

# MATH597

## Analysis II

Pingbang Hu

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### Abstract

Notice that since in this course, the cross-referencing between theorems, lemmas, and propositions are quite complex and hard to keep track of, hence in this note, whenever you see a **!** over  $=$ , like  $\stackrel{!}{=}$ , then that **!** is *clickable*! It will direct you to the corresponding theorem, lemma, or proposition we're using to deduce that particular equality.

Notice that there are some proofs is **intended** left as assignments, and for completeness, I put them in [Appendix A](#), use it in your **own risks**! You'll lose the chance to practice and really understand the materials.

Additionally, we'll use [\[FF99\]](#) as our main text, while using [\[Tao13\]](#) and [\[Ax19\]](#) as supplementary references.

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## Lecture 1: $\sigma$ -algebra

05 Jan. 11:00

### 1 Measure

**Example.** Before we start, we first see some examples.

1. Let  $X = \{a, b, c\}$ . Then

$$\mathcal{P}(X) := \{\emptyset, \{a\}, \{b\}, \{c\}, \{a, b\}, \{a, c\}, \{b, c\}, \{a, b, c\}\},$$

which is the *power set* of  $X$ . We see that

$$\#X = n \implies \#\mathcal{P}(X) = 2^n$$

for  $n < \infty$ .

2. If  $n = \infty$ , say  $X = \mathbb{N}$ , then

$$\mathcal{P}(\mathbb{N})$$

is an uncountable set while  $\mathbb{N}$  is a countable set. We can see this as follows. Consider

$$\phi: \mathcal{P}(\mathbb{N}) \rightarrow [0, 1], \quad A \mapsto 0.a_1a_2a_3\dots \text{ (base 2),}$$

where

$$a_i = \begin{cases} 1, & \text{if } i \in A \\ 0, & \text{if } i \notin A, \end{cases}$$

and for example,  $A$  can be  $A = \{2, 3, 6, \dots\} \subseteq \mathbb{N}$ . Note that  $\phi$  is surjective, hence we have

$$\#\mathcal{P}(\mathbb{N}) \geq \#[0, 1].$$

But since  $[0, 1]$  is uncountable, so is  $\mathcal{P}(\mathbb{N})$ .

We like to *measure* the *size* of subsets of  $X$ . Hence, we are intriguing to define a map  $\mu$  such that

$$\mu: \mathcal{P}(X) \rightarrow [0, \infty].$$

**Example.** We first see some examples.

1. Let  $X = \{0, 1, 2\}$ . Then we want to define  $\mu: \mathcal{P}(X) \rightarrow [0, \infty]$ , we can have

- $\mu(A) = \#A$ . Then we have
  - $\mu(\{0, 1\}) = 2$
  - $\mu(\{0\}) = 1$
- $\mu(A) = \sum_{i \in A} 2^i$ . Then we have
  - $\mu(\{0, 1\}) = 2^0 + 2^1 = 3$

2. Let  $X = \{0\} \cup \mathbb{N}$ . Then we want to define  $\mu: \mathcal{P}(\mathbb{N}) \rightarrow [0, \infty]$ , we can have

- $\mu(A) = \#A$ . Then we have
  - $\mu(\{2, 3, 4, 5, \dots\}) = \infty = \mu(\{\text{even numbers}\})$
- $\mu(A) = e^{-1} \sum_{i \in A} \frac{1}{i!}$ . Then we have
  - $\mu(\{0, 2, 4, 6, \dots\}) = e^{-1} (1 + \frac{1}{2!} + \frac{1}{3!} + \dots)$
- $\mu(A) = \sum_{i \in A} a_i$

3. Let  $X = \mathbb{R}$ . Then we want to define  $\mu: \mathcal{P}(\mathbb{R}) \rightarrow [0, \infty]$ , we can have

- $\mu(A) = \#A$
- $\mu((a, b)) = b - a$ .

**Problem.** Can we extend this map to all of  $\mathcal{P}(\mathbb{R})$ ?

**Answer.** No!

- $\mu((a, b)) = e^b - e^a$ .

**Problem.** Can we extend this map to all of  $\mathcal{P}(\mathbb{R})$ ?

**Answer.** No!

We immediately see the problems. To extend our native measure method into  $\mathbb{R}$  is hard and will cause something counter-intuitive!<sup>1</sup> Hence, rather than define measurement on *all* subsets in the power set of  $X$ , we only focus on *some* subsets. In other words, we want to define

$$\mu: \mathcal{P}(\mathbb{R}) \supset \mathcal{A} \rightarrow [0, \infty].$$

## 1.1 $\sigma$ -algebras

We start from the definition of the most fundamental element in measure theory.

<sup>1</sup>[https://en.wikipedia.org/wiki/Banach-Tarski\\_paradox](https://en.wikipedia.org/wiki/Banach-Tarski_paradox)

**Definition 1.1 ( $\sigma$ -algebra).** Let  $X$  be a set. A collection  $\mathcal{A}$  of subsets of  $X$ , i.e.,  $\mathcal{A} \subset \mathcal{P}(X)$  is called a  $\sigma$ -algebra on  $X$  if

- $\emptyset \in \mathcal{A}$ .
- $\mathcal{A}$  is closed under complements. i.e., if  $A \in \mathcal{A}$ ,  $A^c = X \setminus A \in \mathcal{A}$ .
- $\mathcal{A}$  is closed under countable unions. i.e., if  $A_i \in \mathcal{A}$ , then  $\bigcup_{i=1}^{\infty} A_i \in \mathcal{A}$ .

**Remark.** There are some easy properties we can immediately derive.

- $X \in \mathcal{A}$  from  $X = X \setminus \underbrace{\emptyset}_{\in \mathcal{A}}$  and  $\mathcal{A}$  is closed under complement.
- $\bigcap_{i=1}^{\infty} A_i = \left( \bigcup_{i=1}^{\infty} A_i^c \right)^c$ , namely  $\mathcal{A}$  is closed under countable intersections.
- $A_1 \cup A_2 \cup \dots \cup A_n = A_1 \cup A_2 \cup \dots \cup A_n \cup \emptyset \cup \emptyset \cup \dots$ , hence  $\mathcal{A}$  is closed under finite unions and intersections.

An immediate definition can be given. We now define so-called *Borel set*.

**Definition 1.2 (Borel set).** Given a topological space  $X$ , a *Borel set* is any set in  $X$  that can be formed from open sets through the operations of countable union, countable intersection and relative complement.

## Lecture 2: Measure

07 Jan. 11:00

**Example.** Again, we first see some examples.

1. Let  $\mathcal{A} = \mathcal{P}(X)$ , which is the power  $\sigma$ -algebra.
2. Let  $\mathcal{A} = \{\emptyset, X\}$ , which is a trivial  $\sigma$ -algebra.
3. Let  $B \subset X$ ,  $B \neq \emptyset$ ,  $B \neq X$ . Then we see that  $\mathcal{A} = \{\emptyset, B, B^c, X\}$  is a  $\sigma$ -algebra.

**Lemma 1.1.** Let  $\mathcal{A}_\alpha$ ,  $\alpha \in I$ , be a family of  $\sigma$ -algebra on  $X$ . Then

$$\bigcap_{\alpha \in I} \mathcal{A}_\alpha$$

is a  $\sigma$ -algebra on  $X$ .

**Remark.** Notice that  $I$  may be an uncountable intersection.

*Proof.* A simple proof can be made as follows. Firstly,  $\emptyset \in \mathcal{A}_\alpha$  for every  $\alpha$  clearly. Moreover, closure under complement and countable unions for every  $\mathcal{A}_\alpha$  implies the same must be true for  $\bigcap_{\alpha \in I} \mathcal{A}_\alpha$ . Hence,  $\bigcap_{\alpha \in I} \mathcal{A}_\alpha$  is a  $\sigma$ -algebra. ■

The above allows us to give the following definition.

**Definition 1.3 (Generation of  $\sigma$ -algebra).** Given  $\mathcal{E} \subset \mathcal{P}(X)$ , where  $\mathcal{E}$  is not necessarily a  $\sigma$ -algebra. Let  $\langle \mathcal{E} \rangle$  be the intersection of all  $\sigma$ -algebras on  $X$  containing  $\mathcal{E}$ , then we call  $\langle \mathcal{E} \rangle$  the  $\sigma$ -algebra generated by  $\mathcal{E}$ .

**Remark.** Clearly,  $\langle \mathcal{E} \rangle$  is the smallest  $\sigma$ -algebra containing  $\mathcal{E}$ , and it is unique. To check the uniqueness, we suppose there are two different  $\langle \mathcal{E} \rangle_1$  and  $\langle \mathcal{E} \rangle_2$  generated from  $\mathcal{E}$ . It's easy to show

$$\langle \mathcal{E} \rangle_1 \subseteq \langle \mathcal{E} \rangle_2,$$

and by symmetry, they are equal.

**Example.** We see that  $\{\emptyset, B, B^c, X\} = \langle \{B\} \rangle = \langle \{B^c\} \rangle$ .

**Lemma 1.2.** We have

1. Given  $\mathcal{A}$  a  $\sigma$ -algebra,  $\mathcal{E} \subset \mathcal{A} \subset \mathcal{P}(X) \implies \langle \mathcal{E} \rangle \subset \mathcal{A}$
2.  $\mathcal{E} \subset \mathcal{F} \subset \mathcal{P}(X) \implies \langle \mathcal{E} \rangle \subset \langle \mathcal{F} \rangle$

*Proof.* We'll see that after proving the first claim, the second follows smoothly.

1. The first claim is trivial, since we know that  $\langle \mathcal{E} \rangle$  is the smallest  $\sigma$ -algebra containing  $\mathcal{E}$ , then if  $\mathcal{E} \subset \mathcal{A}$ , we clearly have  $\langle \mathcal{E} \rangle \subset \mathcal{A}$  by the definition.
2. The second claim is also easy. From the first claim and the definition, we have

$$\mathcal{E} \subset \mathcal{F} \subset \langle \mathcal{F} \rangle \implies \langle \mathcal{E} \rangle \subset \langle \mathcal{F} \rangle.$$

■

At this point, we haven't put any specific structure on  $X$ . Now we try to describe those spaces with good structure, which will give the space some nice properties.

**Definition 1.4 (Borel  $\sigma$ -algebra).** For a topological space  $X$ , the *Borel  $\sigma$ -algebra* on  $X$ , denoted as  $\mathcal{B}(X)$ , is the  $\sigma$ -algebra generated by the collection of all open sets in  $X$ .

**Example.** We see that  $\mathcal{B}(\mathbb{R})$  contains

- $\mathcal{E}_1 = \{(a, b) \mid a < b; a, b \in \mathbb{R}\}$ .
- $\mathcal{E}_2 = \{[a, b] \mid a < b; a, b \in \mathbb{R}\}$  since  $[a, b] = \bigcap_{n=1}^{\infty} (a - \frac{1}{n}, b + \frac{1}{n})$ .
- $\mathcal{E}_3 = \{(a, b] \mid a < b; a, b \in \mathbb{R}\}$  since  $(a, b] = \bigcap_{n=1}^{\infty} (a, b + \frac{1}{n})$ .
- $\mathcal{E}_4 = \{[a, b) \mid a < b; a, b \in \mathbb{R}\}$  since  $[a, b) = \bigcap_{n=1}^{\infty} (a - \frac{1}{n}, b)$ .

- $\mathcal{E}_5 = ((a, \infty) \mid a \in \mathbb{R})$  since  $(a, \infty) = \bigcup_{n=1}^{\infty} (a, a+n)$ .
- $\mathcal{E}_6 = ([a, \infty) \mid a \in \mathbb{R})$  since  $[a, \infty) = \bigcup_{n=1}^{\infty} [a, a+n)$ .
- $\mathcal{E}_7 = ((-\infty, b) \mid b \in \mathbb{R})$  since  $(-\infty, b) = \bigcup_{n=1}^{\infty} (b-n, b)$ .
- $\mathcal{E}_8 = ((-\infty, b] \mid b \in \mathbb{R})$  since  $(-\infty, b] = \bigcup_{n=1}^{\infty} (b-n, b]$ .

**Proposition 1.1.**  $\mathcal{B}(\mathbb{R}) = \langle \mathcal{E}_i \rangle$  for each  $i = 1, \dots, 8$ .

*Proof.* Firstly, we see that  $\mathcal{E}_i \subset \mathcal{B}(\mathbb{R}) \implies \langle \mathcal{E}_i \rangle \subset \mathcal{B}(\mathbb{R})$  by Lemma 1.2. Secondly, by definition,  $\mathcal{B}(\mathbb{R}) = \langle \mathcal{E} \rangle$  where

$$\mathcal{E} = \{O \subseteq \mathbb{R} \mid O \text{ is open in } \mathbb{R}\}.$$

It's enough to show  $\mathcal{E} \subset \langle \mathcal{E}_i \rangle$  since if so,  $\langle \mathcal{E} \rangle \subseteq \langle \mathcal{E}_i \rangle$ , and clearly  $\langle \mathcal{E} \rangle \supseteq \langle \mathcal{E}_i \rangle = \mathcal{B}(\mathbb{R})$ , then we will have  $\langle \mathcal{E} \rangle = \langle \mathcal{E}_i \rangle$ . Let  $O \subset \mathbb{R}$  be an open set, i.e.,  $O \in \mathcal{E}$ . We claim that every open set in  $\mathbb{R}$  is a countable union of disjoint open intervals.<sup>2</sup>

Thus,

$$O = \bigcup_{j=1}^{\infty} I_j,$$

where  $I_j$  open interval with the form of  $(a, b), (-\infty, b), (a, \infty), (-\infty, \infty)$ .

For example,  $\mathcal{E}_1$  is trivially true, and

$$(a, b) = \underbrace{\bigcup_{n=1}^{\infty} \underbrace{\left[a + \frac{1}{n}, b - \frac{1}{n}\right]}_{\in \mathcal{E}_2}}_{\in \langle \mathcal{E}_2 \rangle}$$

shows the case for  $\mathcal{E}_2$  and

$$(a, \infty) = \bigcup_{k=1}^{\infty} (a, a+k)$$

shows the case for  $\mathcal{E}_5$ . It's now straightforward to check open intervals are in  $\langle \mathcal{E}_i \rangle$  for every  $i$ . ■

Now, to put a structure on a space, we define the following.

**Definition 1.5 (Measurable space,  $\mathcal{A}$ -measurable set).** A *measurable space* or *Borel space* is a tuple of a set  $X$  and a  $\sigma$ -algebra  $\mathcal{A}$  on  $X$ , denoted by  $(X, \mathcal{A})$ .

<sup>2</sup><https://math.stackexchange.com/questions/318299/any-open-subset-of-bbb-r-is-a-countable-union-of-disjoint-open-intervals>

**Definition 1.6 (Measurable set).** Given a measurable space  $(X, \mathcal{A})$ , every  $E \in \mathcal{A}$  is a so-called  $\mathcal{A}$ -measurable set.

## 1.2 Measures

With the definition of measurable space, we now can refine our measure function  $\mu$  as follows.

**Definition 1.7 (Measure, Measure space).** Given a measurable space on  $(X, \mathcal{A})$ , a *measure* is a function  $\mu$  such that

$$\mu: \mathcal{A} \rightarrow [0, \infty]$$

with

1.  $\mu(\emptyset) = 0$
2.  $\mu\left(\bigcup_{i=1}^{\infty} A_i\right) = \sum_{i=1}^{\infty} \mu(A_i)$  if  $A_1, A_2, \dots \in \mathcal{A}$  are **disjoint**. We call this *Countable additivity*.

We denote  $(X, \mathcal{A}, \mu)$  a *measure space*.

**Notation.** We denote  $[0, \infty] := [0, \infty) \cup \{\infty\}$ .

**Remark.** The motivation of why we only want countable additivity but not uncountable additivity can be seen by the following example. We'll consider the most intuitive measure on  $\mathbb{R}, \mathcal{B}(\mathbb{R})$ .

Since we have

$$(0, 1] = (1/2, 1] \cup (1/4, 1/2] \cup (1/8, 1/4] \cup \dots$$

and also

$$(0, 1] = \bigcup_{x \in (0, 1]} \{x\}.$$

Specifically, in the first case, we are claiming that

$$1 = \underbrace{\frac{1}{2}}_{\mu((\frac{1}{2}, 1])} + \underbrace{\frac{1}{4}}_{\mu((\frac{1}{4}, \frac{1}{2}])} + \underbrace{\frac{1}{8}}_{\mu((\frac{1}{8}, \frac{1}{4}])} + \dots;$$

while in the second case, we are claiming that

$$1 = \sum_{x \in (0, 1]} 0$$

since  $\mu(x) = 0$  for  $x \in \mathbb{R}$ , which is clearly not what we want.

**Example.** We see some examples.

1. For any  $(X, \mathcal{A})$ , we let  $\mu(A) := \#A$ . This is called *counting measure*.
2. Let  $x_0 \in X$ . For any  $(X, \mathcal{A})$ , the *Dirac-Delta measure* at  $x_0$  is

$$\mu(A) = \begin{cases} 1, & \text{if } x_0 \in A; \\ 0, & \text{if } x_0 \notin A. \end{cases}$$

3. For  $(\mathbb{N}, \mathcal{P}(\mathbb{N}))$ ,

$$\mu(A) = \sum_{i \in A} a_i,$$

where  $a_1, a_2, \dots \in [0, \infty)$ .

### Lecture 3: Construct a Measure

10 Jan. 11:00

**Note.** If  $A, B \in \mathcal{A}$  and  $A \subset B$ , then

$$\mu(B \setminus A) + \mu(A) = \mu(B) \implies \mu(B \setminus A) = \mu(B) - \mu(A) \text{ if } \mu(A) < \infty.$$

**Theorem 1.1.** Given  $(X, \mathcal{A}, \mu)$  be a *measure space*.

1. Monotonicity.

$$A, B \in \mathcal{A}, A \subset B \implies \mu(A) \leq \mu(B).$$

2. Countable subadditivity.

$$A_1, A_2, \dots \in \mathcal{A} \implies \mu\left(\bigcup_{i=1}^{\infty} A_i\right) \leq \sum_{i=1}^{\infty} \mu(A_i).$$

3. Continuity from below/ monotone convergence theorem (MCT) for sets.

$$\begin{cases} A_1, A_2, \dots \in \mathcal{A} \\ A_1 \subset A_2 \subset A_3 \subset \dots \end{cases} \implies \mu\left(\bigcup_{i=1}^{\infty} A_i\right) = \lim_{n \rightarrow \infty} \mu(A_n).$$

4. Continuity from above.

$$\begin{cases} A_1, A_2, \dots \in \mathcal{A} \\ A_1 \supset A_2 \supset A_3 \supset \dots \\ \mu(A_1) < \infty \end{cases} \implies \mu\left(\bigcap_{i=1}^{\infty} A_i\right) = \lim_{n \rightarrow \infty} \mu(A_n).$$

*Proof.* We prove this theorem one by one.

1. Since  $A \subset B$ , hence we have

$$\mu(B) = \mu\left(\underbrace{(B \setminus A) \cup A}_{\text{disjoint}}\right) \stackrel{!}{=} \underbrace{\mu(B \setminus A) + \mu(A)}_{\geq 0} \geq \mu(A).$$



2. This should be trivial from [countable additivity](#) with the fact that  $\mu(A) \geq 0$  for all  $A$ .
3. Let  $B_1 = A_1$ ,  $B_i = A_i \setminus A_{i-1}$  for  $i \geq 2$ , then

$$\bigcup_{i=1}^{\infty} A_i = \bigcup_{i=1}^{\infty} B_i$$

are a disjoint union and  $B_i \in \mathcal{A}$ , hence we see that

$$\mu\left(\bigcup_{i=1}^{\infty} A_i\right) = \sum_{i=1}^{\infty} \mu(B_i) = \lim_{n \rightarrow \infty} \sum_{i=1}^n \mu(B_i).$$

With  $\mu\left(\bigcup_{i=1}^n B_i\right) = \mu(A_n)$ , we have

$$\mu\left(\bigcup_{i=1}^{\infty} A_i\right) = \lim_{n \rightarrow \infty} \sum_{i=1}^n \mu(B_i) = \lim_{n \rightarrow \infty} \mu\left(\bigcup_{i=1}^n B_i\right) = \lim_{n \rightarrow \infty} \mu(A_n).$$

4. Let  $E_i = A_1 \setminus A_i \implies E_i \in \mathcal{A}$ ,  $E_1 \subset E_2 \subset \dots$ . We then have

$$\bigcup_{i=1}^{\infty} E_i = \bigcup_{i=1}^{\infty} (A_1 \setminus A_i) = A_1 \setminus \left(\bigcap_{i=1}^{\infty} A_i\right),$$

which implies

$$\bigcap_{i=1}^{\infty} A_i = A_1 \setminus \left(\bigcup_{i=1}^{\infty} E_i\right) \implies \mu\left(\bigcap_{i=1}^{\infty} A_i\right) = \mu(A_1) - \mu\left(\bigcup_{i=1}^{\infty} E_i\right)$$

since  $\mu\left(\bigcup_{i=1}^{\infty} E_i\right) \leq \mu(A_1) < \infty$ . Then from [continuity from below](#), we further have

$$\mu\left(\bigcap_{i=1}^{\infty} A_i\right) = \mu(A_1) - \lim_{n \rightarrow \infty} \mu(E_n) = \mu(A_1) - \lim_{n \rightarrow \infty} (\mu(A_1) - \mu(A_n)).$$

From [monotonicity](#), we see that  $\mu(A_n) \leq \mu(A_1) < \infty$ , hence we can split the limit and further get

$$\mu\left(\bigcap_{i=1}^{\infty} A_i\right) = \mu(A_1) - \mu(A_1) + \lim_{n \rightarrow \infty} \mu(A_n) = \lim_{n \rightarrow \infty} \mu(A_n).$$

■

**Example.** Given  $(\mathbb{N}, \mathcal{P}(\mathbb{N}))$ , [counting measure](#)). Then we see

- $A_n = \{n, n+1, n+2, \dots\} \implies \mu(A_n) = \infty$
- $A_1 \supset A_2 \supset A_3 \supset \dots$

- $\bigcap_{i=1}^{\infty} A_i = \emptyset \implies \mu\left(\bigcap_{i=1}^{\infty} A_i\right) = 0$

**Remark.** We see that in this case, since  $\mu(A_1) \not\leq \infty$ , hence [continuity from above](#) doesn't hold.

We now try to characterize some properties of a measure space.

**Definition 1.8 ( $\mu$ -null,  $\mu$ -subnull, Complete measure space).** Given  $(X, \mathcal{A}, \mu)$ ,

- $A \subset X$  is a  $\mu$ -null set if  $A \in \mathcal{A}$  and  $\mu(A) = 0$ .
- $A \subset X$  is a  $\mu$ -subnull set if  $\exists \mu$ -null set  $B$  such that  $A \subset B$ .
- $(X, \mathcal{A}, \mu)$  is a complete measure space if every  $\mu$ -subnull set is  $\mathcal{A}$ -measurable.

**Note.** We see that for a  $\mu$ -subnull set, it's not necessary  $\mathcal{A}$ -measurable.

There are some useful terminologies we'll use later relating to  $\mu$ -null.

**Definition 1.9 (Almost everywhere).** Given  $(X, \mathcal{A}, \mu)$ , a statement  $P(x)$ ,  $x \in X$  holds  $\mu$ -almost everywhere (a.e.) if the set

$$\{x \in X : P(x) \text{ does not hold}\}$$

is  $\mu$ -null.

It's always pleasurable working with finite rather than infinite, hence we give the following definition.

**Definition 1.10 (Finite measure).** , Given  $(X, \mathcal{A}, \mu)$

- $\mu$  is a finite measure if  $\mu(X) < \infty$ .
- $\mu$  is a  $\sigma$ -finite measure if  $X = \bigcup_{n=1}^{\infty} X_n$ ,  $X_n \in \mathcal{A}$ ,  $\mu(X_n) < \infty$ .

