N}})_{l_n}}$

Theorem 2.3.8: Completeness of product spaces

Let (X, d) be a complete metric space. Then the product space $(X^{\mathbb{N}}, D)$ is complete.

Theorem 2.3.9: Completeness of \mathbb{R}

- **Thm (Least Upper Bound Principle):** Every non-empty bounded above subset of \mathbb{R} has a least upper bound
- **Thm (Monotone Convergence):** Every bounded monotone sequence of real numbers has a limit
- **Thm (ϵ -convergence):** Let A be a non-empty bounded subset of \mathbb{R} and let ϵ be positive. If the distance between any two elements of A is $< \epsilon$, then

$$\sup(A) - \inf(A) \leq \epsilon$$

- **Thm:** Every Cauchy sequence of real numbers is convergent

Definition 2.3.10: Limit Superior and Inferior

Let $(x_n)_{n=1}^{\infty}$ be a Cauchy sequence in \mathbb{R} . Then $(x_n)_{n=1}^{\infty}$ is bounded. Define:

$$I_n = \inf\{x_n, x_{n+1}, \dots\} \quad S_n = \sup\{x_n, x_{n+1}, \dots\}$$

Thm: $(S_n)_{n=1}^{\infty}$ and $(I_n)_{n=1}^{\infty}$ are monotone and bounded

$$I_1 \leq I_n \leq S_n \leq S_1, \quad n = 1, 2, \dots$$

Therefore $I_n \rightarrow I$ and $S_n \rightarrow S$ for some reals I and S . Since $S_n - I_n \rightarrow 0$ we have $S = I$. We also have $x_n \rightarrow S = I$

Limsup and Liminf

- The limit of the sequence $(I_n)_{n=1}^{\infty}$ is called the **limit inferior** of $(x_n)_{n=1}^{\infty}$ and is denoted by $\liminf x_n$

$$\liminf x_n = \lim_{n \rightarrow +\infty} I_n = \lim_{n \rightarrow +\infty} \inf\{x_n, x_{n+1}, \dots\}$$

- The limit of the sequence $(S_n)_{n=1}^{\infty}$ is called the **limit superior** of $(x_n)_{n=1}^{\infty}$ and is denoted by $\limsup x_n$

$$\limsup x_n = \lim_{n \rightarrow +\infty} S_n = \lim_{n \rightarrow +\infty} \sup\{x_n, x_{n+1}, \dots\}$$

- $\liminf x_n$ is the smallest subsequential limit of $(x_n)_{n=1}^{\infty}$
- $\limsup x_n$ is the largest subsequential limit of $(x_n)_{n=1}^{\infty}$
- $(x_n)_{n=1}^{\infty}$ converges iff $\liminf x_n = \limsup x_n$

Definition 3.0.2: Compacting Compactness

Let $X = \mathbb{R}$ and d be the standard metric. Let K be a subset of \mathbb{R}

Compactness

The following definitions are equivalent:

1. K is said to be **compact** iff every sequence of elements of K has a subsequence that converges to an element of K
2. K is **compact** iff every open cover of K has a finite subcover

Sequential Compactness

3. K is **sequentially compact** iff every sequence in K has a subsequence that converges to an element of K

For the case $K = X$ it's just the definition (1) defined above

Uniform Continuity

4. Let $(X, d_X), (Y, d_Y)$ be metric spaces. A function $f : X \rightarrow Y$ is said to be **uniformly continuous** iff for every $\epsilon > 0$ there exists a $\delta > 0$ such that, for all x, x' in X with $d_X(x, x') < \delta$ we have

$$d_Y(f(x), f(x')) < \epsilon$$

Totally bounded Spaces

5. A metric space (X, d) is said to be **totally bounded** iff for every positive δ , X can be covered by a finite number of open balls of radius δ .
6. If (X, d) is totally bounded then it is bounded, but the converse is not necessarily true

Example 3.0.3: Examples of compactness

Compact sets

- $[a, b]$ is compact
- \emptyset is compact
- $\mathbb{R} \cup \{-\infty, +\infty\}$ is compact!