**Exercise.** Every [measure space](#) can be [completed](#). Namely, we can always find a bigger  $\sigma$ -algebra to [complete](#) the space.

### 1.3 Outer Measures

We start by giving a definition.

**Definition 1.11 (Outer measure).** An *outer measure* on  $X$  is a map

$$\mu^*: \mathcal{P}(X) \rightarrow [0, \infty]$$

such that

- $\mu^*(\emptyset) = 0$
- (monotonicity)  $\mu^*(A) \leq \mu^*(B)$  if  $A \subset B$
- (countable subadditivity)  $\mu^*\left(\bigcup_{i=1}^{\infty} A_i\right) \leq \sum_{i=1}^{\infty} \mu^*(A_i)$  for every  $A_i \subset X$ .

**Example.** For  $A \subset \mathbb{R}$ ,

$$\mu^*(A) = \inf \left\{ \sum_{i=1}^{\infty} (b_i - a_i) : \bigcup_{i=1}^{\infty} (a_i, b_i) \supset A \right\}$$

is an *outer measure* due to the [Proposition 1.2](#) we're going to show.

**Remark.** We see that an *outer measure* need not be a *measure*. Check [Definition 1.7](#).

**Proposition 1.2.** Let  $\mathcal{E} \subset \mathcal{P}(X)$  such that  $\emptyset, X \in \mathcal{E}$ . Let

$$\rho: \mathcal{E} \rightarrow [0, \infty]$$

such that  $\rho(\emptyset) = 0$ . Then

$$\mu^*(A) := \inf \left\{ \sum_{i=1}^{\infty} \rho(E_i) : \forall_{i \in \mathbb{N}} E_i \in \mathcal{E}, \bigcup_{i=1}^{\infty} E_i \supset A \right\}$$

is an *outer measure* on  $X$ .

**Note.** Recall the Tonelli's Theorem<sup>3</sup> for series:

If  $a_{ij} \in [0, \infty]$ ,  $\forall i, j \in \mathbb{N}$ , then

$$\sum_{(i,j) \in \mathbb{N}^2} a_{ij} = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} a_{ij} = \sum_{j=1}^{\infty} \sum_{i=1}^{\infty} a_{ij}.$$

Specifically, in [\[Tao13\]](#) Theorem 0.0.2.

## Lecture 4: Carathéodory extension Theorem

12 Jan. 11:00

**As previously seen.** We now prove the [Proposition 1.2](#).

*Proof.* We need to prove

<sup>3</sup>[https://en.wikipedia.org/wiki/Fubini%27s\\_theorem](https://en.wikipedia.org/wiki/Fubini%27s_theorem)

- $\mu^*$  is well-defined. i.e., inf is taken over a non-empty set. This is trivial since  $X \in \mathcal{E}$  and  $X \supset A$  for any  $A \in \mathcal{E}$ .
- $\mu^*(\emptyset) = 0$ . Since  $\emptyset \in \mathcal{E}$  and

$$\mu^*(\emptyset) = \inf \left\{ \sum_{i=1}^{\infty} \rho(E_i) : \forall E_i \in \mathcal{E}, \bigcup_{i=1}^{\infty} E_i \supset \emptyset \right\} = 0$$

since  $\rho(\emptyset) = 0$  for all  $i$  and further, by Squeeze Theorem<sup>4</sup>, we see that

$$\lim_{n \rightarrow \infty} \sum_{i=1}^n \rho(\emptyset) = 0.$$

- $A \subset B \implies \mu^*(A) \leq \mu^*(B)$ . We simply show this by contradiction. Suppose  $A \subset B$  and  $\mu^*(A) > \mu^*(B)$ , then by definition of  $\mu^*$ , we have

$$\begin{aligned} \mu^*(A) &= \inf \left\{ \sum_{i=1}^{\infty} \rho(E_i) : \forall E_i \in \mathcal{E}, \bigcup_{i=1}^{\infty} E_i \supset A \right\} \\ &> \inf \left\{ \sum_{i=1}^{\infty} \rho(E_i) : \forall E_i \in \mathcal{E}, \bigcup_{i=1}^{\infty} E_i \supset B \right\} = \mu^*(B). \end{aligned}$$

Now, let  $B = (B \setminus A) \cup A$ , then we have

$$\begin{aligned} \mu^*(A) &= \inf \left\{ \sum_{i=1}^{\infty} \rho(E_i) : \forall E_i \in \mathcal{E}, \bigcup_{i=1}^{\infty} E_i \supset A \right\} \\ &> \inf \left\{ \sum_{i=1}^{\infty} \rho(E_i) : \forall E_i \in \mathcal{E}, \bigcup_{i=1}^{\infty} E_i \supset (B \setminus A) \cup A \right\} = \mu^*(B). \end{aligned}$$

Now, since  $B \setminus A \supseteq \emptyset$ , then this inequality can't hold, hence a contradiction<sup>5</sup>.

- Countable subadditivity. Let  $A_1, A_2, \dots \in X$ . If one of  $\mu^*(A_n) = \infty$ , then result holds. So we may assume  $\mu^*(A_n) < \infty$  for all  $n \in \mathbb{N}$ . Now, fix any  $\epsilon > 0$ , we will show that

$$\mu^* \left( \bigcup_{n=1}^{\infty} A_n \right) \leq \sum_{n=1}^{\infty} \mu^*(A_n) + \epsilon.$$

For each  $n \in \mathbb{N}$ ,  $\exists E_{n,1}, E_{n,2}, \dots \in \mathcal{E}$  such that

$$\bigcup_{k=1}^{\infty} E_{n,k} \supset A_n$$

and

$$\mu^*(A_n) + \frac{\epsilon}{2^n} \geq \sum_{k=1}^{\infty} \rho(E_{n,k}).$$

Then we see that

$$\bigcup_{k=1}^{\infty} A_n \subset \bigcup_{n=1}^{\infty} \bigcup_{k=1}^{\infty} E_{k,n} = \bigcup_{(n,k) \in \mathbb{N}^2} E_{k,n},$$

<sup>4</sup>[https://en.wikipedia.org/wiki/Squeeze\\_theorem](https://en.wikipedia.org/wiki/Squeeze_theorem)

<sup>5</sup>This is an important trick!!

which implies

$$\mu^* \left( \bigcup_{n=1}^{\infty} A_n \right) \leq \sum_{(n,k) \in \mathbb{N}^2} \rho(E_{k,n}) \stackrel{!}{=} \sum_{n=1}^{\infty} \sum_{k=1}^{\infty} \rho(E_{k,n}) \leq \sum_{n=1}^{\infty} \left( \mu^*(A_n) + \frac{\epsilon}{2^n} \right)$$

from the inequality just derived. Now, since the last term is just

$$\sum_{n=1}^{\infty} \left( \mu^*(A_n) + \frac{\epsilon}{2^n} \right) = \sum_{n=1}^{\infty} \mu^*(A_n) + \epsilon,$$

hence we finally have

$$\mu^* \left( \bigcup_{n=1}^{\infty} A_n \right) \leq \sum_{n=1}^{\infty} \mu^*(A_n) + \epsilon$$

for arbitrarily small fixed  $\epsilon > 0$ , hence the subadditivity is proved. ■

**Definition 1.12 (Carathéodory measurable).** Let  $\mu^*$  be an **outer measure** on  $X$ . We say  $A \subset X$  is *Carathéodory measurable* (*C-measurable*) with respect to  $\mu^*$  if

$$\forall E \subset X, \mu^*(E) = \mu^*(E \cap A) + \mu^*(E \setminus A).$$

**Lemma 1.3.** Let  $\mu^*$  be an **outer measure** on  $X$ . Suppose  $B_1, \dots, B_N$  are disjoint **C-measurable** sets. Then,

$$\forall E \subset X, \mu^* \left( E \cap \left( \bigcup_{i=1}^N B_i \right) \right) = \sum_{i=1}^N \mu^*(E \cap B_i).$$

*Proof.* Since we have

$$\begin{aligned} \mu^* \left( E \cap \left( \bigcup_{i=1}^N B_i \right) \right) &= \mu^*(E' \cap B_1) + \mu^*(E' \setminus B_1) \text{ }^6 \\ &= \mu^* \left( E \cap \left( \bigcup_{i=1}^N B_i \cap B_1 \right) \right) + \mu^* \left( E \cap \left( \bigcup_{i=1}^N B_i \right) \cap B_1^c \right) \\ &= \mu^*(E \cap B_1) + \mu^* \left( E \cap \left( \bigcup_{i=2}^N B_i \right) \right) \end{aligned}$$

where the equality comes from the fact that  $B_1$  is **C-measurable** and disjoint from  $B_i, i \neq 1$ . Then, we simply iterate this argument and have the result. ■

**Remark.** This implies that if we restrict an **outer measure** on a **C-measurable** set, then it becomes finite additive.

<sup>6</sup>Here,  $E' := E \cap \left( \bigcup_{i=1}^N B_i \right)$  for the simplicity of notation.

**Theorem 1.2 (Carathéodory extension Theorem).** Let  $\mu^*$  be an outer measure on  $X$ . Let  $\mathcal{A}$  be the collection of C-measurable sets (with respect to  $\mu^*$ ). Then,

1.  $\mathcal{A}$  is a  $\sigma$ -algebra on  $X$ .
2.  $\mu = \mu^*|_{\mathcal{A}}$  is a measure on  $(X, \mathcal{A})$ .
3.  $(X, \mathcal{A}, \mu)$  is a complete measure space.

*Proof.* We divide the proof in several steps.

1. We show  $\mathcal{A}$  is a  $\sigma$ -algebra by showing

- (a)  $\emptyset \in \mathcal{A}$ . To show this, we simply check that  $\emptyset$  is C-measurable. We see that

$$\forall_{E \subset X} \mu^*(E) = \mu^*(E \cap \emptyset) + \mu^*(E \setminus \emptyset) = \mu^*(E),$$

which just shows  $\emptyset \in \mathcal{A}$ .

- (b)  $\mathcal{A}$  closed under complements. This is equivalent to say that if  $A$  is C-measurable, so is  $A^c$ . We see that if  $A$  is C-measurable, then for every  $E \subset X$ ,

$$\mu^*(E) = \mu^*(E \cap A) + \mu^*(E \setminus A).$$

Observing that  $E \cap A = E \setminus A^c$  and  $E \setminus A = E \cap A^c$ , hence

$$\mu^*(E) = \mu^*(E \setminus A^c) + \mu^*(E \cap A^c).$$

We immediately see that above implies  $A^c \in \mathcal{A}$ .

- (c)  $\mathcal{A}$  closed under countable unions.

**Note.** To show  $\mathcal{A}$  closed under countable unions, we show that  $\mathcal{A}$  is closed under:

finite unions  $\xRightarrow{\text{then}}$  countable disjoint unions  $\xRightarrow{\text{then}}$  countable unions.

- We show  $\mathcal{A}$  is closed under finite unions.

**Claim.**  $A, B \in \mathcal{A} \implies A \cup B \in \mathcal{A}$ .

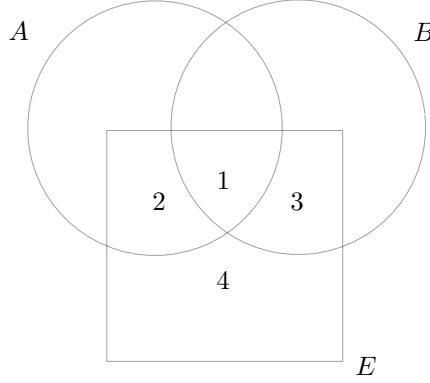
Fix  $E \subset X$  arbitrary. We need to show that

$$\mu^*(E) = \mu^*(E \cap (A \cup B)) + \mu^*(E \setminus (A \cup B)),$$

i.e.,

$$\mu^*(1 \cup 2 \cup 3 \cup 4) = \mu^*(1 \cup 2 \cup 3) + \mu^*(4)$$

given  $A, B \in \mathcal{A}$ .



- Since  $A$  is **C-measurable**,
  - \*  $\mu^*(1 \cup 2 \cup 3 \cup 4) = \mu^*(1 \cup 2) + \mu^*(3 \cup 4)$
  - \*  $\mu^*(1 \cup 2 \cup 3) = \mu^*(1 \cup 2) + \mu^*(3)$
- Since  $B$  is **C-measurable**,
  - \*  $\mu^*(3 \cup 4) = \mu^*(3) + \mu^*(4)$

Hence, we have

$$\begin{aligned} \mu^*(1 \cup 2 \cup 3 \cup 4) &= \mu^*(1 \cup 2) + \mu^*(3 \cup 4) \\ &= \mu^*(1 \cup 2) + \mu^*(3) + \mu^*(4) \\ &= \mu^*(1 \cup 2 \cup 3) + \mu^*(4). \end{aligned}$$

- We show  $\mathcal{A}$  is closed under countable disjoint unions.

Let  $A_1, A_2, \dots \in \mathcal{A}$  and disjoint. Fix  $E \subset X$  arbitrary. Since  $\mu^*$  is countably subadditive,

$$\mu^*(E) \leq \mu^*\left(E \cap \bigcup_{i=1}^{\infty} A_i\right) + \mu^*\left(E \setminus \bigcup_{i=1}^{\infty} A_i\right),$$

hence we only need to show another way around.

Fix  $N \in \mathbb{N}$ , we have  $\bigcup_{n=1}^N A_n \in \mathcal{A}$  since  **$N$  is finite**, and

$$\begin{aligned} \mu^*(E) &= \mu^*\left(E \cap \left(\bigcup_{n=1}^N A_n\right)\right) + \mu^*\left(E \setminus \left(\bigcup_{n=1}^N A_n\right)\right) \\ &\geq \underbrace{\sum_{n=1}^N \mu^*(E \cap A_n)}_{=\mu^*\left(E \cap \left(\bigcup_{n=1}^N A_n\right)\right)} + \underbrace{\mu^*\left(E \setminus \bigcup_{n=1}^{\infty} A_n\right)}_{\leq \mu^*\left(E \setminus \left(\bigcup_{n=1}^N A_n\right)\right)} \\ &\stackrel{!}{=} \mu^*\left(E \cap \left(\bigcup_{n=1}^N A_n\right)\right) + \mu^*\left(E \setminus \left(\bigcup_{n=1}^N A_n\right)\right) \end{aligned}$$

Now, take  $N \rightarrow \infty$  then we are done.

- We show  $\mathcal{A}$  is closed under countable unions.

DIY

The proof will be *continued*...

## Lecture 5: Hahn-Kolmogorov Theorem

14 Jan. 11:00

Firstly, we see a stronger version of [Lemma 1.3](#) we have seen before.

**Lemma 1.4.** Let  $\mu^*$  be an [outer measure](#) on  $X$ . Suppose  $B_1, B_2, \dots$  are disjoint [C-measurable](#) sets. Then,

$$\forall E \subset X, \mu^* \left( E \cap \left( \bigcup_{i=1}^{\infty} B_i \right) \right) = \sum_{i=1}^{\infty} \mu^* (E \cap B_i).$$

*Proof.*

$$\sum_{n=1}^{\infty} \mu^* (E \cap B_i) \geq \mu^* \left( E \cap \bigcup_{n=1}^{\infty} B_n \right) \geq \mu^* \left( E \cap \left( \bigcup_{n=1}^N B_n \right) \right) \stackrel{!}{=} \sum_{n=1}^N \mu^* (E \cap B_n).$$

Now, we just take  $N \rightarrow \infty$  (or note that  $N \in \mathbb{N}$  is arbitrary, we then get the result according to [Squeeze Theorem](#)<sup>7</sup>). ■

Let's continue the proof of [Theorem 1.2](#).

2. Since from [Definition 1.7](#), we need to show

- $\mu(\emptyset) = 0$ . This means that we need to show  $\mu^*|_{\mathcal{A}}(\emptyset) = 0$ . Since  $\emptyset \in \mathcal{A}$  and  $\mu^*$  is an [outer measure](#), hence from the [property](#) of [outer measure](#), it clearly holds.
- [Countable additivity](#) of  $\mu^*$  on  $\mathcal{A}$  follows from the [Lemma 1.4](#) with  $E = X$

3. The proof is given in [Theorem A.1](#). ■

### 1.4 Hahn-Kolmogorov Theorem

We see that we can start with any collection of open sets  $\mathcal{E}$  and any  $\rho$  such that it assigns [measure](#) on  $\mathcal{E}$ , then it induces an [outer measure](#) by [Proposition 1.2](#), finally [complete](#) the [outer measure](#) by [Theorem 1.2](#).

Specifically, we have

$$(\mathcal{E}, \rho) \xrightarrow{\text{Proposition 1.2}} (\mathcal{P}(X), \mu^*) \xrightarrow{\text{Theorem 1.2}} (\mathcal{A}, \mu)$$

To introduce this concept, we see that we can start with a more general definition compared to [σ-algebra](#) we are working on till now.

<sup>7</sup>[https://en.wikipedia.org/wiki/Squeeze\\_theorem](https://en.wikipedia.org/wiki/Squeeze_theorem)



**Definition 1.13 (Algebra).** Let  $X$  be a set. A collection  $\mathcal{A}$  of subsets of  $X$ , i.e.,  $\mathcal{A} \subset \mathcal{P}(X)$  is called an *algebra on  $X$*  if

- $\emptyset \in \mathcal{A}$ .
- $\mathcal{A}$  is closed under complements. i.e., if  $A \in \mathcal{A}$ ,  $A^c = X \setminus A \in \mathcal{A}$ .
- $\mathcal{A}$  is closed under **finite** unions. i.e., if  $A_i \in \mathcal{A}$ , then  $\bigcup_{i=1}^n A_i \in \mathcal{A}$  for  $n < \infty$ .

**Remark.** The only difference between an [algebra](#) and a  [\$\sigma\$ -algebra](#) is whether they are closed under **countable** unions in the definition.

Now, we can look at a more general setup compared to an [outer measure](#).

**Definition 1.14 (Pre-measure).** Let  $\mathcal{A}_0$  be an [algebra](#) on  $X$ . We say

$$\mu_0: \mathcal{A}_0 \rightarrow [0, \infty]$$

is a *pre-measure* if

1.  $\mu_0(\emptyset) = 0$
2. (finite additivity)  $\mu_0\left(\bigcup_{i=1}^n A_i\right) = \sum_{i=1}^n \mu_0(A_i)$  if  $A_1, \dots, A_n \in \mathcal{A}_0$  are disjoint.
3. (countable additivity within the [algebra](#)) If  $A \in \mathcal{A}_0$  and  $A = \bigcup_{n=1}^{\infty} A_n$ ,  $A_n \in \mathcal{A}_0$ , disjoint, then

$$\mu_0(A) = \sum_{n=1}^{\infty} \mu_0(A_n).$$

**Lemma 1.5.** (1) + (3)  $\implies$  (2) in [Definition 1.14](#).

*Proof.* It's easy to see that since  $\mu_0$  is monotone. ■

**Theorem 1.3 (Hahn-Kolmogorov Theorem).** Let  $\mu_0$  be a [pre-measure](#) on [algebra](#)  $\mathcal{A}_0$  on  $X$ . Let  $\mu^*$  be the [outer measure](#) induced by  $(\mathcal{A}_0, \mu_0)$  in [Proposition 1.2](#). Let  $\mathcal{A}$  and  $\mu$  be the [Carathéodory  \$\sigma\$ -algebra](#) and [measure](#) for  $\mu^*$ , then  $(\mathcal{A}, \mu)$  extends  $(\mathcal{A}_0, \mu_0)$ . i.e.,

$$\mathcal{A} \supset \mathcal{A}_0, \quad \mu|_{\mathcal{A}_0} = \mu_0.$$

*Proof.* We prove this theorem in two parts.

- We first show  $\mathcal{A} \supset \mathcal{A}_0$ . Let  $A \in \mathcal{A}_0$ , we want to show  $A \in \mathcal{A}$ , i.e.,  $A$  is [C-measurable](#), i.e.,

$$\forall E \subset X \quad \mu^*(E) = \mu^*(E \cap A) + \mu^*(E \cap A^c).$$

We first fix an  $E \subset X$ . From [countable subadditivity](#) of  $\mu^*$ , we have

$$\mu^*(E) \leq \mu^*(E \cap A) + \mu^*(E \cap A^c).$$

Hence, we only need to show another direction. If  $\mu^*(E) = \infty$ , then  $\mu^*(E) = \infty \geq \mu^*(E \cap A) + \mu^*(E \cap A^c)$  clearly. So, assume  $\mu^*(E) < \infty$ .

Fix  $\epsilon > 0$ . By the [Proposition 1.2](#) of  $\mu^*$ ,  $\exists B_1, B_2, \dots \in \mathcal{A}_0$ ,  $\bigcup_{n=1}^{\infty} B_n \supset E$  such that

$$\mu^*(E) + \epsilon \geq \sum_{n=1}^{\infty} \mu_0(B_n) = \sum_{n=1}^{\infty} \left( \underbrace{\mu_0(B_n \cap A)}_{\in \mathcal{A}_0} + \underbrace{\mu_0(B_n \cap A^c)}_{\in \mathcal{A}_0} \right)$$

by the [finite additivity](#) of  $\mu_0$ . Note that

$$\left\{ \begin{array}{l} \bigcup_{n=1}^{\infty} (B_n \cap A) \supset E \cap A \\ \bigcup_{n=1}^{\infty} (B_n \cap A^c) \subset E \cap A^c \end{array} \right. \implies \mu^*(E) + \epsilon \geq \mu^*(E \cap A) + \mu^*(E \cap A^c)$$

since

$$\mu^*(E \cap A) \leq \mu^* \left( \bigcup_{n=1}^{\infty} (B_n \cap A) \right) \leq \sum_{n=1}^{\infty} \mu^*(B_n \cap A)$$

and

$$\mu^*(E \cap A^c) \leq \mu^* \left( \bigcup_{n=1}^{\infty} (B_n \cap A^c) \right) \leq \sum_{n=1}^{\infty} \mu^*(B_n \cap A^c).$$

We then see that for any  $\epsilon > 0$ , the inequality

$$\mu^*(E) + \epsilon \geq \mu^*(E \cap A) + \mu^*(E \cap A^c)$$

holds, hence so does

$$\mu^*(E) \geq \mu^*(E \cap A) + \mu^*(E \cap A^c),$$

which implies  $\mathcal{A} \supset \mathcal{A}_0$ .

The proof will be [continued](#)...

## Lecture 6: Hahn-Kolmogorov Theorem and Extension.

18 Jan. 11:00

Let's continue the proof of [Theorem 1.3](#).

- Let  $A \in \mathcal{A}_0$ , we want to show that

$$\mu(A) = \mu_0(A).$$

– Firstly, let

$$B_i = \begin{cases} A, & \text{if } i = 1 \\ \emptyset, & \text{if } i \geq 2 \end{cases} \in \mathcal{A}_0,$$

hence  $\bigcup_{i=1}^{\infty} B_i = A$ , then we see that

$$\mu^*(A) \leq \sum_{i=1}^{\infty} \mu_0(B_i) = \mu_0(A)$$

from the [definition](#) of  $\mu^*$  and [countable additivity within the algebra](#) of  $\mu_0$ .

– Secondly, let  $B_i \in \mathcal{A}_0$ ,  $\bigcup_{i=1}^{\infty} B_i \supset A$  be arbitrary. Let  $C_1 = A \cap B_1 \in \mathcal{A}_0$ ,  $C_i = A \cap B_i \setminus \left( \bigcup_{j=1}^{i-1} B_j \right) \in \mathcal{A}_0$  for  $i \geq 2$  since the operations are finite. Then we see

$$A = \bigcup_{i=1}^{\infty} C_i \in \mathcal{A}_0$$

are disjoint countable unions, by [countable additivity within the algebra](#), we therefore have

$$\mu_0(A) = \sum_{i=1}^{\infty} \mu_0(C_i) \leq \sum_{i=1}^{\infty} \mu_0(B_i) \implies \mu_0(A) \leq \mu^*(A)$$

by taking the infimum from the [definition](#) of  $\mu^*$ .

Combine these two inequality, we see that

$$\mu^*(A) = \mu_0(A),$$

for every  $A \in \mathcal{A}_0$ , which implies

$$\mu(A) = \mu_0(A)$$

for every  $A \in \mathcal{A}_0$  from [Theorem 1.2](#), where we extend  $\mu^*$  to  $\mu$  respect to  $\mathcal{A}_0$ . ■

**Definition 1.15 (HK extension).**  $(\mathcal{A}, \mu)$  obtained from [Theorem 1.3](#) is the *Hahn-Kolmogorov extensions* of  $(\mathcal{A}_0, \mu_0)$ .

We can show the uniqueness of [HK extension](#).

**Theorem 1.4 (Uniqueness of HK extension).** Let  $\mathcal{A}_0$  be an [algebra](#) on  $X$ ,  $\mu_0$  be a [pre-measure](#) on  $\mathcal{A}_0$ . Let  $(\mathcal{A}, \mu)$  be the [HK extension](#) of  $(\mathcal{A}_0, \mu_0)$ . Let  $(\mathcal{A}', \mu')$  be another extension of  $(\mathcal{A}_0, \mu_0)$ . Then if  $\mu_0$  is [σ-finite](#),  $\mu = \mu'$  on  $\mathcal{A} \cap \mathcal{A}'$ .

**Note.** Notice that  $\mathcal{A}_0 \subset \mathcal{A}, \mathcal{A}'$  since they both extend  $\mathcal{A}_0$ .

*Proof.* Let  $A \in \mathcal{A} \cap \mathcal{A}'$ , we need to show

$$\underbrace{\mu(A)}_{\mu^*(A)} = \mu'(A).$$

Firstly, it's easy to show that  $\mu^*(A) \geq \mu'(A)$  by choosing the arbitrary cover of  $A$  and using the [definition](#) of  $\mu^*$ .

Secondly, we will show that  $\mu(A) \leq \mu'(A)$ .

- Assume  $\mu(A) < \infty$ , and fix  $\epsilon > 0$ . Then there exists  $B_i \in \mathcal{A}_0$  with  $B := \bigcup_{i=1}^{\infty} B_i \supset A$  such that

$$\mu(A) + \epsilon = \mu^*(A) + \epsilon \geq \sum_{i=1}^{\infty} \mu_0(B_i) \stackrel{!}{=} \sum_{i=1}^{\infty} \mu(B_i) \geq \mu\left(\bigcup_{i=1}^{\infty} B_i\right) = \mu(B).$$

This implies that

$$\mu(B \setminus A) = \mu(B) - \mu(A) \leq \epsilon$$

where the first equality comes from  $A \subset B$  and  $\mu(A) < \infty$ . On the other hand,

$$\mu(B) = \lim_{N \rightarrow \infty} \mu\left(\bigcup_{i=1}^N B_i\right) \stackrel{8}{=} \lim_{N \rightarrow \infty} \mu'\left(\bigcup_{i=1}^N B_i\right) = \mu'(B),$$

hence,

$$\mu(A) \leq \mu(B) = \mu'(B) = \mu'(A) + \mu'(B \setminus A) \stackrel{9}{\leq} \mu'(A) + \mu(B \setminus A) \leq \mu'(A) + \epsilon$$

for arbitrary  $\epsilon$ , so we conclude  $\mu(A) \leq \mu'(A)$ .

- Assume  $\mu(A) = \infty$ . Since  $\mu_0$  is [σ-finite](#), so we know  $X = \bigcup_{n=1}^{\infty} X_n$  for some  $X_n \in \mathcal{A}_0$  such that

$$\mu_0(X_n) < \infty.$$

Replacing  $X_n$  by  $X_1 \cup \dots \cup X_n \in \mathcal{A}_0$ , we may assume that

$$X_1 \subset X_2 \subset \dots$$

Then,

$$\forall_{n \in \mathbb{N}} \mu(A \cap X_n) < \infty \stackrel{!}{\implies} \mu(A \cap X_n) \leq \mu'(A \cap X_n).$$

From the continuity of [measure](#), we then have

$$\mu(A) = \lim_{n \rightarrow \infty} \mu(A \cap X_n) \leq \lim_{n \rightarrow \infty} \mu'(A \cap X_n) = \mu'(A).$$

■

<sup>8</sup> $\mu = \mu'$  on  $\mathcal{A}_0$ .

<sup>9</sup>From the first part.

**Corollary 1.1.** Let  $\mu_0$  be a [pre-measure](#) on [algebra](#)  $\mathcal{A}_0$  on  $X$ . Suppose  $\mu_0$  is  [\$\sigma\$ -finite](#), then

$\exists!$  [measure](#)  $\mu$  on  $\langle \mathcal{A}_0 \rangle$  that extends  $\mathcal{A}_0$ .

Furthermore,

- The completion of  $(X, \langle \mathcal{A}_0 \rangle, \mu)$  is the [HK extension](#) of  $(\mathcal{A}_0, \mu_0)$ .

- 

$$\mu(A) = \inf \left\{ \sum_{i=1}^{\infty} \mu_0(B_i) \mid B_i \in \mathcal{A}_0, \forall_{i \in \mathbb{N}} \bigcup_{i=1}^{\infty} B_i \supset A \right\}$$

for all  $A \in \overline{\langle \mathcal{A}_0 \rangle}$ .

## Lecture 7: Borel Measures

21 Jan. 11:00

### 1.5 Borel Measures on $\mathbb{R}$

We first introduce so-called *distribution function*.

**Definition 1.16 (Distribution function).** An [increasing](#)<sup>a</sup> function

$$F: \mathbb{R} \rightarrow \mathbb{R}$$

and [right-continuous](#).  $F$  is then a *distribution function*.

<sup>a</sup>Here, increasing means  $F(x) \leq F(y)$  for  $x < y$ .

**Example.** Here are some examples of right-continuous functions.

1.  $F(x) = x$ .

2.  $F(x) = e^x$ .

3. Define

$$F(x) = \begin{cases} 1, & \text{if } x \geq 0 \\ 0, & \text{if } x < 0. \end{cases}$$

4. Let  $\mathbb{Q} := \{r_1, r_2, \dots\}$ . Define

$$F_n(x) = \begin{cases} 1, & \text{if } x \geq r_n \\ 0, & \text{if } x < r_n, \end{cases}$$

and

$$F(x) := \sum_{n=1}^{\infty} \frac{F_n(x)}{2^n}.$$

Then  $F$  is a distribution function (hence right-continuous). This is shown in [Lemma A.1](#).

**Note.** If  $F$  is increasing, and

$$F(\infty) := \lim_{x \nearrow \infty} F(x), \quad F(-\infty) := \lim_{x \searrow -\infty} F(x)$$

exist in  $[-\infty, \infty]$ .

In probability theory, cumulative distribution function (CDF) is a distribution function with  $F(\infty) = 1$ ,  $F(-\infty) = 0$ .<sup>10</sup>

Now, we can define a *Borel measure* on  $(X, \mathcal{B}(\mathbb{R}))$ .

**Definition 1.17 (Borel measure).** A *Borel measure* is any **measure**  $\mu$  defined on the  **$\sigma$ -algebra** of **Borel sets**.

**Definition 1.18 (Locally finite).** Let  $X$  be a Hausdorff topological space,  $\mu$  on  $(X, \mathcal{B}(X))$  is called *locally finite* if  $\mu(K) < \infty$  for every compact set  $K \subset X$ .

**Note.** Some authors will require a **Borel measure** equipped with the **locally finite** property. But formally, this is not so common.

**Lemma 1.6.** Let  $\mu$  be a **locally finite Borel measure** on  $\mathbb{R}$ , then

$$F_\mu(x) = \begin{cases} \mu((0, x]), & \text{if } x > 0 \\ 0, & \text{if } x = 0 \\ -\mu((x, 0]), & \text{if } x < 0 \end{cases}$$

is a **distribution function**.

*Proof.* To show  $F_\mu$  is increasing, consider  $x < y$  such that

$$F_\mu(x) \leq F_\mu(y)$$

by considering

- $x > 0$ : Then  $F_\mu(x) = \mu((0, x])$  and

$$F_\mu(y) = \mu((0, y]) = \mu((0, x] \cup (x, y]) \geq \mu((0, x]) = F_\mu(x).$$

- $x = 0$ : Then  $F_\mu(x) = 0$  and

$$F_\mu(y) = \mu((0, y]) \geq 0 = F_\mu(0)$$

since  $y > 0$ .

- $x < 0$ : Follows the same argument with  $x > 0$ .

<sup>10</sup>There are distributions [FF99] Ch9., but these are different from distribution functions.

Now, we need to show  $F_\mu$  is right-continuous. Firstly, assume that  $x \geq 0$ , then we see that

$$F_\mu(x) = \mu((0, x]) = \mu((0, x^+])$$

from the fact that a measure is right-continuous.<sup>11</sup> Now, if  $x \leq 0$ , the same argument follows since multiplying  $-1$  will not change the fact that a [measure](#) is continuous. ■

**Definition 1.19 (Half intervals).** We call

$$\emptyset, (a, b], (a, \infty), (-\infty, b], (-\infty, \infty)$$

*half-intervals*.

**Lemma 1.7.** Let  $\mathcal{H}$  be the collection of finite disjoint unions of [half-intervals](#). Then,  $\mathcal{H}$  is an [algebra](#) on  $\mathbb{R}$ .

*Proof.* We see that

- $\emptyset \in \mathcal{H}$ . Clearly.
- To show  $\mathcal{H}$  is closed under complements, we have
  - $\emptyset^c = \mathbb{R} = (-\infty, \infty) \in \mathcal{H}$ .
  - $(a, b]^c = (-\infty, a] \cup (a, \infty) \in \mathcal{H}$ .<sup>12</sup>
  - $(a, \infty)^c = (-\infty, a] \in \mathcal{H}$ .
  - $(-\infty, b]^c = (b, \infty) \in \mathcal{H}$ .
  - $(-\infty, \infty)^c = \emptyset \in \mathcal{H}$ .
- $\mathcal{H}$  is closed under finite unions, clearly.

■

<sup>11</sup>Actually, a measure is always continuous.

<sup>12</sup>Since it's a two disjoint union of half intervals.

**Proposition 1.3 (Distribution function defines a pre-measure).** Let  $F: \mathbb{R} \rightarrow \mathbb{R}$  be a [distribution function](#). For a [half interval](#)  $I$ , define

$$\ell(I) := \ell_F(I) = \begin{cases} 0, & \text{if } I = \emptyset; \\ F(b) - F(a), & \text{if } I = (a, b]; \\ F(\infty) - F(a), & \text{if } I = (a, \infty]; \\ F(b) - F(-\infty), & \text{if } I = (-\infty, b]; \\ F(\infty) - F(-\infty), & \text{if } I = (-\infty, \infty). \end{cases}$$

Define  $\mu_0 := \mu_{0,F}$  as

$$\mu_{0,F}: \mathcal{H} \rightarrow [0, \infty]$$

by

$$\mu_0(A) = \sum_{k=1}^N \ell(I_k) \text{ if } A = \bigcup_{k=1}^N I_k,$$

where  $A$  is a finite disjoint union of [half intervals](#)  $I_1, \dots, I_N$ . Then,  $\mu_0$  is a [pre-measure](#) on  $\mathcal{H}$ .

*Proof.* We see that

1.  $\mu_0$  is well-defined.
2.  $\mu_0(\emptyset) = 0$ .
3.  $\mu_0$  is finite additive.
4.  $\mu_0$  is [countable additivity within  \$\mathcal{H}\$](#) .

Suppose  $A \in \mathcal{H}$  where  $A = \bigcup_{i=1}^{\infty} A_i$  is a countable disjoint union. It is enough to consider the case that  $A = I$ ,  $A_k = I_k$  are all half-intervals.<sup>13</sup>

Focus on the case  $I = (a, b]$ . Let

$$(a, b] = \bigcup_{n=1}^{\infty} (a_n, b_n],$$

which is a disjoint union. Then we only need to check

$$F(b) - F(a) = \sum_{n=1}^{\infty} (F(b_n) - F(a_n)).$$

- Since  $(a, b] \supset \bigcup_{n=1}^N (a_n, b_n]$  for any fixed  $N \in \mathbb{N}$ , hence

$$\forall_{N \in \mathbb{N}} F(b) - F(a) \geq \sum_{n=1}^N (F(b_n) - F(a_n)).$$

<sup>13</sup>Since  $\mathcal{H}$  is only a collection of *finite* disjoint [half intervals](#), hence after considering  $A = I$ , we can apply the same argument iteratively and stop in finite steps. Formally, we can consider  $H \in \mathcal{H}$ ,  $H = \bigcup_{i=1}^{\infty} A^i$ , where  $A^i$  being a [half interval](#). Then by the above argument, we have  $A^i = I^i$  and so on.



By letting  $N \rightarrow \infty$ , we have

$$F(b) - F(a) \geq \sum_{n=1}^{\infty} (F(b_n) - F(a_n)).$$

- Fix  $\epsilon > 0$ . Since  $F$  is right-continuous,  $\exists a' > a$  such that

$$F(a') - F(a) < \epsilon.$$

For each  $n \in \mathbb{N}$ ,  $\exists b'_n > b_n$  such that

$$F(b'_n) - F(b_n) < \frac{\epsilon}{2^n}.$$

Then, we have

$$[a', b] \subset \bigcup_{n=1}^{\infty} (a_n, b'_n),$$

hence

$$\exists_{N \in \mathbb{N}} [a', b] \subset \bigcup_{n=1}^N (a_n, b'_n),^{14}$$

which is only finitely many unions now. In this case, we have

$$F(b) - F(a') \leq \sum_{n=1}^N F(b'_n) - F(a_n).$$

Finally, we see that

$$\begin{aligned} F(b) - F(a) &\leq F(b) - F(a') + \epsilon \\ &\leq \sum_{n=1}^{\infty} (F(b'_n) - F(a_n)) + \epsilon \\ &\leq \sum_{n=1}^{\infty} \left( F(b_n) - F(a_n) + \frac{\epsilon}{2^n} \right) + \epsilon \\ &= \sum_{n=1}^{\infty} (F(b_n) - F(a_n)) + 2\epsilon \end{aligned}$$

for any fixed  $\epsilon > 0$ , hence

$$F(b) - F(a) \leq \sum_{n=1}^{\infty} (F(b_n) - F(a_n)).$$

Combine these two inequalities, we have

$$F(b) - F(a) = \sum_{n=1}^{\infty} (F(b_n) - F(a_n))$$

as we desired.

---

<sup>14</sup>This essentially follows from the fact that open sets are closed under countable unions, hence the equality will not hold, even after taking the limit.



**Remark.** It's again the  $\frac{\epsilon}{2^n}$  trick we saw before!

## Lecture 8: Lebesgue-Stieltjes Measure on $\mathbb{R}$

24 Jan. 11:00

To classify all **measures**, we now see this last theorem to complete the task.

**Theorem 1.5 (Locally finite Borel measures on  $\mathbb{R}$ ).** We have

1.  $F: \mathbb{R} \rightarrow \mathbb{R}$  a **distribution function**, then there exists a **unique locally finite Borel measure**  $\mu_F$  on  $\mathbb{R}$  satisfying

$$\mu_F((a, b]) = F(b) - F(a)$$

for every  $a < b$ .

2. Suppose  $F, G: \mathbb{R} \rightarrow \mathbb{R}$  are **distribution functions**. Then,

$$\mu_F = \mu_G$$

on  $\mathcal{B}(\mathbb{R})$  if and only if  $F - G$  is a constant function.

*Proof.*



HW.

**Remark.** **Theorem 1.5** simply states that given a **distribution function**, if we restrict our attention on **locally finite measures** on  $\mathbb{R}$  following our usual convention, then it defines the **measure** on  $\mathcal{B}(\mathbb{R})$  uniquely up to a *constant shift*.

### 1.6 Lebesgue-Stieltjes Measure on $\mathbb{R}$

We see that

$$F \text{ distribution function} \xRightarrow{!} \mu_F \text{ on Carathéodory } \sigma\text{-algebra } \mathcal{A}_{\mu_F} \supset \mathcal{B}(\mathbb{R}).$$

Furthermore, we have

$$(\mathcal{A}_{\mu_F}, \mu_F) = \overline{(\mathcal{B}(\mathbb{R}), \mu_F)}.$$

**Definition 1.20 (Lebesgue-Stieltjes measure).** Given a **distribution function**  $F$ , we say  $\mu_F$  on  $\mathcal{A}_{\mu_F}$  is called the *Lebesgue-Stieltjes measure* corresponding to  $F$ .

**Definition 1.21 (Lebesgue measure, Lebesgue  $\sigma$ -algebra).** From **Definition 1.20**, if  $F(x) = x$ , then the induced  $(\mathcal{A}_{\mu_F}, \mu_F)$  is denoted as  $(\mathcal{L}, m)$ , where  $\mathcal{L}$  is called *Lebesgue  $\sigma$ -algebra*, and  $m$  is called *Lebesgue measure*.

**Remark.** Recall that  $\mathcal{L}$  is induced by [Theorem 1.2](#), namely given  $m$ , for all  $A \subset \mathbb{R}$ , we have

$$\mathcal{L} := \left\{ A \subset \mathbb{R} \mid \forall_{E \subset \mathbb{R}} m(A) = m(A \cap E) + m(A \setminus E) \right\}$$

**Note.** We see that since  $F$  is right-continuous and increasing, hence

$$F(x^-) \leq F(x) = F(x^+).^{15}$$

**Example.** We first see some examples.

1.  $\mu_F((a, b]) = F(b) - F(a)$ . Then

- $\mu_F(\{a\}) = F(a) - F(a^-)$
- $\mu_F([a, b]) = F(b) - F(a^-)$
- $\mu_F((a, b)) = F(b^-) - F(a)$

This is so-called *discrete measure*.

2. We define

$$F(x) = \begin{cases} 1, & \text{if } x \geq 0; \\ 0, & \text{if } x < 0. \end{cases}$$

Then

- $\mu_F(\{0\}) = 1$
- $\mu_F(\mathbb{R}) = 1$
- $\mu_F(\mathbb{R} \setminus \{0\}) = 0$ . This is easy to see since  $\mathbb{R} \setminus \{0\} = (-\infty, 0) \cup (0, \infty)$ , hence

$$\begin{aligned} \mu_F(\mathbb{R} \setminus \{0\}) &= \mu_F((-\infty, 0) \cup (0, \infty)) \\ &= \underbrace{\mu_F((-\infty, 0))}_{0-0^{16}} + \underbrace{\mu_F((0, \infty))}_{1-1^{17}} = 0. \end{aligned}$$

We call that  $\mu_F$  is the *Dirac measure* at 0.

3. Denote  $\mathbb{Q} = \{r_1, r_2, \dots\}$ , and we define

$$F(x) = \sum_{n=1}^{\infty} \frac{F_n(x)}{2^n} \text{ where } F_n(x) = \begin{cases} 1, & \text{if } x \geq r_n; \\ 0, & \text{if } x < r_n. \end{cases}$$

Then

- $\mu_F(\{r_i\}) > 0$  for all  $r_i \in \mathbb{Q}$ .

<sup>15</sup>Some text will use  $x-$  and  $x+$  instead of  $x^-$  and  $x^+$ , respectively.

<sup>16</sup>It follows from  $F(0^-) - F(-\infty) = 0 - 0 = 0$ .

<sup>17</sup>It follows from  $F(\infty) - F(0) = 1 - 1 = 0$ .

- $\mu_F(\mathbb{R} \setminus \mathbb{Q}) = 0$ .

This is shown in [Lemma A.2](#).

4. If  $F$  is continuous at  $a$ , then  $\mu_F(\{a\}) = 0$ .
5.  $F(x) = x$ , then recall that we denote  $\mu_F := m$ , and we have
  - $m((a, b]) = m((a, b)) = m([a, b]) = b - a$ .
6.  $F(x) = e^x$ 
  - $\mu_F((a, b]) = \mu_F((a, b)) = e^b - e^a$ .

**Example (Middle thirds Cantor set).** Let  $C := \bigcap_{n=1}^{\infty} K_n$ , where we have

$$\begin{aligned} K_0 &:= [0, 1] \\ K_1 &:= K_0 \setminus \left( \frac{1}{3}, \frac{2}{3} \right) \\ K_2 &:= K_1 \setminus \left( \frac{1}{9}, \frac{2}{9} \right) \cup \left( \frac{7}{9}, \frac{8}{9} \right) \\ &\vdots \\ K_n &:= K_{n-1} \setminus \bigcup_{k=1}^{3^n-1} \left( \frac{3k+1}{3^{n+1}}, \frac{3k+2}{3^{n+1}} \right). \end{aligned}$$

We see that  $C$  is uncountable and with  $m(C) = 0$ . And observe that  $x \in C$  if and only if  $x = \sum_{n=1}^{\infty} \frac{a_n}{3^n}$  for some  $a_n \in \{0, 2\}$ . Hence, we can instead formulate  $K_n$  by

$$K_n = \bigcup_{\substack{a_i \in \{0, 2\} \\ 1 \leq i \leq n}} \left[ \sum_{i=1}^{\infty} \frac{a_i}{3^i}, \sum_{i=1}^{\infty} \frac{a_i}{3^i} + \frac{1}{3^n} \right].$$

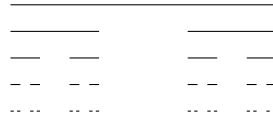


Figure 1: The top line corresponds to  $K_0$ , and then  $K_1$ , etc.

The proof of  $m(C) = 0$  is given in [Lemma A.3](#).

### 1.6.1 Cantor Function

Consider  $F$  as follows. We define a function  $F$  to be 0 to the left of 0, and 1 to the right of 1. Then, define  $F$  to be  $\frac{1}{2}$  on  $(\frac{1}{3}, \frac{2}{3})$ ,  $\frac{1}{4}$  on  $(\frac{1}{9}, \frac{2}{9})$ ,  $\frac{3}{4}$  on  $(\frac{7}{9}, \frac{8}{9})$  and so on. This is so-called *Cantor Function*. We can show  $F$  is continuous and increasing, which makes  $F$  a distribution function. Also, we see that the measure this  $F$  induced is called *Cantor measure*.



Figure 2: Cantor Function (Devil's Staircase).

We see that  $F$  is *continuous* and increasing. Furthermore,

| Cantor Measure $\mu_F$              |        | Lebesgue Measure $m$                     |
|-------------------------------------|--------|--|
| $\mu_F(\mathbb{R} \setminus C) = 0$ |        | $m(\mathbb{R} \setminus C) = \infty > 0$ |
| $\mu_F(C) = 1$                      | $\iff$ | $m(C) = 0$                               |
| $\mu_F(\{a\}) = 0$                  |        | $m(\{a\}) = 0$                           |

**Remark.**  $\mu_F$  and  $m$  are said to be **singular** to each other.

## 1.7 Regularity Properties of Lebesgue-Stieltjes Measures

We first see a lemma.