Not Compact sets

- $(0, 1)$ is not compact
- \mathbb{R} is not compact

Theorem 3.0.4: Lebesgue's Lemma

Let (X, d) be a sequentially compact metric space and $X = \bigcup_{i \in I} G_i$ be an open cover of X . There exists a $\delta > 0$ such that for any two points $x, y \in X$ with $d(x, y) < \delta$ there exists an i such that $x, y \in G_i$. Any such δ is called a **Lebesgue number** of the open cover

Lemma: Let (X, d) be a sequentially compact metric space and $X = \bigcup_{i \in I} G_i$ be an open cover of X . Then there exists a $\delta > 0$ such that any nonempty subset of X of diameter $< \delta$ can be covered by a single G_i

Theorem 3.0.5: big theorem bank of obvious shit

Regular Compactness

- For a set K in \mathbb{R} with the standard metric:
 - K is compact $\iff K$ is closed and bounded
 - K is compact \iff every open cover of K has a finite cover
- For a set K in \mathbb{R}^n with the Euclidean metric:
 - K is compact $\iff K$ is closed and bounded
- For a set K in \mathbb{R}
 - Every open cover of K has a finite subcover $\implies K$ is closed and bounded $\implies K$ is compact
- Every open cover of the interval $[a, b]$, where $a, b \in \mathbb{R}$, $a \leq b$ has a finite subcover

Continuous Functions

- Let $K \subseteq \mathbb{R}$ be compact, and $f : K \rightarrow \mathbb{R}$ continuous:
 - f is bounded
 - f has a maximum and minimum (EVT)
- Let (X, d) be a metric space, K be a sequentially compact subset of X and $f : K \rightarrow \mathbb{R}$ be a continuous function:
 - f has a maximum and a minimum. In particular, f is bounded. (EVT ..again)

Sequential compactness stuff

Let (X, d) be a metric space, and $K \subseteq X$:

- Let $K \neq \emptyset$, and let d_K be the induced metric on K .
 - K (sequentially) compact \iff the metric space (K, d_K) is (sequentially) compact
- K sequentially compact $\implies K$ is closed and bounded
- (X, d) and K are both sequentially compact $\iff K$ is closed
- (X, d) is sequentially compact $\implies (X, d)$ is complete
- (X, d) is compact $\implies (X, d)$ is sequentially compact
- K is compact $\iff K$ is sequentially compact
- (X, d) is compact, and let A be an infinite subset of $X \implies A$ has at least one limit point

Uniform Continuity

Let (X, d_X) be a sequentially compact metric space, (Y, d_Y) be a metric space and $f : X \rightarrow Y$ be a continuous function. Then f is uniformly continuous

Totally Compact Spaces

Let (X, d) be a metric space:

- (X, d) is sequentially compact $\implies (X, d)$ is totally bounded
- (X, d) is compact $\iff (X, d)$ complete and totally bounded

Thm: Every sequentially compact metric space is compact. (From now on, refer to sequentially compact spaces as compact)

Definition 3.0.6: Countable and Uncountable Sets

A set S is said to be:

- **Infinitely countable** iff there is a bijection $f : \mathbb{N} \rightarrow S$
- **Countable** if it is finite or infinitely countable
- **Uncountable** iff it isn't countable

Examples

- $\{1, 2, 3\}$ and \mathbb{R} are countable sets
- \mathbb{Q} is infinitely countable
- \mathbb{R} is uncountable

3 Compactness

Definition 3.0.1: Open Covers and Subcovers

An **open cover** of a set S in a metric space is a family $(G_i)_{i \in I}$ of open sets such that $S \subset \bigcup_{i \in I} G_i$. A **subcover** of an open cover

$(G_i)_{i \in I}$ is a sub-family $(G_i)_{i \in I'}$ where $I' \subset I$, such that $S \subset \bigcup_{i \in I'} G_i$

Theorem 3.0.7: Dense Subset equivalence

Let (X, d) be a metric space and $D \subseteq X$. The following are equivalent:

1. D is dense
2. For every $x \in X$ and $\epsilon > 0$ there exists $y \in D$ s.t. $d(x, y) < \epsilon$
3. For every $x \in X$ there is a sequence $(y_n)_{n=1}^\infty$ of elements of D s.t. $y_n \rightarrow x$
4. For every element $x \in X$ and every open nbhd G of x , $G \cap D \neq \emptyset$
5. D intersects every non-empty open set

Definition 3.0.8: Separable spaces

A metric space is said to be **separable** iff it has a countable dense subset

Examples

- \mathbb{R} with the standard metric is a separable metric because \mathbb{Q} is dense and countable
- \mathbb{R}^n with the Euclidean metric is a separable metric space because \mathbb{Q}^n is dense and countable
- \mathbb{C} with its standard metric is a separable metric space because $\{z \in \mathbb{C} : \operatorname{Re}(z), \operatorname{Im}(z) \in \mathbb{Q}\}$
- ℓ^2 is separable, and ℓ^p is separable for $1 \leq p < \infty$

Theorem 3.0.9: Weierstrass Approximation Theorem

Let $f : [a, b] \rightarrow \mathbb{R}$ be a continuous function and $\epsilon > 0$. There exists a polynomial p with *real* coefficients s.t. for all $x \in [a, b]$

$$|f(x) - p(x)| < \epsilon$$

Let $f : [a, b] \rightarrow \mathbb{R}$ be a continuous function and $\epsilon > 0$. There exists a polynomial p with *rational* coefficients s.t. for all $x \in [a, b]$

$$|f(x) - p(x)| < \epsilon$$

Theorem 3.0.10: more theorems

The set of all polynomials with rational coefficients is countable

Thm: $C([a, b])$ is separable

Theorem 3.0.11: Separability of subspaces

Let (X, d) be a separable metric space, $A \subseteq X$, $A \neq \emptyset$, and d_A be the induced metric on A . Then the metric space (A, d_A) is separable

Thm: Every compact metric space is separable (compact \implies separable)

Theorem 3.0.12: Open Ball countability

Let (X, d) be a separable metric space and let D be a countable dense subset of X . Let

$$\mathcal{B} = \{B(c, r) : c \in D, r \in \mathbb{Q}^+\}$$

be the set of all open balls with centers in D and rational radii. Then \mathcal{B} is countable and every open set in X can be written as a union of elements of \mathcal{B}

Definition 3.0.13: Open Bases and Second Countability

Open Bases

Let (X, \mathcal{T}) be a topological space. An **open base** (or **base**) for the topology \mathcal{T} is a family \mathcal{B} of open sets such that every open set in \mathcal{T} can be written as a union of elements of \mathcal{B}

Second Countability

A topological space (X, \mathcal{T}) is said to satisfy the **second Axiom of Countability**, or is **second countable** iff it has a countable open base

Thm: In a separable metric space, every family of pairwise disjoint non-empty open sets is countable

Thm: On the real line with the standard metric, every open set can be written as a countable union of disjoint open intervals

Definition 3.0.14: Continuous Extensions

Let $(X, d_X), (Y, d_Y)$ be metric spaces, D be a dense subset of X , $f, g : X \rightarrow Y$ continuous functions s.t. $f(x) = g(x)$ for all $x \in D$. Then $f = g$

Let $(X, d_X), (Y, d_Y)$ be metric spaces, $D \subseteq X$ be dense, $f : D \rightarrow Y$ be uniformly continuous, and assume that (Y, d_Y) is complete. Then f has a unique continuous extension $F : X \rightarrow Y$

Theorem 3.0.15: complete ms props

Let (X, d) be a metric space, F be a nonempty subset of X and d_F be the induced metric on F . If the metric space (F, d_F) is complete then F is a closed subset of X

Thm: Let (X, d) be a complete metric space, F be a nonempty subset of X , and d_F be the induced metric on F . If F is a closed subset of X , then the metric space (F, d_F) is complete

Thm: Let (X, d) be a complete metric space, $A \subseteq X$, $A \neq \emptyset$. Then

1. The metric space $(\bar{A}, d_{\bar{A}})$ is complete
2. If $A \subseteq B \subseteq X$ and (B, d_B) is complete, then $\bar{A} \subseteq B$

Definition 3.0.16: Isometries

Let (X, d_X) and (Y, d_Y) be metric spaces. A function $f : X \rightarrow Y$ is called a **isometry** iff for all $x_1, x_2 \in X$,

$$d_Y(f(x_1), f(x_2)) = d_X(x_1, x_2)$$

Thm: Let (X, d_X) and (Y, d_Y) be metric spaces and $f : X \rightarrow Y$ be an isometry. Then f is an injection. If, moreover, f is a surjection (hence f bij.) then $f^{-1} : Y \rightarrow X$ is also an isometry