**Lemma 1.8.** Let  $\mu$  be **Lebesgue-Stieltjes measure** on  $\mathbb{R}$ . Then we have

$$\begin{aligned} \mu(A) &\stackrel{!}{=} \inf \left\{ \sum_{i=1}^{\infty} \mu((a_i, b_i]) \mid \bigcup_{i=1}^{\infty} (a_i, b_i] \supset A \right\} \\ &= \inf \left\{ \sum_{i=1}^{\infty} \mu((a_i, b_i)) \mid \bigcup_{i=1}^{\infty} (a_i, b_i) \supset A \right\} \end{aligned}$$

for every  $A \in \mathcal{A}_\mu$

*Proof.* The second equality follows from the **continuity of the measure**. ■

**Remark.** This is similar to

$$(a, b) = \bigcup_{n=1}^{\infty} (a, b - 1/n], \quad (a, b] = \bigcap_{n=1}^{\infty} (a, b + 1/n].$$

## Lecture 9: Properties of Lebesgue-Stieltjes measure

26 Jan. 11:00

**As previously seen.** Let  $X \subset [0, \infty]$ . Recall that

- Finite supremum.

$$\alpha = \sup X < \infty \iff \begin{cases} \forall_{x \in X} \alpha \geq x \\ \forall_{\epsilon > 0} \exists_{x \in X} x + \epsilon \geq \alpha. \end{cases}$$

- Infinite supremum.

$$\alpha = \sup X = \infty \iff \forall_{L > 0} \exists_{x \in X} x \geq L.$$

This should be useful latter on.

**Theorem 1.6 (Regularity).** Let  $\mu$  be [Lebesgue-Stieltjes measure](#). Then, for all  $A \in \mathcal{A}_\mu$ ,

1. (outer regularity)  $\mu(A) = \inf\{\mu(O) \mid O \supset A, O \text{ is open}\}$
2. (inner regularity)  $\mu(A) = \sup\{\mu(K) \mid K \subset A, K \text{ is compact}\}$

*Proof.* We check them separately.

1. DIY
2. Let  $s := \sup\{\mu(K) \mid K \subset A, K \text{ is compact}\}$ , then by [monotonicity](#), we have  $\mu(A) \geq s$ . To show the other direction, we consider

- $A$  is a bounded set.

Then  $\overline{A} \in \mathcal{B}(\mathbb{R}) \subset \mathcal{A}_\mu$ ,  $\overline{A}$  is also bounded  $\implies \mu(\overline{A}) < \infty$ . Fix  $\epsilon > 0$ , then by [outer regularity](#), there exists an open  $O \supset \overline{A} \setminus A$ , and  $\mu(O) - \mu(\overline{A} \setminus A) = \mu(O \setminus (\overline{A} \setminus A)) \leq \epsilon$ . Let  $K := \underbrace{A \setminus O}_{K \subset A} = \underbrace{\overline{A} \setminus O}_{\text{compact}}$ , we

show that

$$\mu(K) \geq \mu(A) - \epsilon.$$

- $A$  is an unbounded set with  $\mu(A) < \infty$ .

Let  $A = \bigcup_{n=1}^{\infty} A_n$ ,  $A_n = A \cap [-n, n]$  where  $A_1 \subset A_2 \subset \dots$ , then

$$\lim_{n \rightarrow \infty} \mu(A_n) = \mu(A) < \infty.$$

- $A$  is an unbounded set with  $\mu(A) = \infty$ .

We can show that

$$\lim_{n \rightarrow \infty} \mu(A_n) = \mu(A) = \infty.$$

Fix  $L > 0$ , then  $\exists N$  such that  $\mu(A_N) \geq L$ .

■

**Definition 1.22** ( $G_\delta$ -set,  $F_\sigma$ -set). Let  $X$  be a topological space. Then

- A  $G_\delta$ -set is  $G = \bigcap_{i=1}^{\infty} O_i$ ,  $O_i$  open.
- A  $F_\sigma$ -set is  $F = \bigcup_{i=1}^{\infty} F_i$ ,  $F_i$  closed.

**Theorem 1.7.** Let  $\mu$  be a Lebesgue-Stieltjes measure. Then *TFAE*<sup>a</sup>:

1.  $A \in \mathcal{A}_\mu$
2.  $A = G \setminus M$ ,  $G$  is a  $G_\delta$ -set,  $M$  is a  $\mu$ -null set.
3.  $A = F \setminus N$ ,  $F$  is a  $F_\sigma$ -set,  $N$  is a  $\mu$ -null set.

<sup>a</sup>TFAE: The following are equivalent.

*Proof.* We see that (2.)  $\implies$  (1.) and (3.)  $\implies$  (1.) are clear.

- (1.)  $\implies$  (3.)

– Assume  $\mu(A) < \infty$ . From the inner regularity, we have

$$\forall n \in \mathbb{N} \exists \text{compact } K_n \subset A \text{ such that } \mu(K_n) + \frac{1}{n} \geq \mu(A).$$

Let  $F = \bigcup_{n=1}^{\infty} K_n$ , then  $N = A \setminus F$  is  $\mu$ -null.

Check!

– Assume  $\mu(A) = \infty$ . Let  $A = \bigcup_{k \in \mathbb{Z}} A_k$ ,  $A_k = A \cap (k, k+1]$ . From what we have just shown above,

$$\forall k \in \mathbb{Z} \ A_k = F_k \cup N_k, \quad A = \underbrace{\left( \bigcup_k F_k \right)}_{F_\sigma\text{-set}} \cup \underbrace{\left( \bigcup_k N_k \right)}_{\mu\text{-null}}.$$

- (1.)  $\implies$  (2.)

We see that

$$A^c = F \cup N, \quad A = F^c \cap N^c = F^c \setminus N.$$

■

**Proposition 1.4.** Let  $\mu$  be a Lebesgue-Stieltjes measure, and  $A \in \mathcal{A}_\mu$ ,  $\mu(A) < \infty$ . Then we have

$$\forall \epsilon > 0 \exists I = \bigcup_{i=1}^{N(\epsilon)} I_i$$

disjoint open intervals such that  $\mu(A \triangle I) \leq \epsilon$ .

*Proof.* Using **outer regularity** and the fact that every open set is  $\bigcup_{i=1}^{\infty} I_i$ , where  $I_i$  are disjoint open intervals. ■

DIY

We now see some properties of **Lebesgue measure**.

**Theorem 1.8.** Let  $A \in \mathcal{L}$ , then we have  $A + s \in \mathcal{L}$ ,  $rA \in \mathcal{L}$  for all  $r, s \in \mathbb{R}$ . i.e.,

$$m(A + s) = m(A), \quad m(rA) = |r| \cdot m(A).$$

*Proof.* ■

DIY

**Example.** We now see some examples.

1. Let  $\mathbb{Q} = \{r_i\}_{i=1}^{\infty}$  which is dense in  $\mathbb{R}$ . Let  $\epsilon > 0$ , and

$$O = \bigcup_{i=1}^{\infty} \left( r_i - \frac{\epsilon}{2^i}, r_i + \frac{\epsilon}{2^i} \right).$$

We see that  $O$  is open and dense<sup>18</sup> in  $\mathbb{R}$ . But we see

$$m(O) \leq \sum_{i=1}^{\infty} \frac{2\epsilon}{2^i} = 2\epsilon.$$

Furthermore,  $\partial O = \overline{O} \setminus O$ ,  $m(\partial O) = \infty$

2. There exists uncountable set  $A$  with  $m(A) = 0$ .
3. There exists  $A$  with  $m(A) > 0$  but  $A$  contains no non-empty open intervals.
4. There exists  $A \notin \mathcal{L}$ . e.g. Vitali set.<sup>19</sup>
5. There exists  $A \in \mathcal{L} \setminus \mathcal{B}(\mathbb{R})$ .

## Lecture 10: Integration

26 Jan. 11:00

## 2 Integration

### 2.1 Measurable Function

We start with a definition.

**Definition 2.1 (Measurable function).** Suppose  $(X, \mathcal{A})$ ,  $(Y, \mathcal{B})$  are **measurable spaces**. Then we say  $f: X \rightarrow Y$  is  $(\mathcal{A}, \mathcal{B})$ -*measurable* if

$$\forall_{B \in \mathcal{B}} f^{-1}(B) \in \mathcal{A}.$$

**Remark.** If  $\mathcal{A}$  and  $\mathcal{B}$  are given, we'll sometimes say  $f$  is **measurable** if it'll not cause any confusions.

<sup>18</sup>[https://en.wikipedia.org/wiki/Dense\\_set](https://en.wikipedia.org/wiki/Dense_set)

<sup>19</sup>[https://en.wikipedia.org/wiki/Vitali\\_set](https://en.wikipedia.org/wiki/Vitali_set)



**Lemma 2.1.** Given two measurable spaces  $(X, \mathcal{A})$  and  $(Y, \mathcal{B})$ , and suppose  $\mathcal{B} = \langle \mathcal{E} \rangle$  for some  $\mathcal{E} \subset Y$ . Then,

$$f: X \rightarrow Y \text{ is } (\mathcal{A}, \mathcal{B})\text{-measurable} \iff \forall_{E \in \mathcal{E}} f^{-1}(E) \in \mathcal{A}.$$

*Proof.* We see that the *only if* part ( $\implies$ ) is clear. On the other direction, we consider the following. Let  $\mathcal{D} = \{E \subset Y \mid f^{-1}(E) \in \mathcal{A}\}$ , then

- $\mathcal{E} \subset \mathcal{D}$  by assumption
- $\mathcal{D}$  is a  $\sigma$ -algebra

Check!

hence, we see that  $\langle \mathcal{E} \rangle = \mathcal{B} \subset \mathcal{D}$  from Lemma 1.2. The result then follows from the definition of  $(\mathcal{A}, \mathcal{B})$ -measurable. ■

**Note.** Recall that

- $f^{-1}(E^c) = f^{-1}(E)^c$
- $f^{-1}\left(\bigcup_{\alpha} E_{\alpha}\right) = \bigcup_{\alpha} f^{-1}(E_{\alpha})$

**Definition 2.2 ( $\mathcal{A}$ -measurable).** Let  $(X, \mathcal{A})$  be a measurable space. Then,

$$\left. \begin{array}{l} f: X \rightarrow \mathbb{R} \\ f: X \rightarrow \overline{\mathbb{R}} \\ f: X \rightarrow \mathbb{C} \end{array} \right\} \text{ is } \mathcal{A}\text{-measurable if } \left\{ \begin{array}{l} f \text{ is } (\mathcal{A}, \mathcal{B}(\mathbb{R}))\text{-measurable} \\ f \text{ is } (\mathcal{A}, \mathcal{B}(\overline{\mathbb{R}}))\text{-measurable} \\ \Re f, \Im f: X \rightarrow \mathbb{R} \text{ are } \mathcal{A}\text{-measurable.} \end{array} \right.$$

**Notation.** Notice that

- $\overline{\mathbb{R}} = [-\infty, \infty]$
- $\mathcal{B}(\overline{\mathbb{R}}) = \{E \subset \overline{\mathbb{R}} \mid E \cap \mathbb{R} \in \mathcal{B}(\mathbb{R})\}$ .
- $\Re f$  is the real part of  $f$ , while  $\Im f$  is the imaginary part of  $f$ .

**Example.** We see that

- $\mathcal{A} = \mathcal{P}(X) \implies$  Every function is  $\mathcal{A}$ -measurable.
- $\mathcal{A} = \{\emptyset, X\} \implies$  The only  $\mathcal{A}$ -measurable functions are constant functions.

**Definition 2.3 (Lebesgue measurable).** A Lebesgue measurable function  $f$  is a measurable function

$$f: (\mathbb{R}, \mathcal{L}) \rightarrow (\mathbb{C}, \mathcal{B}(\mathbb{C})).$$

**Lemma 2.2.** Given  $f: X \rightarrow \mathbb{R}$ , *TFAE*.

1.  $f$  is  $\mathcal{A}$ -measurable
2.  $\forall a \in \mathbb{R}, f^{-1}((a, \infty)) \in \mathcal{A}$
3.  $\forall a \in \mathbb{R}, f^{-1}([a, \infty)) \in \mathcal{A}$
4.  $\forall a \in \mathbb{R}, f^{-1}((-\infty, a)) \in \mathcal{A}$
5.  $\forall a \in \mathbb{R}, f^{-1}((-\infty, a]) \in \mathcal{A}$

*Proof.* The result follows from Lemma 2.1 we just saw. ■

**Remark (Operations preserve  $\mathcal{A}$ -measurability).** Given  $f, g: X \rightarrow \mathbb{R}$  and is  $\mathcal{A}$ -measurable, then

1.  $\phi: \mathbb{R} \rightarrow \mathbb{R}$ ,  $\mathcal{A}$ -measurable<sup>20</sup>, then

$$\phi \circ f: X \rightarrow \mathbb{R}$$

is  $\mathcal{A}$ -measurable.

2.  $-f, 3f, f^2, |f|$  are all  $\mathcal{A}$ -measurable, and  $\frac{1}{f}$  is  $\mathcal{A}$ -measurable if  $f(x) \neq 0, \forall x \in X$ .
3.  $f + g$  is  $\mathcal{A}$ -measurable. We see this from

$$(f + g)^{-1}((a, \infty)) = \bigcup_{r \in \mathbb{Q}} (f^{-1}((r, \infty)) \cap g^{-1}((a - r, \infty)))$$

with Lemma 2.2.

4.  $f \cdot g$  is  $\mathcal{A}$ -measurable. We see this from

$$f(x)g(x) = \frac{1}{2} ((f(x) + g(x))^2 - f(x)^2 - g(x)^2).$$

5. We see that

$$(f \vee g)(x) := \max\{f(x), g(x)\} \text{ and } (f \wedge g)(x) := \min\{f(x), g(x)\}$$

are  $\mathcal{A}$ -measurable.

6. Let  $f_n: X \rightarrow \overline{\mathbb{R}}$  be  $\mathcal{A}$ -measurable. Then

$$\sup_{n \in \mathbb{N}} f_n, \inf_{n \in \mathbb{N}} f_n, \limsup_{n \rightarrow \infty} f_n, \liminf_{n \rightarrow \infty} f_n$$

are  $\mathcal{A}$ -measurable.

*Proof.* Consider  $\sup_{n \in \mathbb{N}} f_n =: g$ , then

$$g^{-1}((a, \infty]) = \bigcup_{n \in \mathbb{N}} f_n^{-1}((a, \infty])$$

for  $\sup_n f_n(x) = g(x) > a$ . A similar argument can prove the case of  $\inf_{n \in \mathbb{N}} f_n$ . check

And notice that  $\limsup_{n \rightarrow \infty} f_n = \inf_{k \in \mathbb{N}} \sup_{n \geq k} f_n$ , then the similar argument also proves this case. ■

7. If  $\lim_{n \rightarrow \infty} f_n(x)$  converges for every  $x \in X$ , then  $f$  is  $\mathcal{A}$ -measurable.

8. If  $f: \mathbb{R} \rightarrow \mathbb{R}$  is continuous

$\implies f$  is Borel measurable

$\implies f$  is Lebesgue measurable

since the preimage of an open set of a continuous function is open, then we consider  $f^{-1}((a, \infty))$ .

**Definition 2.4 (Support).** The *support* of function  $f: X \rightarrow \overline{\mathbb{R}}$  is

$$\text{supp } f := \{x \in X \mid f(x) \neq 0\}.$$

**Definition 2.5 (Positive and Negative part).** For  $f: X \rightarrow \overline{\mathbb{R}}$ , let  $f^+ := f \vee 0$  and  $f^- := (-f) \vee 0$ ,<sup>a</sup> where we call  $f^+$  the *positive part* of  $f$  while  $f^-$  the *negative part* of  $f$ .

<sup>a</sup>i.e.,  $f^+(x) = \max\{f(x), 0\}$ ,  $f^-(x) = \max\{-f(x), 0\}$

**Remark.** If  $\text{supp } f^+ \cap \text{supp } f^- = \emptyset$  and  $f(x) = f^+(x) - f^-(x)$ , then

$f$  is  $\mathcal{A}$ -measurable  $\iff f^+, f^-$  are  $\mathcal{A}$ -measurable.

**Definition 2.6 (Characteristic (Indicator) function).** For  $E \subset X$ , the *characteristic (indicator) function* of  $E$  is

$$\chi_E(x) = \mathbb{1}_E(x) = \begin{cases} 1, & \text{if } x \in E; \\ 0, & \text{if } x \in E^c. \end{cases}$$

**Remark.** We see that  $\mathbb{1}_E$  is  $\mathcal{A}$ -measurable  $\iff E \in \mathcal{A}$ .

**Definition 2.7 (Simple function).** Let  $(X, \mathcal{A})$  be a measurable space. Then a *simple function*  $\phi: X \rightarrow \mathbb{C}$  that is  $\mathcal{A}$ -measurable and takes only finitely many values.

**Remark.** We see that if

$$\phi(X) = \{c_1, \dots, c_N\},$$

<sup>20</sup>In this case, we also call it *Borel measurable*.

then

$$E_i = \phi^{-1}(\{c_i\}) \in \mathcal{A} \implies \phi = \sum_{i=1}^N \underbrace{c_i}_{\neq \pm\infty} \mathbb{1}_{\underbrace{E_i}_{\in \mathcal{A}}}.$$

## Lecture 11: Integration of nonnegative functions

31 Jan. 11:00

As previously seen. For a [simple function](#)  $\phi$ ,  $c_i$  can actually be in  $\mathbb{C}$ .

**Theorem 2.1.** Given a [measurable space](#)  $(X, \mathcal{A})$  and let  $f: X \rightarrow [0, \infty]$ , the followings are equivalent.

1.  $f$  is a [mathcal{A}-measurable](#) function.
2. There exists [simple functions](#)  $0 \leq \phi_1(x) \leq \phi_2(x) \leq \dots \leq f(x)$  such that

$$\forall_{x \in X} \lim_{n \rightarrow \infty} \phi_n(x) = f(x)$$

i.e.,  $f$  is a [pointwise upward](#) limit of [simple functions](#).

*Proof.* We'll prove both directions.

- It's clear that (2.)  $\implies$  (1.) from the fact that  $f(x) = \sup_n \phi_n(x)$  and [the remark](#).
- We want to show that (1.)  $\implies$  (2.). Assume  $f$  is [mathcal{A}-measurable](#), and fix  $n \in \mathbb{N}$ .

Let  $F_n = f^{-1}([2^n, \infty]) \in \mathcal{A}$ . Also, for  $0 \leq k \leq 2^{2^n} - 1$ ,  $E_{n,k} = f^{-1}([\frac{k}{2^n}, \frac{k+1}{2^n}]) \in \mathcal{A}$ .

Then, define  $\phi_n$  be

$$\phi_n = \sum_{k=0}^{2^{2^n}-1} \frac{k}{2^n} \mathbb{1}_{E_{n,k}} + 2^n \mathbb{1}_{F_n},$$

we have

- $0 \leq \phi_1(x) \leq \phi_2(x) \leq \dots \leq f(x)$  for every  $x \in X$
- $\forall x \in X \setminus F_n$ , we have  $0 \leq f(x) - \phi_n(x) \leq \frac{1}{2^n}$

Furthermore, we see that

$$F_1 \supset F_2 \supset \dots, \quad \bigcap_{n=1}^{\infty} F_n = f^{-1}(\{\infty\}),$$

then

- $x \in f^{-1}([0, \infty]) = X \setminus \bigcap_{n=1}^{\infty} F_n \implies \lim_{n \rightarrow \infty} \phi_n(x) = f(x)$
- $x \in f^{-1}(\{\infty\}) = \bigcap_{n=1}^{\infty} F_n \implies f_n(x) \geq 2^n \implies \lim_{n \rightarrow \infty} \phi_n(x) = \infty = f(x)$

■

**Corollary 2.1.** If  $f$  is bounded on a set  $A \subset \mathbb{R}$ , i.e.,  $\exists L > 0$  such that

$$\forall_{x \in A} |f(x)| \leq L,$$

then there exists a sequence of [simple functions](#)  $\{\phi_n\}$  such that  $\phi_n \rightarrow f$  [uniformly](#) on  $A$ .

*Proof.*

■

DIY

**Corollary 2.2.** If  $f: X \rightarrow \mathbb{C}$  is a [measurable function](#) if and only if there exists [simple functions](#)  $\phi_n: X \rightarrow \mathbb{C}$  such that

$$0 \leq |\phi_1(x)| \leq |\phi_2(x)| \leq \dots \leq |f(x)|$$

with

$$\forall_{x \in X} \lim_{n \rightarrow \infty} \phi_n(x) = f(x).$$

*Proof.*

■

DIY

## 2.2 Integration of Nonnegative Functions

We start with our first definition about integral.

**Definition 2.8 (Integration of nonnegative function).** Let  $(X, \mathcal{A}, \mu)$  be a [measure space](#), and  $\phi: X \rightarrow [0, \infty]$  such that

$$\phi = \sum_{i=1}^N c_i \mathbb{1}_{E_i}$$

be a [simple function](#). Define

$$\int \phi = \int \phi \, d\mu = \int_X \phi \, d\mu = \sum_{i=1}^N c_i \mu(E_i).$$

Furthermore, for  $A \in \mathcal{A}$ ,

$$\int_A \phi = \int \phi \, d\mu = \int \phi \mathbb{1}_A \, d\mu.$$

**Note.** Note that

- In the expression  $\sum_{i=1}^N c_i \mu(E_i)$ , we're using the convention  $0 \cdot \infty = 0$ .

- The function  $\phi \mathbb{1}_A$  is also a **simple function** since both  $\phi$  and  $\mathbb{1}_A$  are **simple function**.

**Proposition 2.1.** Suppose we have  $\phi, \psi \geq 0$  be two **simple functions**. Then,

- **Definition 2.8** is well-defined.
- $\int c\phi = c \int \phi$  for  $c \in [0, \infty)$ .
- $\int \phi + \psi = \int \phi + \int \psi$ .
- $\phi(x) \geq \psi(x)$  for all  $x \implies \int \phi \geq \int \psi$ .
- $\nu(A) = \int_A \phi d\mu$  is a **measure** on  $(X, \mathcal{A})$ .

*Proof.*



DIY

**Definition 2.9 (Generalization of Integration of nonnegative function).** Given  $(X, \mathcal{A}, \mu)$  with  $f: X \rightarrow [0, \infty]$  be  **$\mathcal{A}$ -measurable**. Define

$$\int f = \int f d\mu = \sup \left\{ \int \phi : 0 \leq \phi \leq f \text{ such that } \phi \text{ is simple} \right\}.$$

**Note.** Note that

- If  $f$  is a **simple function**, the **Definition 2.8** and **Definition 2.9** of  $\int f$  are the same.
- $\int cf = c \int f$  for  $c \in [0, \infty)$ .
- If  $f \geq g \geq 0 \implies \int f \geq \int g$ .
- But  $\int f + g = \int f + \int g$  is not trivial.

**Theorem 2.2 (Monotone Convergence Theorem (MCT)).** Given  $(X, \mathcal{A}, \mu)$  be a **measure space**. Then if

- $f_n: X \rightarrow [0, \infty]$  be  **$\mathcal{A}$ -measurable** for every  $n \in \mathbb{N}$ ;
- $0 \leq f_1(x) \leq f_2(x) \leq \dots$  for every  $x \in X$ ;
- $\lim_{n \rightarrow \infty} f_n(x) = f(x)$  for every  $x \in X$ ,

we have

$$\lim_{n \rightarrow \infty} \int f_n = \int f.$$

*Proof.* Note that if  $\lim_{n \rightarrow \infty} \int f_n$  exists, then it's equal to  $\sup_n \int f_n$ .

Then

- $f_n \leq f \implies \int f_n \leq \int f \implies \lim_{n \rightarrow \infty} \int f_n \leq \int f$ .

- Fix a **simple function**  $0 \leq \phi \leq f$ , then it's enough to show  $\lim_{n \rightarrow \infty} \int f_n \geq \int \phi$ .

We first fix  $\alpha = (0, 1)$ , then it's also enough to show

$$\lim_{n \rightarrow \infty} \int f_n \geq \alpha \int \phi.$$

Let  $A_n := \{x \in X \mid f_n(x) \geq \alpha \phi(x)\}$ , then since  $f_n$  is **measurable**,

- $A_n \in \mathcal{A}$
- $A_1 \subset A_2 \subset A_3 \subset \dots$
- $\bigcup_{n=1}^{\infty} A_n = X$

Check!

We then have

$$\int f_n \geq \int f_n \mathbb{1}_{A_n} \geq \int \alpha \phi \mathbb{1}_{A_n} = \alpha \int_{A_n} \phi = \alpha \nu(A_n)$$

where  $\nu(A) = \int_A \phi$  is a **measure**. This implies

$$\lim_{n \rightarrow \infty} \int f_n \geq \alpha \lim_{n \rightarrow \infty} \nu(A_n) \stackrel{21}{=} \alpha \nu(X) = \alpha \int \phi.$$

■

**Corollary 2.3 (Linearity of nonnegative integral).** Let  $f, g \geq 0$  be **measurable**, then

$$\int f + g = \int f + \int g.$$

*Proof.* There exists **simple functions**  $\phi_n$  and  $\psi_n$  such that

- $0 \leq \phi_1 \leq \phi_2 \leq \dots$  and  $\phi_n \rightarrow f$  **pointwise**
- $0 \leq \psi_1 \leq \psi_2 \leq \dots$  and  $\psi_n \rightarrow g$  **pointwise**

Then,

$$\int (f + g) \stackrel{!}{=} \lim_{n \rightarrow \infty} \int (\phi_n + \psi_n) = \lim_{n \rightarrow \infty} \int \phi_n + \int \psi_n \stackrel{!}{=} \int f + \int g.$$

■

## Lecture 12: Fatou's Lemma

2 Feb. 11:00

We start with a useful corollary.

<sup>21</sup>This follows from the **continuity of measure from below**

**Corollary 2.4 (Tonelli's theorem for nonnegative series and integrals).** Given  $g_n \geq 0$  for every  $n \in \mathbb{N}$  and let  $g_n$  be measurable, then

$$\int \sum_{n=1}^{\infty} g_n = \sum_{n=1}^{\infty} \int g_n.$$

**Remark.** Recall that we have seen [two series case](#) before. We'll later see two integrals cases.

*Proof.* Let  $f_N := \sum_{n=1}^N g_n$  such that  $\lim_{N \rightarrow \infty} f_N = \sum_{n=1}^{\infty} g_n =: f$ , then since  $g_n \geq 0$ , we have  $0 \leq f_1 \leq f_2 \leq \dots$  with

$$\lim_{N \rightarrow \infty} f_N(x) = \sum_{n=1}^{\infty} g_n(x).$$

By [Theorem 2.2](#), we have

$$\lim_{N \rightarrow \infty} \underbrace{\int \sum_{n=1}^N g_n}_{f_N} = \underbrace{\int \sum_{n=1}^{\infty} g_n}_f.$$

Now, since the terms in the limit on the left-hand side is just a finite sum, by [Corollary 2.3](#), we have

$$\underbrace{\lim_{N \rightarrow \infty} \sum_{n=1}^N \int g_n}_{\sum_{n=1}^{\infty} \int g_n} = \lim_{N \rightarrow \infty} \int \sum_{n=1}^N g_n = \int \sum_{n=1}^{\infty} g_n,$$

hence

$$\int \sum_{n=1}^{\infty} g_n = \sum_{n=1}^{\infty} \int g_n.$$

■

**Theorem 2.3 (Fatou's Lemma).** Suppose  $f_n \geq 0$  and measurable, then

$$\int \liminf_{n \rightarrow \infty} f_n \leq \liminf_{n \rightarrow \infty} \int f_n.$$

**Remark.** Recall that

$$\liminf_{n \rightarrow \infty} f_n := \lim_{k \rightarrow \infty} \inf_{n \geq k} f_n = \sup_{k \in \mathbb{N}} \inf_{n \geq k} f_n$$

and

$$\exists \lim_{n \rightarrow \infty} a_n \iff \limsup_{n \rightarrow \infty} a_n = \liminf_{n \rightarrow \infty} a_n.$$



*Proof.* Let  $g_k = \inf_{n \geq k} f_n$ , then  $g_k$  is measurable and  $0 \leq g_1 \leq g_2 \leq \dots$ . Now, from Theorem 2.2, we have

$$\int \lim_{k \rightarrow \infty} g_k = \lim_{k \rightarrow \infty} \int g_k.$$

Notice that the left-hand side is just  $\int \liminf_{n \rightarrow \infty} f_n$ , while the right-hand side is just  $\lim_{k \rightarrow \infty} \int \inf_{n \geq k} f_n$ , i.e.,

$$\int \liminf_{n \rightarrow \infty} f_n = \lim_{k \rightarrow \infty} \int \inf_{n \geq k} f_n.$$

We see that we want to take the inf outside the integral on the right-hand side. Observe that

$$\forall_{m \geq k} \inf_{n \geq k} f_n \leq f_m \implies \forall_{m \geq k} \int \inf_{n \geq k} f_n \leq \int f_m \implies \int \inf_{n \geq k} f_n \leq \inf_{m \geq k} \int f_m.$$

Then, we have

$$\int \liminf_{n \rightarrow \infty} f_n = \lim_{k \rightarrow \infty} \int \inf_{n \geq k} f_n \leq \lim_{k \rightarrow \infty} \inf_{m \geq k} \int f_m = \liminf_{m \rightarrow \infty} \int f_m.$$

■

**Example.** Given  $(\mathbb{R}, \mathcal{L}, m)$ .

1. **Escape to horizontal infinity.** Let  $f_n := \mathbb{1}_{(n, n+1)}$ . We immediately see that

- $f_n \rightarrow 0$  pointwise
- $\int f_n = 1$  for every  $n$
- $\int f = 0$

From Theorem 2.3, we have a strict inequality

$$0 = \int \liminf_{n \rightarrow \infty} f_n, \liminf_{n \rightarrow \infty} \int f_n = 1.$$

2. **Escape to width infinity.** Let  $f_n := \frac{1}{n} \mathbb{1}_{(0, n)}$ .
3. **Escape to vertical infinity.** Let  $f_n := n \mathbb{1}_{(0, \frac{1}{n})}$ .

**Lemma 2.3 (Markov's inequality).** Let  $f \geq 0$  be measurable. Then

$$\forall_{c \in (0, \infty)} \mu(\{x \mid f(x) \geq c\}) \leq \frac{1}{c} \int f.$$

*Proof.* Denote  $\{x \mid f(x) \geq c\} =: E$ , then

$$f(x) \geq c \mathbb{1}_E(x) \implies \int f \geq c \int \mathbb{1}_E = c \cdot \mu(E).$$

■

**Remark.** Notice that  $E = f^{-1}([c, \infty])$ , hence  $E$  is measurable.

**Proposition 2.2.** Let  $f \geq 0$  be measurable. Then,

$$\int f = 0 \iff f = 0 \text{ a.e..}$$

i.e.,

$$\int f \, d\mu = 0 \iff \mu(A) = 0$$

where  $A = \{x \mid f(x) > 0\} = f^{-1}((0, \infty])$ .

*Proof.* Firstly, assume that  $f = \phi$  is a simple function. We may write

$$\phi = \sum_{i=1}^N c_i \mathbb{1}_{E_i}$$

where  $E_i$  are disjoint and  $c_i \in (0, \infty)$ . Then,

$$\begin{aligned} \int \phi &= \sum_{i=1}^N c_i \mu(E_i) = 0 \\ \iff \mu(E_1) = \dots = \mu(E_N) &= 0 \\ \iff \mu(A) = 0, \quad A = \bigcup_{i=1}^N E_i. \end{aligned}$$

Now, assume that  $f$  is a general function where  $f \geq 0$  is the only constraint.

1. Assume  $\mu(A) = 0$  (i.e.,  $f = 0$  a.e.). Let  $0 \leq \phi \leq f$ , where  $\phi$  is simple. Then

$$\forall_{x \in A^c} \phi(x) = 0$$

since  $f(x) = 0, \forall x \in A^c$ . This implies that  $\phi = 0$  a.e. since  $\mu(A) = 0$ , so  $\int \phi = 0$ . We then have

$$\int f = 0$$

from Definition 2.9.

2. Assume  $\int f = 0$ . Let  $A_n = f^{-1}([\frac{1}{n}, \infty])$ . Then we see that

- $A_1 \subset A_2 \subset \dots$
- $\bigcup_{n=1}^{\infty} A_n = f^{-1}\left(\bigcup_{n=1}^{\infty} [\frac{1}{n}, \infty]\right) = f^{-1}((0, \infty)) = A$ .

We then have

$$\mu(A_n) = \mu\left(\left\{x \mid f(x) \geq \frac{1}{n}\right\}\right) \stackrel{!}{\leq} n \int f = 0,$$

which further implies

$$\mu(A) = \lim_{n \rightarrow \infty} \mu(A_n) = 0$$

from the [continuity of measure from below](#).

■

**Corollary 2.5.** If  $f, g \geq 0$  are both [measurable](#) and  $f = g$  [a.e.](#), then

$$\int f = \int g.$$

*Proof.* Let  $A = \{x \mid f(x) \neq g(x)\}$ <sup>22</sup>. Then by assumption,  $\mu(A) = 0$ , hence

$$f \mathbb{1}_A = 0 \text{ [a.e.](#), } \quad g \mathbb{1}_A = 0 \text{ [a.e.](#)..}$$

This further implies that

$$\begin{aligned} \int f &= \int f(\mathbb{1}_A + \mathbb{1}_{A^c}) \\ &\stackrel{!}{=} \int f \mathbb{1}_A + \int f \mathbb{1}_{A^c} \\ &= \int f \mathbb{1}_{A^c} = \int g \mathbb{1}_{A^c} \\ &= \int g \mathbb{1}_{A^c} + \int g \mathbb{1}_A = \int g. \end{aligned}$$

■

**Corollary 2.6.** Let  $f_n \geq 0$  be [measurable](#). Then

1. 
$$\left. \begin{array}{l} 0 \leq f_1 \leq f_2 \leq \dots \leq f \text{ [a.e.](#)} \\ \lim_{n \rightarrow \infty} f_n = f \text{ [a.e.](#)} \end{array} \right\} \implies \lim_{n \rightarrow \infty} \int f_n = \int f.$$
2. 
$$\lim_{n \rightarrow \infty} f_n = f \text{ [a.e.](#)} \implies \int f \leq \liminf_{n \rightarrow \infty} \int f_n.$$

*Proof.*

■

DIY

**Remark.** Almost all the theorems we've proved can be replaced by theorems dealing with [almost everywhere](#) condition.

## Lecture 13: Integration of Complex Functions

4 Feb. 11:00

### 2.3 Integration of Complex Functions

As usual, we start with a definition.

<sup>22</sup> $A$  is [measurable](#) indeed.

**Definition 2.10 (Integrable).** Let  $(X, \mathcal{A}, \mu)$  be a **measure space** and let  $f: X \rightarrow \overline{\mathbb{R}}$  and  $g: X \rightarrow \mathbb{C}$  be **measurable**.<sup>a</sup>

Then  $f, g$  are called *integrable* if  $\int |f| < \infty$  and  $\int |g| < \infty$ , and we define

$$\int f = \int f^+ - \int f^-, \quad \int g = \int \Re g + i \int \Im g.$$

Furthermore, for  $f: X \rightarrow \overline{\mathbb{R}}$ , we define

$$\int f = \begin{cases} \infty, & \text{if } \int f^+ = \infty, \int f^- < \infty; \\ -\infty, & \text{if } \int f^+ < \infty, \int f^- = \infty. \end{cases}$$

<sup>a</sup>Recall that for a complex-valued function like  $g$ , this means that both  $\Re g$  and  $\Im g$  are **measurable**.

We now see a lemma.

**Lemma 2.4.** Let  $f, g: X \rightarrow \overline{\mathbb{R}}$  or  $\mathbb{C}$  **integrable**. Assume that  $f(x) + g(x)$  is well-defined for all  $x \in X$ .<sup>a</sup>

Then we have

1.  $f + g, cf$  for all  $c \in \mathbb{C}$  are **integrable**.
2.  $\int f + g = \int f + \int g$ . This is not trivial since  $(f + g)^+ \neq f^+ + g^+$ .
3.  $|\int f| \leq \int |f|$ .

<sup>a</sup>That is, we never see  $\infty + (-\infty)$  or  $(-\infty) + \infty$ .

*Proof.* Check [FF99] page 53. ■

**Lemma 2.5.** Let  $(X, \mathcal{A}, \mu)$  be a **measure space** and let  $f$  be an **integrable** function on  $X$ . Then

1.  $f$  is finite **a.e.** i.e.,  $\{x \in X \mid |f(x)| = \infty\}$  is a **null set**.
2. The set  $\{x \in X \mid f(x) \neq 0\}$  is  **$\sigma$ -finite**.

*Proof.* \_\_\_\_\_ ■

HW 5  
Q8 by  
Lemma 2.3

**Proposition 2.3.** Let  $(X, \mathcal{A}, \mu)$  be a **measure space**, then

1. If  $h$  is **integrable** on  $X$ , then

$$\forall_{E \in \mathcal{A}} \int_E h = 0 \iff \int |h| = 0 \iff h = 0 \text{ a.e.}$$

2. If  $f, g$  are **integrable** on  $X$ , then

$$\forall_{E \in \mathcal{A}} \int_E f = \int_E g \iff f = g \text{ a.e.}$$

*Proof.* We prove this one by one.

1. We see that the second equivalence is done in **Proposition 2.2**, hence we prove the first equivalence only. Since we have

$$\int |h| = 0 \implies \left| \int_E h \right| \leq \int_E |h| \leq \int |h| = 0,$$

which shows one implication. Now assume that  $\int_E h = 0$  for all  $E \in \mathcal{A}$ , then we can write  $h$  as

$$h = u + iv = (u^+ - u^-) + i(v^+ - v^-).$$

Let  $B := \{x \in X \mid u^+(x) > 0\}$ , then by assumption, we have

$$0 = \int_B h = \Re \int_B h = \int_B u = \int_B u^+ = \int_B u^+ + \int_{B^c} u^+ = \int u^+,$$

hence  $u^+ = 0$  **almost everywhere**. Similarly, we have  $u^-, v^+, v^-$  are all zero **almost everywhere**. This gives us that  $h$  is zero **almost everywhere** as desired.

2. \_\_\_\_\_

DIY

■

**Theorem 2.4 (Dominated Convergence Theorem).** Let  $(X, \mathcal{A}, \mu)$  be a **measure space**, and

- Let  $f_n$  be **integrable** on  $X$ .
- $\lim_{n \rightarrow \infty} f_n(x) = f(x)$  **almost everywhere**.
- There is a  $g: X \rightarrow [0, \infty]$  such that  $g$  is **integrable** and

$$\forall_{n \in \mathbb{N}} |f_n(x)| \leq g(x) \text{ a.e.}$$

Then we have

$$\lim_{n \rightarrow \infty} \int f_n = \int f = \int \lim_{n \rightarrow \infty} f_n.$$

*Proof.* Let  $F$  be the countable union of [null set](#) on which the three conditions may fail. Then we see that after modifying the definition of  $f_n, f$  and  $g$  on  $F$ , we may assume that all three conditions hold everywhere since modifying on a [null set](#) does not change the integral.

We now consider the  $\mathbb{R}$ -valued case only. Note that the second and the third conditions imply that  $f$  is [integrable](#) since  $|f| \leq g(x)$ . We then see that  $g + f_n \geq 0$  and  $g - f_n \geq 0$  because  $-g \leq f_n \leq g$ . From [Theorem 2.3](#), we have

 Check  $\mathbb{C}$ -valued case

$$\int g + f \leq \liminf_{n \rightarrow \infty} \int g + f_n, \quad \int g - f \leq \liminf_{n \rightarrow \infty} \int g - f_n.$$

From the [linearity of integral](#), we have

$$\int g + \int f \leq \int g + \liminf_{n \rightarrow \infty} \int f_n, \quad \int g - \int f \leq \int g - \liminf_{n \rightarrow \infty} \int f_n.$$

Now, since  $\int g < \infty$ , we can cancel it, which gives

$$\int f \leq \liminf_{n \rightarrow \infty} \int f_n, \quad -\int f \leq \liminf_{n \rightarrow \infty} \int -f_n = -\limsup_{n \rightarrow \infty} \int f_n,$$

which implies

$$\int f \leq \liminf_{n \rightarrow \infty} \int f_n \leq \limsup_{n \rightarrow \infty} \int f_n \leq \int f.$$

This shows that the limit exists, and the desired result indeed holds. ■

**Corollary 2.7 (Tonelli's theorem for series and integrals).** Suppose  $f_n$  are [integrable](#) functions such that

$$\sum_{n=1}^{\infty} \int |f_n| < \infty,$$

then we have

$$\int \sum_{n=1}^{\infty} f_n = \sum_{n=1}^{\infty} \int f_n.$$

*Proof.* Take  $G(x)$  to be

$$G(x) := \sum_{n=1}^{\infty} |f_n(x)|,$$

then we see

$$G(x) \geq |F_N(x)|$$

where

$$F_N(x) := \sum_{n=1}^N f_n(x).$$

By [Corollary 2.4](#), we have

$$\int G(x) = \sum_{n=1}^{\infty} \int |f_n(x)| < \infty.$$

Lastly, from [Theorem 2.4](#), the result follows. ■

**Remark.** Compare to [Corollary 2.4](#), we see that we further generalize the result!

## Lecture 14: $L^1$ Space

7 Feb. 11:00

### 2.4 $L^1$ Space

We now introduce another space called  $L^p$  spaces, which are function spaces defined using a natural generalization of the [p-norm](#) for finite-dimensional vector spaces. We sometimes call it Lebesgue spaces also.

Before we start, we need to define a *norm*.

**Definition 2.11 (Seminorm).** Let  $V$  be a vector space over field  $\mathbb{R}$  or  $\mathbb{C}$ . A *seminorm* on  $V$  is

$$\|\cdot\| : V \rightarrow [0, \infty)$$

such that

- $\|cv\| = |c| \|v\|$  for every  $v \in V$  and every scalar  $c$ .
- $\|v + w\| \leq \|v\| + \|w\|$  for every  $v, w \in V$ .

**Definition 2.12 (Norm).** A *norm* is a [seminorm](#) with

- $\|v\| = 0 \iff v = 0$ .

**Lemma 2.6.** A [normed](#) vector space is a metric space with metric

$$\rho(v, w) = \|v - w\|.$$

*Proof.*



DIY

**Example ( $p$ -norm).**  $V = \mathbb{R}^d$  with

$$\|x\|_p = \begin{cases} \left( \sum_{i=1}^d |x_i|^p \right)^{1/p}, & \text{if } p \in [0, \infty); \\ \max_{1 \leq i \leq d} |x_i|, & \text{if } p = \infty \end{cases}$$

is a [normed](#) vector space. The unit ball

$$\{x \in \mathbb{R}^d \mid \|x\|_p \leq 1\}$$

for different  $p$  has the following figures.



**Remark.** All  $\|\cdot\|_p$  norms induce the same topology. i.e., if  $U$  is open in  $p$ -norm, it is open in  $p'$ -norm as well.

**Note.** Recall that we say  $f$  is **integrable** means

$$\int |f| < \infty,$$

and if  $f = g$  **a.e.**, then

$$\int f = \int g$$

**Definition 2.13 ( $L^1$  Space).** Given  $(X, \mathcal{A}, \mu)$ ,

$$f \in L^1(X, \mathcal{A}, \mu) (= L^1(X, \mu) = L^1(X) = L^1(\mu))$$

means that  $f$  is an **integrable** function on  $X$ .

**Lemma 2.7.**  $L^1(X, \mathcal{A}, \mu)$  is a vector space with **seminorm**

$$\|f\|_1 = \int |f|.$$

*Proof.*

■

Check this  
is indeed a  
**seminorm**.

**Definition 2.14 ( $L^1$  Space with equivalence class).** Define  $f \sim g$  if  $f = g$  **a.e.**, then

$$L^1(X, \mathcal{A}, \mu) / \sim = L^1(X, \mathcal{A}, \mu),$$

i.e., we simply denote the collection of equivalence classes by itself.<sup>a</sup>

<sup>a</sup>By some abusing of notation of  $L^1$ .



**Remark.** We have

- With Definition 2.14,  $L^1(X, \mathcal{A}, \mu)$  is a **normed** vector space.
- We say that the  $L^1$ -metric  $\rho(f, g)$  is simply

$$\rho(f, g) = \int |f - g|.$$

#### 2.4.1 Dense Subsets of $L^1$

**Note.** Recall the definition of a *dense set*<sup>23</sup>.

**Definition 2.15 (Step function).** A *step function* on  $\mathbb{R}$  is

$$\psi = \sum_{i=1}^N c_i \mathbb{1}_{I_i},$$

where  $I_i$  is an interval.

**Theorem 2.5.** We have the following.

1. {integrable simple functions} is dense in  $L^1(X, \mathcal{A}, \mu)$  (with respect to  $L^1$ -metric).
2.  $(X, \mathcal{A}, \mu) = (\mathbb{R}, \mathcal{A}_\mu, \mu)$ , where  $\mu$  is a Lebesgue-Stieltjes-measure. Then {integrable simple functions} is dense in  $L^1(\mathbb{R}, \mathcal{A}_\mu, \mu)$ .
3.  $C_c(\mathbb{R})$  is dense in  $L^1(\mathbb{R}, \mathcal{L}, m)$ .

**Notation.** We denote the collection of continuous functions with compact support by  $C_c(\mathbb{R})$ .

*Proof.* We prove this one by one.

1. Since there exists simple functions  $0 \leq |\phi_1| \leq |\phi_2| \leq \dots \leq |f|$ , where  $\phi_n \rightarrow f$  pointwise. Then by Theorem 2.4, we have

$$\lim_{n \rightarrow \infty} \int \underbrace{|f_n - f|}_{\leq |\phi_n| + |f| \leq 2|f|} = 0$$

where  $2|f|$  is in  $L^1$ .

2. Let  $\mathbb{1}_E$  approximate by  $\sum_{i=1}^{\infty} c_i \mathbb{1}_{I_i}$ . From Theorem 1.6 for Lebesgue-Stieltjes-measure,

$$\forall \epsilon' > 0 \exists I = \bigcup_{i=1}^N I_i \text{ such that } \mu(E \triangle I) \leq \epsilon'.$$

<sup>23</sup>[https://en.wikipedia.org/wiki/Dense\\_set](https://en.wikipedia.org/wiki/Dense_set)

3. To approximate  $\mathbb{1}_{(a,b)}$ , we simply consider function  $g \in C_c(\mathbb{R})$  such that

$$\int |\mathbb{1}_{(a,b)} - g| \leq \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon.$$

■

## Lecture 15: Riemann Integral

9 Feb. 11:00

### 2.5 Riemann Integrability

We are now working in  $(\mathbb{R}, \mathcal{L}, m)$ . Let's first revisit the definition of Riemann Integral. Let  $P$  be a partition of  $[a, b]$  as

$$P = \{a = t_0 < t_1 < \dots < t_k = b\}.$$

Then the *lower Riemann sum* of  $f$  using  $P$  is equal to  $L_P$ , which is defined as

$$L_P = \sum_{i=1}^K \left( \inf_{[t_{i-1}, t_i]} f \right) (t_i - t_{i-1}),$$

and the *upper Riemann sum* of  $f$  using  $P$  is equal to  $U_P$ , which is defined as

$$U_P = \sum_{i=1}^K \left( \sup_{[t_{i-1}, t_i]} f \right) (t_i - t_{i-1}).$$

Then we call

- *Lower Riemann integral* of  $f = \underline{I} = \sup_P L_P$
- *Upper Riemann integral* of  $f = \bar{I} = \inf_P U_P$

**Definition 2.16 (Riemann (Darboux) integrable).** A bounded function  $f: [a, b] \rightarrow \mathbb{R}$  is called *Riemann (Darboux) integrable* if

$$\underline{I} = \bar{I}$$

If so, then  $\underline{I} = \bar{I} = \int_a^b f(x) dx$ .