Thm: The metric spaces (X, d_X) and (Y, d_Y) are said to be **isometric** iff there exists an isometry f from X onto Y

Thm: if two metric spaces are isometric and one of them is complete/compact/connected/... then so is the other

Theorem 3.0.17: Isometry completion

Let (X, d) be a bounded metric space and let $C(X, \mathbb{R})$ be the set of all bounded continuous functions $f : X \rightarrow \mathbb{R}$ equipped with the metric

$$d_\infty(f_1, f_2) = \sup\{|f_1(t) - f_2(t)| : t \in X\}$$

For each $x \in X$, define $F_X : X \rightarrow \mathbb{R}$ be $F_X(x') = d(x, x')$. Then

1. $F_X \in C(X, \mathbb{R})$
2. The map $X \rightarrow C(X, \mathbb{R}), x \mapsto F_X$ is an isometry
3. $X^* = \{F_X : x \in X\}$, equipped with the induced metric, is a subspace of $C(X, \mathbb{R})$ isometric to X
4. The closure $\overline{X^*}$ of X^* in $C(X, \mathbb{R})$, equipped with the induced metric, is a complete metric space
5. X^* is dense in $\overline{X^*}$

Definition 3.0.18: Completion of a Metric Space

Let (X, d) be a metric space. A **completion** of (X, d_X) is any metric space (Y, d_Y) with the following properties

1. (Y, d_Y) is complete
2. (Y, d_Y) has a subspace X^* isometric to (X, d_X)
3. X^* is dense in Y

It can be shown that any two completions of X are isometric to each other, i.e. a completion is unique up to isometries

Definition 3.0.19: Construction of Completion via Cauchy

Let (X, d) be a metric space and let \mathcal{C} be the set of all Cauchy sequences of elements of X . We define an equivalence relation \sim in \mathcal{C} as follows: Let $x = (x_n)_{n \in \mathbb{N}}$, $y = (y_n)_{n \in \mathbb{N}} \in \mathcal{C}$. We say that $x \sim y$ iff $d(x_n, y_n) \rightarrow 0$. Distinct equivalence classes are disjoint and partition \mathcal{C} . The set of all equivalence classes is called the **quotient space**, denoted \mathcal{C}/\sim .

Define a metric D on \mathcal{C}/\sim as follows:

Let $\alpha, \beta \in \mathcal{C}/\sim$. Then

$$\alpha = [(x_1, \dots, x_n, \dots)] \text{ and } \beta = [(y_1, \dots, y_n, \dots)]$$

for some $(x_1, \dots, x_n, \dots), (y_1, \dots, y_n, \dots) \in \mathcal{C}$. Define

$$D(\alpha, \beta) = \lim_{n \rightarrow +\infty} d(x_n, y_n)$$

$(\mathcal{C}/\sim, D)$ is complete. Additionally, the following is an isometry:

$$X \rightarrow \mathcal{C}/\sim \quad x \mapsto ([x, x, \dots, x, \dots])$$

Let X^* be its range. The metric space (X^*, D_{X^*}) is isometric to (X, d) , $(\overline{X^*}, D_{\overline{X^*}})$ is a complete metric space, and X^* is dense in $\overline{X^*}$.

Definition 3.0.20: Connected and Disconnected Spaces

A metric space (X, d) is said to be **disconnected** iff there exists non-empty disjoint open sets G_1 and G_2 such that

$$X = G_1 \cup G_2$$

Otherwise the metric space is called **connected**.

A non-empty subset A of a metric space (X, d) is said to be disconnected iff the metric space (A, d_A) , where d_A is the induced metric, is disconnected.

Theorem 3.0.21: Connected Theorems

A subset O of A is open in (A, d_A) iff $O = A \cup G$ for some G that is open in X .

Therefore, A is disconnected iff there exist open subsets G_1, G_2 of X s.t.

- $A = (A \cap G_1) \cup (A \cap G_2)$, which is equivalent to $A \subseteq G_1 \cup G_2$
- $A \cap G_1 \neq \emptyset$, $A \cap G_2 \neq \emptyset$
- $(A \cap G_1) \cap (A \cap G_2) = \emptyset$, which is equivalent to $A \cap G_1 \cap G_2 = \emptyset$

Thm: \mathbb{R} with the standard metric is connected.