**Note.** We see that

- If  $P \subset P'$ , then

$$L_P \leq L_{P'}, \quad U_{P'} \leq U_P.$$

- Recall that continuous functions on  $[a, b]$  are [Riemann integrable](#) on  $[a, b]$ .

**Theorem 2.6.** Let  $f: [a, b] \rightarrow \mathbb{R}$  be a bounded function. Then

1. If  $f$  is Riemann integrable, then  $f$  is Lebesgue measurable, thus Lebesgue integrable. Further,

$$\int_a^b f(x) dx = \int_{[a,b]} f dm.$$

2. If  $f$  is Riemann integrable  $\iff f$  is continuous Lebesgue a.e.<sup>a</sup>

<sup>a</sup>Here, we mean that the set where  $f$  is discontinuous is a null set under Lebesgue measure.

*Proof.* There exists  $P_1 \subset P_2 \subset \dots$  such that  $L_{P_n} \nearrow \underline{I}$  and  $U_{P_n} \searrow \bar{I}$ .<sup>24</sup> Now, define simple (step) functions

$$\begin{aligned} \bullet \phi_n &= \sum_{i=1}^K \left( \inf_{[t_{i-1}, t_i]} f \right) \mathbb{1}_{(t_{i-1}, t_i]} \\ \bullet \psi_n &= \sum_{i=1}^K \left( \sup_{[t_{i-1}, t_i]} f \right) \mathbb{1}_{(t_{i-1}, t_i]} \end{aligned}$$

if  $P_n = \{a = t_0 < t_1 < \dots < t_K\}$ . Let  $\phi := \sup_n \phi_n$  and  $\psi := \inf_n \psi_n$ . We then see that  $\phi, \psi$  are Lebesgue (Borel) measurable function.

**Note.** Note that

$$\begin{aligned} \bullet \exists M > 0 \text{ such that } \forall_{n \in \mathbb{N}} |\phi_n|, |\psi_n| &\leq M \mathbb{1}_{[a,b]} \\ \bullet \int \phi_n dm &= L_{P_n}, \int \psi_n dm = U_{P_n} \end{aligned}$$

By Theorem 2.4 and the fact that  $M \mathbb{1}_{[a,b]} \in L^1(\mathbb{R}, \mathcal{L}, m)$ , we have

$$\underline{I} = \lim_{n \rightarrow \infty} \int \phi_n dm = \int \phi dm, \quad \bar{I} = \int \psi dm.$$

Thus,

$$\begin{aligned} f \text{ is Riemann integrable} &\iff \int \phi = \int \psi \\ &\iff \int (\psi - \phi) = 0 \\ &\iff \psi = \phi \text{ Lebesgue a.e.} \end{aligned}$$

■

## 2.6 Modes of Convergence

As we should already see, there are different *modes* of convergence. Let's formalize them.

<sup>24</sup>Here, we took refinements of  $P_n$  if needed.

**Definition 2.17 (Pointwise, Uniformly convergence).** Let

$$f_n, f: X \rightarrow \mathbb{C},$$

and  $S \subset X$ . Then we say

- $f_n \rightarrow f$  *pointwise* on  $S$  if

$$\forall_{x \in S} \forall_{\epsilon > 0} \exists_{N \in \mathbb{N}} \forall_{n \geq N} |f_n(x) - f(x)| < \epsilon.$$

- $f_n \rightarrow f$  *uniformly* on  $S$  if

$$\forall_{\epsilon > 0} \exists_{N \in \mathbb{N}} \forall_{x \in S} \forall_{n \geq N} |f_n(x) - f(x)| < \epsilon.$$

**Remark.** We see that we can replace  $\forall \epsilon > 0$  by  $\forall k \in \mathbb{N}$  with  $\epsilon$  changing to  $\frac{1}{k}$ .

**Lemma 2.8.** Let  $B_{n,k}$  be

$$B_{n,k} := \left\{ x \in X \mid |f_n(x) - f(x)| < \frac{1}{k} \right\}.$$

Then

1.  $f_n \rightarrow f$  *pointwise* on  $S$  if and only if

$$S \subset \bigcap_{k=1}^{\infty} \bigcup_{N=1}^{\infty} \bigcap_{n=N}^{\infty} B_{n,k}.$$

2.  $f_n \rightarrow f$  *uniformly* on  $S$  if and only if  $\exists N_1, N_2, \dots \in \mathbb{N}$  such that

$$S \subset \bigcap_{k=1}^{\infty} \bigcap_{n=N_k}^{\infty} B_{n,k}.$$

*Proof.* This essentially follows from [Definition 2.17](#). ■

**Definition 2.18 (Converges a.e., Converges in  $L^1$ ).** Let  $(X, \mathcal{A}, \mu)$  be a *measure space*. Assuming that  $f_n, f$  are *measurable function*, then

1.  $f_n \rightarrow f$  *almost everywhere* means

$$\exists \text{ null set } E \text{ such that } f_n \rightarrow f \text{ pointwise on } E^c.$$

2.  $f_n \rightarrow f$  *in  $L^1$*  means

$$\lim_{n \rightarrow \infty} \|f_n - f\| = 0.$$

**Example.** Given  $(\mathbb{R}, \mathcal{L}, m)$  and let  $f = 0$ . We see the followings.

1.  $f_n = \mathbb{1}_{(n, n+1)}$
2.  $f_n = \frac{1}{n} \mathbb{1}_{(0, n)}$
3.  $f_n = n \mathbb{1}_{(0, \frac{1}{n})}$
4. **Typewriter functions.**



## Lecture 16: Modes of Convergence

11 Feb. 11:00

Let's start with a proposition.

**Proposition 2.4 (Fast  $L^1$  convergence leads to a.e. convergence).** Let  $(X, \mathcal{A}, \mu)$  be a **measure space**, and  $f_n, f$  are all **measurable** functions on  $X$ . Then

$$\sum_{n=1}^{\infty} \|f_n - f\|_1 < \infty \implies f_n \rightarrow f \text{ a.e.}$$

*Proof.* Let

$$E := \bigcup_{k=1}^{\infty} \bigcap_{N=1}^{\infty} \bigcup_{n=N}^{\infty} B_{n,k}^c = \{x \in X \mid f_n(x) \not\rightarrow f(x)\}.$$



**Definition 2.20 (Uniformly a.e., Almost uniformly).** Let  $f_n, f$  be measurable functions on  $(X, \mathcal{A}, \mu)$ .

1.  $f_n \rightarrow f$  *uniformly almost everywhere* means  $\exists$  null set  $F$  such that  $f_n \rightarrow f$  *uniformly* on  $F^c$ .
2.  $f_n \rightarrow f$  *almost uniformly* means  $\forall \epsilon > 0 \exists F \in \mathcal{A}$  such that  $\mu(F) < \epsilon$ ,  $f_n \rightarrow f$  *uniformly* on  $F^c$ .

**Lemma 2.9.** We have

$$f_n \rightarrow f \text{ uniformly on } S \iff \exists N_1, N_2, \dots \in \mathbb{N} \text{ } S \subset \bigcap_{k=1}^{\infty} \bigcap_{n=N_k}^{\infty} B_{n,k}.$$

**Theorem 2.7 (Egorov's Theorem).** Let  $f_n, f$  be measurable functions on  $(X, \mathcal{A}, \mu)$ . Suppose  $\mu(X) < \infty$ , then

$$f_n \rightarrow f \text{ a.e.} \iff f_n \rightarrow f \text{ almost uniformly.}$$

*Proof.* We prove two directions.

•  $\Leftarrow$

DIY

•  $\Rightarrow$  Fix  $\epsilon > 0$ . We see that

$$\begin{aligned} f_n \rightarrow f \text{ a.e.} &\implies \mu \left( \bigcup_{k=1}^{\infty} \bigcap_{N=1}^{\infty} \bigcup_{n=N}^{\infty} B_{n,k}^c \right) = 0 \\ &\implies \forall_k \mu \left( \bigcap_{N=1}^{\infty} \bigcup_{n=N}^{\infty} B_{n,k}^c \right) = 0. \end{aligned}$$

From *continuity of measure from above* and  $\mu(X) < \infty$ , we further have

$$\forall_k \lim_{N \rightarrow \infty} \mu \left( \bigcup_{n=N}^{\infty} B_{n,k}^c \right) = 0 \implies \forall_k \exists_{N_k \in \mathbb{N}} \mu \left( \bigcup_{n=N_k}^{\infty} B_{n,k}^c \right) < \frac{\epsilon}{2^k}.$$

Now, let

$$F := \bigcup_{k=1}^{\infty} \bigcup_{n=N_k}^{\infty} B_{n,k}^c,$$

we see that  $\mu(F) < \epsilon$ , hence  $f_n \rightarrow f$  *uniformly*.

■

## 3 Product Measure

### 3.1 Product $\sigma$ -algebra

Before we start, we see the setup.

- Product space.

$$X = \prod_{\alpha \in I} X_{\alpha}$$

where  $x = (x_{\alpha})_{\alpha \in I} \in X$ .

- Coordinate map.

$$\pi_{\alpha}: X \rightarrow X_{\alpha}.$$

Now we see the formal definition.

**Definition 3.1 (Product  $\sigma$ -algebra).** Let  $(X_{\alpha}, \mathcal{A}_{\alpha})$  be a measurable space for all  $\alpha \in I$ . Then a product  $\sigma$ -algebra on  $X = \prod_{\alpha \in I} X_{\alpha}$  is

$$\bigotimes_{\alpha \in I} \mathcal{A}_{\alpha} = \left\langle \bigcup_{\alpha \in I} \pi_{\alpha}^{-1}(\mathcal{A}_{\alpha}) \right\rangle,$$

where

$$\pi_{\alpha}^{-1}(\mathcal{A}_{\alpha}) = \{\pi_{\alpha}^{-1}(E) \mid E \in \mathcal{A}_{\alpha}\}.$$

**Notation.** We denote  $I = \{1, \dots, d\} \implies X = \prod_{i=1}^d X_i, x = (x_1, \dots, x_d)$ . Also,

$$\bigotimes_{i=1}^d \mathcal{A}_i = \mathcal{A}_1 \otimes \dots \otimes \mathcal{A}_d.$$

**Lemma 3.1.** If  $I$  is countable, then

$$\bigotimes_{i=1}^{\infty} \mathcal{A}_i = \left\langle \left\{ \prod_{i=1}^{\infty} E_i \mid \forall_i E_i \in \mathcal{A}_i \right\} \right\rangle.$$

*Proof.* If  $E_i \in \mathcal{A}_i$ , then  $\pi_i^{-1}(E_i) = \prod_{j=1}^{\infty} E_j$ , where  $E_j = X$  for  $j \neq i$ . On the other hand, since

$$\prod_{i=1}^{\infty} E_i = \bigcap_{i=1}^{\infty} \pi_i^{-1}(E_i),$$

from Lemma 1.2, the result follows. ■

## Lecture 17: Product Measure

14 Feb. 11:00

We now see a lemma.



**Lemma 3.2.** Suppose  $\mathcal{A}_\alpha = \langle \mathcal{E}_\alpha \rangle$  for every  $\alpha \in I$ . Then

1.  $\pi_\alpha^{-1}(\mathcal{A}_\alpha) = \langle \pi_\alpha^{-1}(\mathcal{E}_\alpha) \rangle$
2.  $\bigotimes_\alpha \mathcal{A}_\alpha = \langle \bigcup_\alpha \pi_\alpha^{-1}(\mathcal{E}_\alpha) \rangle$
3. If  $I$  is countable, then

$$\bigotimes_{i=1}^{\infty} \mathcal{A}_i = \left\langle \left\{ \prod_{i=1}^{\infty} E_i \mid \forall_i E_i \in \mathcal{E}_i \right\} \right\rangle$$

*Proof.* We prove this one by one.

1. Note that for  $f: Y \rightarrow Z$ , and  $\mathcal{B}$  be a  $\sigma$ -algebra on  $Z$ , then  $f^{-1}(\mathcal{B})$  is also a  $\sigma$ -algebra.<sup>25</sup> Hence,  $\pi_\alpha^{-1}$  is a  $\sigma$ -algebra on  $X$ , i.e.,

$$\pi_\alpha^{-1}(\mathcal{E}_\alpha) \subset \pi_\alpha^{-1}(\mathcal{A}_\alpha) \stackrel{!}{\implies} \langle \pi_\alpha^{-1}(\mathcal{E}_\alpha) \rangle \subset \pi_\alpha^{-1}(\mathcal{A}_\alpha).$$

To show the other direction, let  $\mathcal{M}$  being

$$\mathcal{M} = \{B \subset X_\alpha \mid \pi_\alpha^{-1}(B) \in \langle \pi_\alpha^{-1}(\mathcal{E}_\alpha) \rangle\}.$$

We now check

- $\mathcal{M}$  is a  $\sigma$ -algebra.
- $\mathcal{E}_\alpha \subset \mathcal{M}$ . This is true by definition of  $\mathcal{M}$ .

Thus,  $\langle \mathcal{E}_\alpha \rangle = \mathcal{A}_\alpha \subset \mathcal{M}$ . Hence, if  $E \in \mathcal{A}_\alpha$ ,  $E \in \mathcal{M}$ , implying

$$\pi_\alpha^{-1}(E) \in \langle \pi_\alpha^{-1}(\mathcal{E}_\alpha) \rangle,$$

i.e.,  $\mathcal{A}_\alpha \subset \langle \pi_\alpha^{-1}(\mathcal{E}_\alpha) \rangle$ .

2.

3.

Check  
(Easy)!

DIY

DIY

■

<sup>25</sup>Since  $f^{-1}(\emptyset) = \emptyset$ ,  $f^{-1}(B)^c = f^{-1}(B^c)$ , and  $\bigcup_n f^{-1}(B_n) = f^{-1}(\bigcup_n B_n)$ .

**Theorem 3.1.** Suppose  $X_1, \dots, X_d$  are metric spaces. Let  $X = \prod_{i=1}^d X_i$  with product metric defined as

$$\rho(x, y) = \sum_{i=1}^d \rho_i(x_i, y_i).$$

Then,

1.  $\bigotimes_{i=1}^d \mathcal{B}(X_i) \subset \mathcal{B}(X)$
2. If in addition, each  $X_i$  has a countable dense subset,

$$\bigoplus_{i=1}^d \mathcal{B}(X_i) = \mathcal{B}(X).$$

*Proof.*



DIY

**Remark.** We see that

- $\mathcal{B}(\mathbb{R}^d) = \mathcal{B}(\mathbb{R}) \otimes \dots \otimes \mathcal{B}(\mathbb{R})$
- let  $f = u + iv: X \rightarrow \mathbb{C}$ , and  $\mathcal{A}$  be a  $\sigma$ -algebra on  $X$ . Then

$$\forall_{E \in \mathcal{B}(\mathbb{R})} u^{-1}(E), v^{-1}(E) \in \mathcal{A} \iff f^{-1}(F) \in \mathcal{A}, \forall F \in \mathcal{B}(\mathbb{C})$$

with  $\mathcal{B}(\mathbb{C}) = \mathcal{B}(\mathbb{R}^2) = \mathcal{B}(\mathbb{R}) \otimes \mathcal{B}(\mathbb{R})$ .

**Definition 3.2 ( $x$ -section,  $y$ -section).** Let  $X, Y$  be two sets. Then

1. For  $E \subset X \times Y$ ,

$$E_x = \{y \in Y \mid (x, y) \in E\}, \quad E^y = \{x \in X \mid (x, y) \in E\}.$$

2. For  $f: X \times Y \rightarrow \mathbb{C}$ , define

$$f_x: Y \rightarrow \mathbb{C}, \quad f^y: X \rightarrow \mathbb{C}$$

by

$$f_x(y) = f(x, y) = f^y(x).$$

**Example.** We see that

$$(\mathbb{1}_E)_x = \mathbb{1}_{E_x}$$

and

$$(\mathbb{1}_E)^y = \mathbb{1}_{E^y}.$$

**Proposition 3.1.** Given two measurable spaces  $(X, \mathcal{A})$  and  $(Y, \mathcal{B})$ , then

1. If  $E \in \mathcal{A} \otimes \mathcal{B}$ , then

$$\forall_{x \in X} \forall_{y \in Y} E_x \in \mathcal{B}, E^y \in \mathcal{A}.$$

2. If  $f: X \times Y \rightarrow \mathbb{C}$  is  $\mathcal{A} \otimes \mathcal{B}$ -measurable, then

$$\forall_{x \in X} \forall_{y \in Y} f_x \text{ is } \mathcal{B}\text{-measurable, } f^y \text{ is } \mathcal{A}\text{-measurable.}$$

*Proof.* We prove this one by one.

1. Let  $\mathcal{F} := \left\{ E \subset X \times Y \mid \forall_{x \in X} \forall_{y \in Y} E_x \in \mathcal{B}, E^y \in \mathcal{A} \right\}$ , then

- $\mathcal{F}$  is a  $\sigma$ -algebra.

$$- \emptyset \in \mathcal{F}.$$

$$- (E^c)_x = E_x^c.$$

$$- \left( \bigcup_{j=1}^{\infty} E_j \right)_x = \bigcup_{j=1}^{\infty} (E_j)_x.$$

And the same is true for  $y$ .

- Let  $\mathcal{R}_0 := \{A \times B \mid A \in \mathcal{A}, B \in \mathcal{B}\} \subset \mathcal{F}$ , which is again easy to show from definition.

Hence, we see that  $\langle \mathcal{R}_0 \rangle = \mathcal{A} \otimes \mathcal{B} \subset \mathcal{F}$ .

2. Since

$$(f_x)^{-1}(B) = (f^{-1}(B))_x$$

and

$$(f^y)^{-1}(B) = (f^{-1}(B))^y,$$

the result follows from 1. ■

### 3.2 Product Measures

We start with the definition.

**Definition 3.3 (Rectangle).** Given two measurable spaces, a (measurable) rectangle is  $R = A \times B$  where  $A \in \mathcal{A}$  and  $B \in \mathcal{B}$ . Furthermore, we let

$$\mathcal{R}_0 := \{R = A \times B \mid A \in \mathcal{A}, B \in \mathcal{B}\},$$

and

$$\mathcal{R} := \left\{ \bigcup_{i=1}^N R_i \mid N \in \mathbb{N}, R_1, \dots, R_N \text{ disjoint rectangles} \right\}.$$

**Note.** Whenever we're talking about [rectangle](#), they're always [measurable](#).

**Lemma 3.3.**  $\mathcal{R}$  is an [algebra](#), and

$$\langle \mathcal{R}_0 \rangle = \langle \mathcal{R} \rangle = \mathcal{A} \otimes \mathcal{B}.$$

*Proof.* Simply observe that

$$(A \times B)^c = (A^c \times Y) \cup (A \times B^c)$$



DIY

## Lecture 18: Monotone Class

16 Feb. 11:00

Let's start with a theorem.

**Theorem 3.2.** Let  $(X, \mathcal{A}, \mu), (Y, \mathcal{B}, \nu)$  be [measure spaces](#). Then

1. There is a [measure](#)  $\mu \times \nu$  on  $\mathcal{A} \otimes \mathcal{B}$  satisfying

$$(\mu \times \nu)(A \times B) = \mu(A)\nu(B)$$

for every  $A \in \mathcal{A}, B \in \mathcal{B}$ .

2. If  $\mu, \nu$  are [σ-finite](#), then  $\mu \times \nu$  is unique.

*Proof.* We prove this one by one.

1. Define  $\mu: \mathcal{R} \rightarrow [0, \infty]$  by  $\mu(A \times B) = \mu(A)\nu(B)$ , and extending linearly, we have

$$\pi(A \times B) = \mu(A)\nu(B),$$

hence

$$\pi\left(\prod_{i=1}^N A_i \times B_i\right) = \sum_{i=1}^n \pi(A_i \times B_i).$$

We claim that  $\pi$  is a [pre-measure](#). To show this, it's enough to check that  $\pi(A \times B) = \sum_{n=1}^{\infty} \pi(A_n \times B_n)$  if  $A \times B = \prod_n A_n \times B_n$ . Since  $A_n \times B_n$  are disjoint, so

$$\mathbb{1}_{A \times B}(x, y) = \sum_{n=1}^{\infty} \mathbb{1}_{A_n \times B_n}(x, y).$$

Thus,

$$\mathbb{1}_A(x)\mathbb{1}_B(y) = \sum_{n=1}^{\infty} \mathbb{1}_{A_n}(x)\mathbb{1}_{B_n}(y).$$

Integrating with respect to  $x$ , and applying [Proposition 1.3](#), we have

$$\int_X \mathbb{1}_A(x)\mathbb{1}_B(y) d\mu(x) = \sum_{n=1}^{\infty} \int_X \mathbb{1}_{A_n}(x)\mathbb{1}_{B_n}(y) d\mu(x),$$

which implies

$$\mu(A)\mathbb{1}_B(y) = \sum_{n=1}^{\infty} \mu(A_n)\mathbb{1}_{B_n}(y)$$

for every  $y$ . We can then integrate again with respect to  $y$  and apply [Proposition 1.3](#), we have

$$\int_Y \mu(A)\mathbb{1}_B(y) d\nu(y) = \sum_{n=1}^{\infty} \int_Y \mu(A_n)\mathbb{1}_{B_n}(y) d\nu(y),$$

which gives us

$$\mu(A)\nu(B) = \sum_{n=1}^{\infty} \mu(A_n)\nu(B_n).$$

Hence, we see that  $\mu$  is indeed a [pre-measure](#), so [Theorem 1.3](#) gives  $\mu \times \nu$  on  $\langle \mathcal{R} \rangle = \mathcal{A} \otimes \mathcal{B}$  extending  $\pi$  on  $\mathcal{R}$ .

2. If  $\mu, \nu$  are  [\$\sigma\$ -finite](#), then  $\pi$  is  [\$\sigma\$ -finite](#) on  $\mathcal{R}$ , then [Theorem 1.4](#) applies. Moreover, we have that

$$(\mu \times \nu)(E) = \inf \left\{ \sum_{i=1}^{\infty} \mu(A_i)\nu(B_i) \mid E \subset \bigcup_{i=1}^{\infty} A_i \times B_i, A_i \in \mathcal{A}, B_i \in \mathcal{B} \right\}.$$

■

### 3.3 Monotone Class Lemma

Let's start with a definition.

**Definition 3.4 (Monotone Class).** If  $X$  is a set, and  $C \subset \mathcal{P}(X)$ , we say that  $C$  is a *monotone class* on  $X$  if

- $C$  is closed under countable increasing unions.
- $C$  is closed under countable decreasing intersections.

**Example.** We see that

1. Every  [\$\sigma\$ -algebra](#) is a [monotone class](#).
2. If  $C_\alpha$  are (arbitrarily many) [monotone classes](#) on a set  $X$ , then  $\bigcap_{\alpha} C_\alpha$  is a [monotone class](#). Furthermore, if  $\mathcal{E} \subset \mathcal{P}(X)$ , there is a unique smallest [monotone class](#) containing  $\mathcal{E}$ , denoted by  $\langle \mathcal{E} \rangle$ , which follows the same idea as in [Definition 1.3](#).

**Theorem 3.3 (Monotone Class Lemma).** Suppose  $\mathcal{A}_0$  is an [algebra](#) on  $X$ . Then  $\langle \mathcal{A}_0 \rangle^a$  is the [monotone class](#) generated by  $\mathcal{A}_0$ .

<sup>a</sup> $\langle \mathcal{A}_0 \rangle$  is the  [\$\sigma\$ -algebra](#) generated by  $\mathcal{A}_0$  by [Definition 1.3](#).

*Proof.* Let  $\mathcal{A} = \langle \mathcal{A}_0 \rangle$  and let  $\mathcal{C}$  be the monotone class generated by  $\mathcal{A}_0$ . Since  $\mathcal{A}$  is a  $\sigma$ -algebra, it's a monotone class. Note that it contains  $\mathcal{A}_0$ , hence  $\mathcal{A} \supset \mathcal{C}$ .

To show  $\mathcal{C} \supset \mathcal{A}$ , it's enough to show that  $\mathcal{C}$  is a  $\sigma$ -algebra. We check that

1.  $\emptyset \in \mathcal{A}_0 \subseteq \mathcal{C}$ .
2. Let  $\mathcal{C}' = \{E \subset X \mid E^c \in \mathcal{C}\}$ .
  - $\mathcal{C}'$  is a monotone class.
  - $\mathcal{A}_0 \subset \mathcal{C}'$  because if  $E \in \mathcal{A}_0$ , then  $E^c \in \mathcal{A}_0$ , so  $E^c \in \mathcal{C}$ , thus  $E \in \mathcal{C}'$ .

We see that  $\mathcal{C}' \subset \mathcal{C}'$ , so  $\mathcal{C}$  is closed under complements.

3. For  $E \subset X$ , let  $\mathcal{D}(E) = \{F \in \mathcal{C} \mid E \cup F \in \mathcal{C}\}$ .
  - $\mathcal{D}(E) \subset \mathcal{C}$ .
  - $\mathcal{D}(E)$  is a monotone class.
  - If  $E \in \mathcal{A}_0$ , then  $\mathcal{A}_0 \subset \mathcal{D}(E)$ . We see this by picking  $F \in \mathcal{A}_0$ , then  $E \cup F \in \mathcal{A}_0 \subset \mathcal{C}$ .

Hence,  $C = \mathcal{D}(E)$  if  $E \in \mathcal{A}_0$ .

4. Let  $\mathcal{D} = \{E \in \mathcal{C} \mid \mathcal{D}(E) = \mathcal{C}\}$ . That is  $\mathcal{D} = \{E \in \mathcal{C} \mid E \cup F, \forall F \in \mathcal{C}\}$ . Then we have
  - $\mathcal{A}_0 \subset \mathcal{D}$  by 3.
  - $\mathcal{D}$  is a monotone class.
  - $\mathcal{D} \subset \mathcal{C}$  by definition.

Thus,  $\mathcal{D} = \mathcal{C}$ , so if  $E, F \in \mathcal{C}$ , then  $E \cup F \in \mathcal{C}$ . This implies that  $\mathcal{C}$  is closed under finite unions.

5. Now to show that  $\mathcal{C}$  is closed under countable unions, let  $E_1, E_2, \dots \in \mathcal{C}$ . We may then define

$$F_N = \bigcup_{n=1}^N E_n \in \mathcal{C}.$$

Then we see that  $F_1 \subset F_2 \subset \dots$ , hence  $\bigcup_N F_N \in \mathcal{C}$ . But this simply implies

$$\bigcup_N F_N = \bigcup_n E_n,$$

so we're done. ■

## Lecture 19: Fubini-Tonelli's Theorem

18 Feb. 11:00

**As previously seen.** If  $E \in \mathcal{A} \otimes \mathcal{B} \implies E_x \in \mathcal{B}, E^y \in \mathcal{A} \forall x \in X, \forall y \in Y$ . Note that the reverse is not true.

### 3.4 Fubini-Tonelli Theorem

We start with a theorem.

**Theorem 3.4 (Tonelli's theorem for characteristic functions).** Given  $(X, \mathcal{A}, \mu)$  and  $(Y, \mathcal{B}, \nu)$  be  $\sigma$ -finite measure space. Suppose  $E \in \mathcal{A} \otimes \mathcal{B}$ , then

1.  $\alpha(x) := \nu(E_x): X \rightarrow [0, \infty]$  is a  $\mathcal{A}$ -measurable function.
2.  $\beta(y) := \mu(E^y): Y \rightarrow [0, \infty]$  is a  $\mathcal{B}$ -measurable function.
3.  $(\mu \times \nu)(E) = \int_X \nu(E_x) d\mu(x) = \int_Y \mu(E^y) d\nu(y)$ .

*Proof.* We prove this one by one.

1. Assume that  $\mu, \nu$  are finite measure. Let

$$C := \{E \in \mathcal{A} \otimes \mathcal{B} \mid \text{Conditions 1., 2., 3., hold}\}.$$

It's enough to prove that  $\langle \mathcal{R} \rangle = \mathcal{A} \otimes \mathcal{B} \subset C$ . We further observe that from the Theorem 3.3 and the fact that  $\mathcal{R}$  is an algebra, it's also enough to show that

- $\mathcal{R} \subset C$ .
- $C$  is a monotone class.

From condition 1.,

$$\alpha(x) = \nu((A \times B)_x) = \begin{cases} \nu(B), & \text{if } x \in A; \\ 0, & \text{if } x \notin A \end{cases} = \nu(B) \mathbb{1}_A.$$

And from condition 2.,

$$(\mu \times \nu)(A \times B) = \mu(A)\nu(B)$$

and

$$\int_X \nu((A \times B)_x) d\mu(x) = \nu(B)\mu(A).$$

Let  $E_n \in C$ ,  $E_1 \subset E_2 \subset \dots$ . We need to show  $E = \bigcup_{n=1}^{\infty} E_n \in C$ . We now see that

$$\begin{aligned} E_x &= \bigcup_{n=1}^{\infty} (E_n)_x, (E_1)_x \subset (E_2)_x \subset \dots \\ \implies \alpha(x) &= \nu(E_x) \stackrel{!}{=} \lim_{n \rightarrow \infty} \nu((E_n)_x) \quad \forall x \in X. \end{aligned}$$

This implies that 1. is proved.

For 3., we see that

$$\begin{aligned} (\mu \times \nu)(E) &\stackrel{!}{=} \lim_{n \rightarrow \infty} (\mu \times \nu)(E_n) \\ &= \lim_{n \rightarrow \infty} \int_X \nu((E_n)_x) d\mu(x) \\ &\stackrel{!}{=} \int_X \nu(E_x) d\mu(x). \end{aligned}$$

Now let  $F_n \in C$ ,  $F_1 \supset F_2 \supset \dots$ . We need to show that  $F = \bigcap_{n=1}^{\infty} F_n \in C$ . Instead of using [Theorem 2.2](#), we now want to use [Theorem 2.4](#), which is applicable since  $\mu(X), \nu(Y) < \infty$  by assumption. Then assume that  $\mu, \nu$  are  $\sigma$ -finite, then

$$X \times Y = \bigcup_{n=1}^{\infty} (X_n \times Y_n), \begin{cases} X_1 \subset X_2 \subset \dots, & \mu(X_k) < \infty \\ Y_1 \subset Y_2 \subset \dots, & \nu(Y_k) < \infty. \end{cases}$$

DIY

**Theorem 3.5 (Fubini-Tonelli's Theorem).** Given two  $\sigma$ -finite measure space  $(X, \mathcal{A}, \mu), (Y, \mathcal{B}, \nu)$ , we have the following two versions.

**(Tonelli)** If  $f: X \times Y \rightarrow [0, \infty]$  is  $\mathcal{A} \otimes \mathcal{B}$ -measurable, then

1.  $g(x) := \int_Y f(x, y) d\nu(y)$ ,  $X \rightarrow [0, \infty]$  is a  $\mathcal{A}$ -measurable function.
2.  $h(y) := \int_X f(x, y) d\mu(x)$ ,  $Y \rightarrow [0, \infty]$  is a  $\mathcal{B}$ -measurable function.
3. We have

$$\int_{X \times Y} f d(\mu \times \nu) = \int_X \left( \int_Y f(x, y) d\nu(y) \right) d\mu(x) = \int_Y \left( \int_X f(x, y) d\mu(x) \right) d\nu(y).$$

**(Fubini)** If  $f \in L^1(X \times Y, \mu \times \nu)$ , then

1.  $f_x \in L^1(Y, \nu)$  for  $\mu$ -a.e.  $x$ , and  $g(x) \in L^1(X, \mu)$  defined  $\mu$ -a.e.
2.  $f^y \in L^1(X, \mu)$  for  $\nu$ -a.e.  $y$ , and  $h(y) \in L^1(Y, \nu)$  defined  $\nu$ -a.e.
3. The iterated integral formulas hold. Namely, we have

$$\int_{X \times Y} f d(\mu \times \nu) = \int_X \left( \int_Y f(x, y) d\nu(y) \right) d\mu(x) = \int_Y \left( \int_X f(x, y) d\mu(x) \right) d\nu(y).$$

*Proof.* Read [\[FF99\]](#). ■

## Lecture 20: Lebesgue Measure on $\mathbb{R}^d$

21 Feb. 11:00

### 3.5 Lebesgue Measure on $\mathbb{R}^d$

**Example.** We first see some examples.

1.  $(\mathbb{R}^2, \mathcal{L} \otimes \mathcal{L}, m \times m)$  is not complete.
  - Let  $A \in \mathcal{L}$ ,  $A \neq \emptyset$ ,  $m(A) = 0$ .
  - Let  $B \subset [0, 1]$ ,  $B \notin \mathcal{L}$  (Vital set for example).
  - Let  $E = A \times B$ ,  $F = A \times [0, 1]$ .



We see that  $E \subset F$ ,  $F \in \mathcal{L} \otimes \mathcal{L}$ ,  $(m \times m)(F) = m(A)m([0, 1]) = 0$ , i.e.,  $F$  is a **null** set. But  $E$  is **not**  $\mathcal{L} \otimes \mathcal{L}$ -measurable-function since otherwise, its sections are all **measurable**.

**Definition 3.5.** Let  $(\mathbb{R}^d, \mathcal{L}^d, m^d)$  be the *completion* of

$$(\mathbb{R}^d, \mathcal{B}(\mathbb{R}^d), m \times \dots \times m),$$

which is same as the *completion* of

$$(\mathbb{R}^d, \mathcal{L} \otimes \dots \otimes \mathcal{L}, m \times \dots \times m).$$

**Remark.** We see that

$$\mathcal{L}^d \supsetneq \mathcal{L} \otimes \dots \otimes \mathcal{L} = \left\langle \left\{ \prod_{i=1}^d E_i \mid E_i \in \mathcal{L} \right\} \right\rangle.$$

**Definition 3.6 (General rectangle).** A *rectangle* in  $\mathbb{R}^d$  is  $R = \prod_{i=1}^d E_i$  where  $E_i \in \mathcal{B}(\mathbb{R})$ .

**Definition 3.7.** We let

$$m^d(E) := \inf \left\{ \sum_{k=1}^{\infty} m^d(R_k) \mid E \subset \bigcup_{k=1}^{\infty} R_k, R_k \text{ is rectangles} \right\}.$$

**Theorem 3.6.** Let  $E \subset \mathcal{L}^d$ . Then

1.  $m^d(E) = \inf \{m^d(O) \mid \text{open } O \supset E\} = \sup \{m^d(K) \mid \text{compact } K \subset E\}$ .
2.  $E = A_1 \cup N_1 = A_2 \setminus N_2$ , where  $A_1$  is  $F_\sigma$ ,  $A_2$  is  $G_\delta$ , and  $N_i$  are **null**.
3. If  $m^d(E) < \infty$ ,  $\forall \epsilon > 0$ ,  $\exists R_1, \dots, R_m$  **rectangles** whose sides are intervals such that

$$m^d \left( E \triangle \left( \bigcup_{i=1}^m R_i \right) \right) < \epsilon.$$

*Proof.* Similar to  $d = 1$  case. ■

**Theorem 3.7.** **Integrable step functions** and  $C_c(\mathbb{R}^d)$ , the collection of continuous functions, are dense in  $L^1(\mathbb{R}^d, \mathcal{L}^d, m^d)$

*Proof.* See [FF99]. ■

**Theorem 3.8.** Lebesgue measure in  $\mathbb{R}^d$  is translation-invariant.

*Proof.* See [FF99]. ■

**Theorem 3.9 (Effect of linear transformation on Lebesgue measure).** If  $T \in \text{GL}(\mathbb{R}^d)$ ,  $e \in \mathcal{L}^d$ , then  $T(E)$  is measurable and

$$m(T(E)) = |\det T| \cdot m(E).$$

*Proof.* See [FF99]. ■

## 4 Differentiation on Euclidean Space

As previously seen. Given  $f: [a, b] \rightarrow \mathbb{R}$ , there are two versions of fundamental theorem of calculus:

1.

$$\int_a^b f'(x) dx = f(b) - f(a).$$

2.

$$\frac{d}{dx} \int_a^x f(t) dt = f(x),$$

which follows from

$$\lim_{r \rightarrow 0^+} \frac{1}{r} \int_x^{x+r} f(t) dt = f(x) = \lim_{r \rightarrow 0^+} \frac{1}{r} \int_{x-r}^x f(t) dt.$$

**Remark.** We see that

$$\lim_{r \rightarrow 0^+} \frac{1}{r} \int_x^{x+r} (f(t) - f(x)) dt = 0 = \lim_{r \rightarrow 0^+} \frac{1}{r} \int_{x-r}^x (f(t) - f(x)) dt,$$

where we have

$$f(x) = \frac{1}{r} \int_x^{x+r} f(t) dt.$$

This generalized to  $f: \mathbb{R}^d \rightarrow \mathbb{R}$ , namely

$$\lim_{r \rightarrow 0^+} \frac{1}{\text{vol}(B(x, r))} \int_{B(x, r)} (f(t) - f(x)) \underbrace{dt}_{\mathbb{R}^d} \stackrel{?}{=} 0.$$

### 4.1 Hardy-Littlewood Maximal Function

We first see our notation.

**Notation.** Given a(n) (open) ball in  $\mathbb{R}^d$ ,  $B = B(a, r)$ , denote  $cB = B(a, cr)$  for  $c > 0$ .

**Lemma 4.1 (Vitali-type covering lemma).** Let  $B_1, \dots, B_k$  be a finite collection of open balls in  $\mathbb{R}^d$ . Then there exists a sub-collection  $B'_1, \dots, B'_m$  of disjoint open balls such that

$$\bigcup_{i=1}^m (3B'_i) \supset \bigcup_{i=1}^k B_i.$$

*Proof.* Greedy Algorithm. ■

## Lecture 21: Hardy-Littlewood Maximal Function and Inequality

25 Feb. 11:00

**Notation.** We let

$$\int_E f \, dm = \int_E f(x) \, dx.$$

The problem we're working on is

$$\frac{1}{m(B(w, r))} \int_{B(x, r)} f(y) \, dy \xrightarrow[r \rightarrow 0]{?} f(x).$$

**Definition 4.1 (Locally integrable).** Given  $f: \mathbb{R}^d \rightarrow \mathbb{C}$  be [Lebesgue measurable](#) function. Then we say  $f$  is *locally integrable* if for every compact  $K \subset \mathbb{R}^d$ ,

$$\int_K |f| \, dm < \infty.$$

We write  $f \in L^1_{\text{loc}}(\mathbb{R}^d)$ .

**Definition 4.2 (Hardy-Littlewood maximal function).** Given  $f \in L^1_{\text{loc}}(\mathbb{R}^d)$ , the *Hardy-Littlewood maximal function* for  $f$  is defined as

$$Hf(x) := \sup \{A_r(x) \mid r > 0\},$$

where

$$A_r(x) := \frac{1}{m(B(x, r))} \int_{B(x, r)} |f(y)| \, dy.$$

**Note.** We note that  $A_r(\cdot)$  means *averaging function*.

**Lemma 4.2.** Let  $f \in L^1_{\text{loc}}(\mathbb{R}^d)$ , then

1.  $A_r(x)$  is jointly continuous for  $(x, r) \in \mathbb{R}^d \times (0, \infty)$ .
2.  $Hf(x)$  is [Borel measurable](#).

*Proof.* We outline the proof.

1. Let  $(x, r) \rightarrow (x^*, r^*) \implies A_r(x) \rightarrow A_{r^*}(x^*)$ . Let  $(x_n, r_n)$  be any sequence which converges to  $x^*, r^*$ , then we consider  $\lim_{n \rightarrow \infty} A_{r_n}(x_n)$  and we can calculate

$$\int \underbrace{|f(y)| \mathbb{1}_{B(x_n, r_n)}(y)}_{:=h_n(y)},$$

then we apply [Theorem 2.4](#) to  $h_n$ .

2. Observe that

$$(Hf)^{-1}(\underbrace{(a, \infty)}_{\text{open}}) = \bigcup_{r>0} A_r^{-1}((a, \infty))$$

is open, since  $A_r^{-1}((a, \infty))$  is open from the 1. Note that the equality comes from the fact that  $Hf = \sup_r A_r$ .

■

**Theorem 4.1 (Hardy-Littlewood maximal inequality).** There exists  $C_d > 0$  such that for every  $f \in L^1(\mathbb{R}^d)$ ,

$$\forall_{\alpha>0} m(\{x \in \mathbb{R}^d \mid Hf(x) > \alpha\}) \leq \frac{C_d}{\alpha} \int |f(x)| \, dx.$$

*Proof.* We first fix  $f \in L^1$  and  $\alpha > 0$ . We define

$$E := \{x \mid Hf(x) > \alpha\},$$

which is a [Borel measurable set](#) by [Lemma 4.2](#). Then

$$x \in E \implies \exists_{r_x>0} A_{r_x}(x) > \alpha \implies m(B(x, r_x)) < \frac{1}{\alpha} \int_{B(x, r_x)} |f(y)| \, dy.$$

From [inner regularity](#), we have

$$m(E) = \sup \{m(K) \mid \text{compact } K \subset E\}.$$

Let  $K \subset E$  be compact, then

$$K \subset \bigcup_{x \in K} B(x, r_x) \xrightarrow{K \text{ compact}} K \subset \bigcup_{i=1}^N B_i \xrightarrow{!} K \subset \bigcup_{i=1}^m \{3B'_j\}.$$

From here, we further have

$$m(K) \leq \sum_{i=1}^m m(3B'_j) = 3^d \sum_{j=1}^m m(B'_j) \leq \frac{3^d}{\alpha} \sum_{j=1}^m \int_{B'_j} |f(y)| \, dy.$$

Now, since  $B'_1, \dots, B'_m$  are disjoint, hence we finally have

$$m(K) \leq \frac{3^d}{\alpha} \int_{\mathbb{R}^d} |f(y)| \, dy.$$

■

## Lecture 22: Lebesgue Differentiation Theorem

07 Mar. 11:00

We should compare the [Hardy-Littlewood maximal inequality](#) to [Markov's inequality](#). Namely, there exists  $C_d > 0$  (can take  $3^d$ ) such that for all  $f \in L^1(\mathbb{R}^d)$ ,  $\alpha > 0$ , we have

$$\begin{cases} m(\{x \mid Hf(x) > \alpha\}) \leq \frac{C_d}{\alpha} \int |f|; \\ m(\{x \mid |f(x)| > \alpha\}) \leq \frac{1}{\alpha} \int |f|. \end{cases}$$

## 4.2 Lebesgue Differentiation Theorem

We start with a theorem!

**Theorem 4.2 (Lebesgue Differentiation Theorem).** Let  $f \in L^1$ , then

$$\lim_{r \rightarrow 0} \frac{1}{m(B(x, r))} \int_{B(x, r)} |f(y) - f(x)| \, dy = 0$$

for [a.e.](#)  $x$ .

*Proof.* The result holds for  $f \in C_c(\mathbb{R}^d)$ , namely for those continuous functions with **compact support**. This is because for any  $\epsilon > 0$ , if  $r$  is small and  $|f(y) - f(x)| < \epsilon$ , then

$$\frac{1}{m(B(x, r))} \int_{B(x, r)} |f(y) - f(x)| \, dy < \epsilon.$$

Now, let  $f \in L^1(\mathbb{R}^d)$  and fix  $\epsilon > 0$ . By density, there exists  $g \in C_c(\mathbb{R}^d)$  with  $\|f - g\|_1 < \epsilon$ . We then have

$$\begin{aligned} \int_{B(x, r)} |f(y) - f(x)| \, dy &\leq \int_{B(x, r)} |f(y) - g(y)| \, dy \\ &\quad + \int_{B(x, r)} |g(y) - g(x)| \, dy \\ &\quad + \int_{B(x, r)} |g(x) - f(x)| \, dy. \end{aligned}$$

Divide all of these by  $m(B(x, r))$ , and take  $\limsup_{r \rightarrow \infty}$ , we need to understand the error terms, namely

$$\frac{1}{m(B(x, r))} \int_{B(x, r)} |f(x) - g(x)| \, dy = |g(x) - f(x)|$$

and

$$\frac{1}{m(B(x, r))} \int_{B(x, r)} |f(y) - g(y)| \, dy \leq (H(f - g))(x).$$

We define

$$Q(x) := \limsup_{r \rightarrow \infty} \frac{1}{m(B(x, r))} \int_{B(x, r)} |f(y) - f(x)| \, dy.$$

We want to show  $m(\{x \in X \mid Q(x) > 0\}) = 0$ . Let  $E_\alpha = \{x \in X \mid Q(x) > \alpha\}$ . It is enough to show  $m(E_\alpha) = 0$  for all  $\alpha > 0$  because  $\{x \in X \mid Q(x) > 0\} = \bigcup_n E_{\frac{1}{n}}$ . We know by the above that

$$Q(x) \leq (H(f - g))(x) + 0 + |g(x) - f(x)|.$$

Therefore,

$$E_\alpha \subset \{x \in X \mid (H(f - g))(x) > \alpha/2\} \cup \{x \in X \mid |g(x) - f(x)| > \alpha/2\}.$$

By the [Hardy-Littlewood maximal inequality](#) and [Markov's inequality](#), we have

$$\begin{cases} m(\{x \mid (H(f - g))(x) > \alpha/2\}) \leq \frac{2C_d}{\alpha} \int |f - g|; \\ m(\{x \mid |g(x) - f(x)| > \alpha/2\}) \leq \frac{2}{\alpha} \int |f - g|. \end{cases}$$

Thus,

$$0 \leq m(E_\alpha) \leq \frac{2C_d}{\alpha} \|f - g\|_1 + \frac{2}{\alpha} \|f - g\|_1 \leq \frac{2(C_d + 1)}{\alpha} \epsilon.$$

Taking  $\epsilon \rightarrow 0$ ,  $m(E_\alpha)$  does not depend on  $\epsilon$  and  $g$ , hence  $m(E_\alpha) = 0$ . ■

**Corollary 4.1.** [Theorem 4.2](#) also holds for  $f \in L^1_{\text{loc}}(\mathbb{R}^d)$ .

*Proof.* Using the fact that  $m^d$  is [σ-finite](#), and apply [Theorem 4.2](#). Specifically, partition  $\mathbb{R}^d$  into countably many compact sets  $K_i$  and apply [Theorem 4.2](#) to  $f \mathbb{1}_{K_i}$  for all  $i$ . ■

**Corollary 4.2.** For  $f \in L^1_{\text{loc}}$ , we have

$$\lim_{r \rightarrow 0} \frac{1}{m(B(x, r))} \int_{B(x, r)} f(y) \, dy = f(x)$$

for [a.e.](#)  $x$ .

*Proof.* Use that

$$f(x) = \frac{1}{m(B(x, r))} \int_{B(x, r)} f(x) \, dy$$

and the triangle inequality. ■

**Definition 4.3 (Lebesgue point).** Let  $f \in L^1_{\text{loc}}(\mathbb{R}^d)$ , the point  $x \in \mathbb{R}^d$  is called a *Lebesgue point* of  $f$  if

$$\lim_{r \rightarrow 0} \frac{1}{m(B(x, r))} \int_{B(x, r)} |f(y) - f(x)| \, dy = 0.$$

**Remark.** [Corollary 4.1](#) tells us that almost all points in  $\mathbb{R}^d$  in  $\mathbb{R}^d$  are [Lebesgue points](#) for  $f$ .