Thm: On the real line with the standard metric, all intervals are connected sets.

Thm: A non-empty subset of the real line is connected iff it is an interval.

Thm: A metric space (X, d) is connected iff the only subsets of X with empty boundary are \emptyset and X .

Thm: Let (X, d_X) be a connected metric space, (Y, d_Y) be a metric space and $f : X \rightarrow Y$ be a continuous surjection. Then (Y, d_Y) is connected as well.

Theorem 3.0.22: Intermediate Value Theorem

Let (X, d) be a connected metric space and $f : X \rightarrow \mathbb{R}$ be a continuous function. If $x_1, x_2 \in X$ with $f(x_1) \neq f(x_2)$ and y is a real number between $f(x_1)$ and $f(x_2)$, then there exists an $x \in X$ such that $f(x) = y$.

Theorem 3.0.23: Clopen

A metric space (X, d) is connected iff the only clopen subsets are \emptyset, X .

Definition 3.0.24: Connected Components

Let (X, d) be a metric space. We define an equivalence relation \sim in X as follows: $x \sim x'$ iff there exists a connected subset C of X that contains both x and x' .

Thm: If $(C_i)_{i \in I}$ is a family of connected subsets of X with nonempty intersection, then $\bigcup_{i \in I} C_i$ is connected.

Theorem 3.0.25: Big equivalence classes

The equivalence class of any point in X is the largest connected subset of X that contains that point (what point?).

Definition 3.0.26: Path Connected Metric Spaces

Let (X, d) be a metric space and $x_0, x_1 \in X$. A **path** in X from x_0 to x_1 is a continuous function $\gamma : [0, 1] \rightarrow X$ s.t. $\gamma(0) = x_0$, $\gamma(1) = x_1$. (X, d) is said to be **path-connected** iff for any two points x_0, x_1 in X there is a path in X from x_0 to x_1 .

A non-empty subset A of X is said to be **path-connected** iff the metric space (A, d_A) , where d_A is the induced metric, is path connected.

Theorem 3.0.27: Path connected theorem

Every path-connected metric space is connected.

Not every connected metric space is necessarily path-connected.

4 Applications

Theorem 4.0.1: Picard's Theorem

Let $f : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$ be a continuous and bounded function, and t_0, x_0 be real numbers. Assume that there exists a positive constant L s.t. for all real t, x_1, x_2 we have:

$$|f(t, x_1) - f(t, x_2)| \leq L|x_1 - x_2|$$

Then, there exists a positive δ and a unique differentiable function $x : [t_0 - \delta, t_0 + \delta] \rightarrow \mathbb{R}$ s.t. for all $t \in [t_0 - \delta, t_0 + \delta]$,

$$x'(t) = f(t, x(t)) \quad \text{and} \quad x(t_0) = x_0$$

Definition 4.0.2: Lipschitz Functions again

Let $(X, d_X), (Y, d_Y)$ be metric spaces. A function $f : X \rightarrow Y$ is said to be a **Lipschitz** function iff there exists a constant L such that for all $x, x' \in X$,

$$d_Y(f(x), f(x')) \leq L d_X(x, x')$$

If $L < 1$, f is said to be a **contraction**.

If $f : \mathbb{R} \rightarrow \mathbb{R}$ is a Lipschitz function and x_0 is any point in \mathbb{R} , then for any $x \in \mathbb{R}$ we have

$$|f(x) - f(x_0)| \leq L|x - x_0|$$

For $x \geq x_0$ this can be expanded to

$$f(x_0) - L(x - x_0) \leq f(x) \leq f(x_0) + L(x - x_0)$$

Let (X, d_X) and (Y, d_Y) be two metric spaces, and $f : X \rightarrow Y$ be a Lipschitz function. Then there exists a smallest Lipschitz constant of f .

Thm: Let I be a non-degenerate open interval on the real line and let $f : I \rightarrow \mathbb{R}$ be a differentiable function. Then f is Lipschitz iff f' is bounded. When that is the case,

$$|f|_{\text{Lip}} = \sup\{|f'(x)| : x \in I\}$$

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