DIY

**Definition 4.4 (Shrink nicely).** We say that  $\{E_r\}_{r>0}$  *shrinks nicely* to  $x$  as  $r \rightarrow 0$  if  $E_r \subset B(x, r)$  and

$$\exists_{c>0} c \cdot m(B(x, r)) \leq m(E_r).$$

**Corollary 4.3.** Suppose  $E_r$  shrink nicely to 0, and  $f \in L^1_{\text{loc}}(\mathbb{R}^d)$ , and  $x$  is a Lebesgue point. Then

$$\begin{cases} \lim_{r \rightarrow 0} \frac{1}{m(E_r)} \int_{E_r+x} |f(y) - f(x)| \, dy = 0; \\ \lim_{r \rightarrow 0} \frac{1}{m(E_r)} \int_{E_r+x} |f(y)| \, dy = f(x). \end{cases}$$

**Corollary 4.4.** If  $f \in L^1_{\text{loc}}(\mathbb{R})$ , then  $F(x) = \int_0^x f(y) \, dy$  is differentiable and  $F'(x) = f(x)$  almost everywhere.

## Lecture 23: Metric, normed and $L^p$ Spaces

09 Mar. 11:00

### 5 Normed Vector Space

#### 5.1 Metric Spaces and Normed Spaces

We have seen the definition of a norm before, now we formally introduce the concept of *metric*.

**Definition 5.1 (Metric).** Let  $Y$  be a set, a function  $\rho: Y \times Y \rightarrow [0, \infty)$  is a *metric* on  $Y$  if

- $\rho(x, y) = \rho(y, x)$  for all  $x, y \in Y$ .
- $\rho(x, z) \leq \rho(x, y) + \rho(y, z)$  for all  $x, y, z \in Y$ .
- $\rho(x, y) = 0$  if and only if  $x = y$ .

**Note.** The followings make sense in a metric space.

1. Open/closed balls.
2. Open/closed sets.
3. Convergence sequences ( $x_n \rightarrow x$  with respect to  $\rho$  if and only if  $\lim_{n \rightarrow \infty} \rho(x_n, x) = 0$ ).
4. Continuous functions.

**Example.** We have the following metric spaces.

1.  $\mathbb{Q}$  with  $\rho(x, y) = |x - y|$ .

2.  $\mathbb{R}$  with  $\rho(x, y) = |x - y|$ .
3.  $\mathbb{R}_+$  with  $\rho(x, y) = |\ln(y/x)|$ .
4.  $\mathbb{R}^d$  with

$$\rho_p(x, y) = \left( \sum_{i=1}^d |x_i - y_i|^p \right)^{1/p}$$

and

$$\rho_\infty(x, y) = \max_{1 \leq i \leq d} |x_i - y_i|.$$

These all give the same open sets, hence they are topologically equivalent.

5.  $C([0, 1])$  with

$$\rho_p(f, g) = \left( \int_0^1 |f - g|^p \right)^{1/p}$$

and

$$\rho_\infty(f, g) = \max_{x \in [0, 1]} |f(x) - g(x)|.$$

6. Let  $(X, \mathcal{A}, \mu)$  be a **measure space** with  $\mu(X) < \infty$ . Let  $Y$  be the set of **measurable functions** on  $X$ , then

$$\rho(f, g) = \int \min\{|f(x) - g(x)|, 1\} \, d\mu(x)$$

is a **metric** and  $f_n \rightarrow f$  in  $\rho$  if and only if  $f_n \rightarrow f$  in **measure**.

Let  $V$  be a vector space over scalar field  $K = \mathbb{R}$  or  $K = \mathbb{C}$ .

**As previously seen (Metric induced by a norm).** Recall the definition of **seminorm** and **norm**. We see that a **norm** induces a metric

$$\rho(v, w) := \|v - w\|,$$

and we have

$$v_n \rightarrow v \iff \lim_{n \rightarrow \infty} \|v_n - v\| = 0.$$

**Example.** We first see some common examples of **normed** vector space.

1.  $L^1(X, \mathcal{A}, \mu)$  with  $\|f\|_1 := \int |f| \, d\mu$ .
2.  $C([0, 1])$  with  $\|f\|_1 := \int_0^1 |f(x)| \, dx$ ,  $\|f\|_\infty := \max_{0 \leq x \leq 1} |f(x)|$ .
3. For  $\mathbb{R}^d$  and  $0 < p < \infty$ , we have

$$\|x\|_p := \left( \sum_{i=1}^d |x_i|^p \right)^{1/p}, \quad \|x\|_\infty := \max_{1 \leq i \leq d} |x_i|.$$



## 5.2 $L^p$ Space

It turns out that we can generalize  $L^1$  into  $L^p$ .

**Definition 5.2 ( $L^p$  space).** Given a **measure space**  $(X, \mathcal{A}, \mu)$  and a **measurable function**  $f$  and  $p$  such that  $0 < p < \infty$ , we define a **seminorm**  $\|\cdot\|_p$  such that

$$\|f\|_p := \left( \int_X |f|^p d\mu \right)^{1/p},$$

which induces the so-called  $L^p$  space  $L^p(X, \mathcal{A}, \mu)$ , where

$$L^p(X, \mathcal{A}, \mu) := \left\{ f \mid \|f\|_p < \infty \right\}.$$

**Remark.** Note that  $\|\cdot\|_p$  is only a **seminorm**. But if we identity functions which are equal **almost everywhere**, then it's indeed a **norm**.

**Example.**  $(\mathbb{R}, \mathcal{L}, m)$  has  $f(x) = x^{-\alpha} \mathbb{1}_{(1, \infty)}(x) \in L^p$  if and only if  $\alpha p > 1$ . In contrast,  $g(x) = x^{-\beta} \mathbb{1}_{(0, 1)}(x) \in L^p$  if and only if  $\beta p < 1$ .

Similar to **Definition 5.2**, we have the following.

**Definition 5.3 ( $\ell^p$  space).** If  $(X, \mathcal{P}(X), \nu)$  is equipped with the **counting measure**, then we say it's an  $\ell^p$  space such that

$$\ell^p(X) := L^p(X, \mathcal{P}(X), \nu).$$

**Remark.** We are interested in  $\ell^p(\mathbb{N})$  in particular. We have

$$\ell^p := \ell^p(\mathbb{N}) = \left\{ a = (a_1, a_2, \dots) \mid \|a\|_p = \left( \sum_{i=1}^{\infty} |a_i|^p \right)^{1/p} < \infty \right\}.$$

**Lemma 5.1.**  $L^p(X, \mathcal{A}, \nu)$  is a vector space for all  $p \in (0, \infty)$ .

*Proof.* We verify the following.

- $c \cdot f \in L^p(X, \mathcal{A}, \mu)$  for  $c \in \mathbb{R}$ . Indeed, since

$$\|cf\|_p = \left( \int |cf|^p d\mu \right)^{1/p} = |c| \|f\|_p < \infty \iff \|f\|_p < \infty,$$

which implies  $c \cdot f \in L^p(X, \mathcal{A}, \mu)$ .

- $f + g \in L^p(X, \mathcal{A}, \mu)$ . Indeed, since for any real numbers  $\alpha, \beta$ , we have

$$(\alpha + \beta)^p \leq (2 \cdot \max\{|\alpha|, |\beta|\})^p = 2^p \cdot \max\{|\alpha|^p, |\beta|^p\} \leq 2^p (|\alpha|^p + |\beta|^p),$$

which implies that for  $f, g \in L^p(X, \mathcal{A}, \mu)$ , we have

$$\|f + g\|_p < \infty \iff \|f + g\|_p^p = \int |f + g|^p d\mu \leq 2^p \int (|f|^p + |g|^p) < \infty.$$

This further implies

$$\|f + g\|_p < \infty \iff \|f\|_p, \|g\|_p < \infty,$$

which is what we want. ■

We see that in the above derivation, it doesn't give us the triangle inequality, namely

$$\|f + g\|_p \leq \|f\|_p + \|g\|_p,$$

hence we need some new results.

**Theorem 5.1 (Hölder's inequality).** Let  $1 < p < \infty$ , and let  $q := p/(p-1)$  so that  $1/p + 1/q = 1$ . Then we have

$$\|f \cdot g\|_1 \leq \|f\|_p \|g\|_q.$$

*Proof.* We prove this in steps.

1. Note that

$$t \leq \frac{t^p}{p} + 1 - \frac{1}{p} = \frac{t^p}{p} + \frac{1}{q}$$

for all  $t \geq 0$ . Hence, by taking  $F(t) := t - t^p/p$  and  $t \geq 0$ , we see that the maximum of  $F$  implies the above inequality.

2. Young's Inequality.<sup>26</sup> We have

$$\alpha\beta \leq \frac{\alpha^p}{p} + \frac{\beta^q}{q}$$

for  $\alpha, \beta > 0$ . This follows by taking  $t := \alpha/\beta^{q-1}$  in the first inequality we obtained.

3. Without loss of generality, we can assume that  $0 < \|f\|_p, \|g\|_q < \infty$ . Now, consider  $F(x) = f(x)/\|f\|_p$ ,  $G(x) = g(x)/\|g\|_q$ . We know that  $\|F\|_p = 1 = \|G\|_q$ . Then by Young's Inequality, we have

$$\int |F(x)G(x)| d\mu \leq \int \frac{|F(x)|^p}{p} + \frac{|G(x)|^q}{q} \implies \frac{\|fg\|_1}{\|f\|_p \|g\|_q} \leq \frac{1}{p} + \frac{1}{q} = 1,$$

which implies our desired result. ■

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<sup>26</sup>[https://en.wikipedia.org/wiki/Young's\\_inequality\\_for\\_products](https://en.wikipedia.org/wiki/Young's_inequality_for_products)

**Example.** For  $p = q = 2$ ,  $X = \{1, \dots, d\}$  with  $\mu$  being the [counting measure](#), then for any  $x, y \in \mathbb{R}^d$ , we have

$$\sum_{i=1}^d |x_i y_i| \leq \sqrt{\sum_{i=1}^d x_i^2} \sqrt{\sum_{i=1}^d y_i^2}$$

We now see how we can obtain the desired triangle inequality.

**Theorem 5.2 (Minkowski's Inequality).** Let  $1 \leq p < \infty$ , then for  $f, g \in L^p$ ,

$$\|f + g\|_p \leq \|f\|_p + \|g\|_p.$$

*Proof.* For  $p = 1$ , it's easy since it's just triangle inequality. Now, we assume that  $1 < p < \infty$ , and we may assume also that  $\|f + g\| \neq 0$  without loss of generality. Then

$$\begin{aligned} \int |f(x) + g(x)|^p &\leq \int |f(x) + g(x)|^{p-1} (|f(x)| + |g(x)|) \\ &\leq \left( \int |f + g|^{(p-1)q} \right)^{1/q} \left[ \left( \int |f|^p \right)^{1/p} + \left( \int |g|^p \right)^{1/p} \right] \\ &\leq \left( \int |f + g|^p \right)^{1/q} (\|f\|_p + \|g\|_p). \end{aligned}$$

We then see that

$$\underbrace{(|f(x) + g(x)|^p)^{1-1/q}}_{(|f(x)+g(x)|^p)^{1/p}} \leq \|f\|_p + \|g\|_p,$$

which is just  $\|f + g\|_p \leq \|f\|_p + \|g\|_p$ . ■

## Lecture 24: Embedding $L^p$ Space

11 Mar. 11:00

**Definition 5.4 (Essential supremum).** For a [measurable function](#)  $f$  on  $(X, \mathcal{A}, \mu)$ , we define

$$\begin{aligned} S &:= \{\alpha \geq 0 \mid \mu(\{x \mid |f(x)| > \alpha\}) = 0\} \\ &= \{\alpha \geq 0 \mid |f(x)| \leq \alpha \text{ a.e.}\}. \end{aligned}$$

Then, we say that the *essential supremum* of  $f$ , denoted as  $\|f\|_\infty$ , is defined as

$$\|f\|_\infty := \begin{cases} \inf S, & \text{if } S \neq \emptyset; \\ \infty, & \text{if } S = \emptyset. \end{cases}$$

**Definition 5.5 ( $L^\infty$  space).** Let  $L^\infty(X, \mathcal{A}, \mu)$  be

$$L^\infty(X, \mathcal{A}, \mu) = \{f \mid \|f\|_\infty < \infty\}.$$

**Definition 5.6** ( $\ell^\infty$  space). We let  $\ell^\infty$  be defined as

$$\ell^\infty = L^\infty(\mathcal{N}, \mathcal{P}(\mathcal{N}), \nu),$$

where  $\nu$  is the [counting measure](#).

**Example.** Consider  $(\mathbb{R}, \mathcal{L}, m)$ . Then

$$f(x) = \frac{1}{x} \mathbb{1}_{(0, \infty)}(x) \notin L^\infty;$$

$$g(x) = x \mathbb{1}_{\mathbb{Q}}(x) + \frac{1}{1+x^2} \in L^\infty.$$

If  $f$  is continuous on  $(\mathbb{R}, \mathcal{L}, m)$ , then  $\|f\|_\infty = \sup_{x \in \mathbb{R}} |f(x)|$ . For  $a \in \ell^\infty$ , we have  $\|a\|_\infty = \sup_{i \in \mathbb{N}} |a_i|$ , and sequences in  $\ell^\infty$  are exactly the bounded sequences.

**Lemma 5.2.** We have the following.

1. Suppose  $f \in L^\infty(X, \mathcal{A}, \mu)$ . Then,

$$\begin{cases} \mu(\{x \mid |f(x)| > \alpha\}) = 0, & \text{if } \alpha \geq \|f\|_\infty; \\ \mu(\{x \mid |f(x)| > \alpha\}) > 0, & \text{if } \alpha < \|f\|_\infty. \end{cases}$$

2.  $|f(x)| \leq \|f\|_\infty$  [almost everywhere](#).
3.  $f \in L^\infty$  if and only if there exists a bounded [measurable function](#)  $g$  such that  $f = g$  [almost everywhere](#).

*Proof.* .



DIY

**Theorem 5.3.** We have the following.

1.  $\|fg\|_1 \leq \|f\|_1 \|g\|_\infty$ .
2.  $\|f+g\|_\infty \leq \|f\|_\infty + \|g\|_\infty$ .
3.  $f_n \rightarrow f$  in  $L^\infty$  if and only if  $f_n \rightarrow f$  [uniformly almost everywhere](#).

**Remark.** The motivation for 1. is that

$$\frac{1}{1} + \frac{1}{\infty} = 1,$$

and we want to have the similar result as in [Theorem 5.1](#).

*Proof.* . We'll do one implication in 3. Let  $A_n = \{x \mid |f_n(x) - f(x)| > \|f_n - f\|_\infty\}$ . Then  $\mu(A_n) = 0$ . Let  $A = \bigcup_n A_n$ , we see that  $\mu(A) = 0$  as well.



DIY

For  $x \in A^c$  and for every  $n$ , we have

$$|f_n(x) - f(x)| \leq \|f_n - f\|_\infty.$$

Given  $\epsilon > 0$ , there is an  $N$  so that

$$\|f_n - f\| < \epsilon$$

for all  $n \geq N$ . But then for all  $x \in A^c$ ,  $|f_n(x) - f(x)| < \epsilon$  as well. ■

**Proposition 5.1.** We have the following.

1. For  $1 \leq p < \infty$ , the collection of **simple functions** with finite measure **support** is dense in  $L^p(X, \mathcal{A}, \mu)$ .
2. For  $1 \leq p < \infty$ , the collection of **step functions** with finite measure **support** is dense in  $L^p(\mathbb{R}, \mathcal{L}, m)$ , so is  $C_c(\mathbb{R})$ .
3. For  $p = \infty$ , the collection of **simple functions** is dense in  $L^\infty(X, \mathcal{A}, \mu)$ .

**Remark.** Note that  $C_c(\mathbb{R})$  is **not** dense in  $L^\infty(\mathbb{R}, \mathcal{L}, m)$ .

*Proof.* .

DIY

### 5.3 Embedding Properties of $L^p$ Spaces

**Definition 5.7 (Equivalent norm).** Two **norms**  $\|\cdot\|, \|\cdot\|'$  on  $V$  are *equivalent* if there exists  $c_1, c_2 > 0$ , such that

$$c_1 \|v\| \leq \|v\|' \leq c_2 \|v\|$$

for all  $v \in V$ .

**Note.** We see that

1. These **norms** gives the same topological properties (open sets, closed sets, convergence, etc.).
2. **Definition 5.7** is an equivalence relation on **norms**.

**Example.** For  $\mathbb{R}^d$  we have the **norms**  $\|\cdot\|_p$  for  $1 \leq p \leq \infty$ . All of these are equivalent. We see that for  $1 \leq p < \infty$ ,

$$\|x\|_p = \left( \sum_{i=1}^d |x_i|^p \right)^{1/p} \leq (d \|x\|_\infty^p)^{1/p} = d^{1/p} \|x\|_\infty.$$

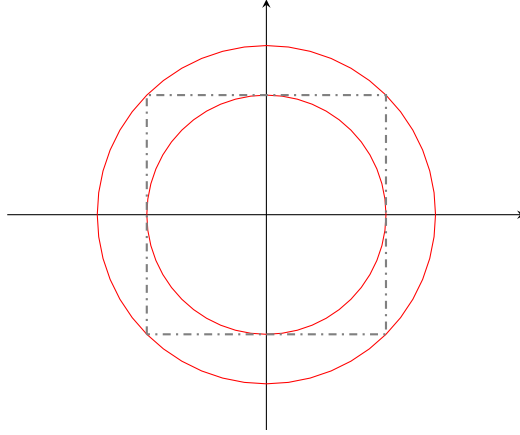
Also,

$$\|x\|_p = \left( \sum_{i=1}^d |x_i|^p \right)^{1/p} \geq (\|x\|_\infty^p)^{1/p} = \|x\|_\infty.$$

Thus,  $\|\cdot\|_p$  is equivalent to  $\|\cdot\|_\infty$  for every  $1 \leq p < \infty$ , and transitivity gives that they are all equivalent.

Another way of thinking of this, by assuming  $v \neq 0$ , and scaling by some  $t$ , we may assume  $v$  lies on the unit circle in one of the **norms**. Then we are squeezing

a unit circle in  $\|\cdot\|'$  between two circles of radius  $c_1, c_2$  in  $\|\cdot\|$ . In picture, we have to show that  $\|\cdot\|_2$  and  $\|\cdot\|_\infty$  are equivalent, we have



since the circles in  $\|\cdot\|_\infty$  are squares.

**Example.** For  $1 \leq p, q \leq \infty$ , we have  $L^p(\mathbb{R}, m)$ -norm and  $L^q(\mathbb{R}, m)$ -norm are not equivalent, even worse, we have that

$$L^p(\mathbb{R}, m) \not\subseteq L^1(\mathbb{R}, m), \quad L^p(\mathbb{R}, m) \not\supseteq L^1(\mathbb{R}, m).$$

## Lecture 25: Banach Spaces

14 Mar. 11:00

**Proposition 5.2.** Suppose  $\mu(X) < \infty$ , then for every  $0 < p < q \leq \infty$ ,  $L^q \subseteq L^p$ .

*Proof.* Suppose  $q < \infty$ , then

$$\int |f|^p \leq \left( \int (|f|^p)^{q/p} \right)^{p/q} \left( \int 1^{q/(q-p)} \right)^{1-p/q} = \left( \int |f|^q \right)^{p/q} \mu(X)^{1-p/q} < \infty$$

where we split  $\int |f|^p$  into  $\int |f|^p \cdot 1$ . From Hölder's inequality with  $q/p > 1$ , we have

$$\|f\|_p \leq \|f\|_q \mu(X)^{1/p-1/q} < \infty.$$

The case that  $q = \infty$  is left as an exercise. ■

DIY

**Proposition 5.3.** If  $0 < p < q \leq \infty$ , then  $\ell^p \subseteq \ell^q$ .

*Proof.* When  $q = \infty$ , we have

$$\|a\|_\infty^p = \left( \sup_i |a_i| \right)^p = \sup_i |a_i|^p \leq \sum_{i=1}^{\infty} |a_i|^p.$$

Thus  $\|a\|_\infty \leq \|a\|_p$ .

When  $q < \infty$ , we see that

$$\sum_{i=1}^{\infty} |a_i|^q = \sum_{i=1}^{\infty} |a_i|^p \cdot |a_i|^{q-p} \leq \|a\|_{\infty}^{q-p} \sum_{i=1}^{\infty} |a_i|^p \leq \|a\|_p^{q-p} \cdot \|a\|_p^p = \|a\|_p^q.$$

Therefore,

$$\|a\|_q \leq \|a\|_p.$$

■

**Proposition 5.4.** For all  $0 < p < q < r \leq \infty$ ,  $L^p \cap L^r \subseteq L^q$ .

*Proof.*

DIY

■

## 5.4 Banach Spaces

Let's start with a definition.

**Definition 5.8 (Cauchy sequence).** Let  $Y, \rho$  be a **metric** space. We call  $x_n$  a *Cauchy sequence* if for every  $\epsilon > 0$ , there exists an  $N \in \mathbb{N}$  such that for all  $n, m \geq N$ ,  $\rho(x_n, x_m) < \epsilon$ .

**Note.** Convergent sequence are **Cauchy**.

**Definition 5.9 (Complete).** A **metric** space  $(Y, \rho)$  is called *complete* if every **Cauchy sequence** in  $Y$  converges.

**Example.** We first see some examples.

1. We see that  $\mathbb{Q}$  with  $\rho(x, y) = |x - y|$  is **not complete**, but  $\mathbb{R}$  with the same **metric** is **complete**.
2.  $C([0, 1])$  with  $\rho(f, g) = \|f - g\|_{\infty}$  is **complete**, but with  $\rho(f, g) = \int |f - g|$  is not.

**Definition 5.10 (Banach space).** A *Banach space* is a **complete normed** vector space.

**Remark.** Namely, a vector space equipped with a **norm** whose **metric induced by the norm** is **complete**.

**Theorem 5.4.** Let  $(V, \|\cdot\|)$  be a **normed** space. Then,

$V$  is **complete**  $\iff$  every absolutely convergent series is convergent.

i.e., if  $\sum_{i=1}^{\infty} \|v_i\| < \infty$ , then  $\left\{ \sum_{i=1}^N v_i \right\}_{N \in \mathbb{N}}$  converges to some  $s \in V$ .

Before we prove [Theorem 5.4](#), we first see one of the result based on this theorem.<sup>27</sup>

**Theorem 5.5 (Riesz-Fischer theorem).** For every  $1 \leq p \leq \infty$ , we have  $L^p(X, \mathcal{A}, \mu)$  is [complete](#), hence a [Banach space](#).

*Proof.* We prove this in steps.

1. We first prove this for  $1 \leq p < \infty$ . Suppose  $f_n \in L^p$  and  $\sum_{n=1}^{\infty} \|f_n\|_p < \infty$ .

We need to show that there is an  $F \in L^p$  such that  $\left\| \sum_{n=1}^N f_n - F \right\|_p \rightarrow 0$  as  $N \rightarrow \infty$ . i.e., we need to show

- (a)  $\sum_{n=1}^{\infty} f_n(x)$  is convergent [a.e.](#) In fact, we can show  $\int \sum_{n=1}^{\infty} |f_n(x)| < \infty$ .

Let  $G(x) = \sum_{n=1}^{\infty} |f_n(x)| = \sup_N \sum_{n=1}^N |f_n(x)|$ ,  $G: X \rightarrow [0, \infty]$ . Also, let  $G_N(x) = \sum_{n=1}^N |f_n(x)|$ . Then, we have

$$0 \leq G_1 \leq G_2 \leq \dots \leq G,$$

and  $G_N \rightarrow G$ . Furthermore,

$$0 \leq G_1^p \leq G_2^p \leq \dots \leq G^p,$$

and  $G_N^p \rightarrow G^p$ . From [monotone convergence theorem](#),

$$\int G^p = \lim_{N \rightarrow \infty} \int G_N^p.$$

From [Minkowski inequality](#), we further have

$$\|G_N\|_p \leq \sum_{n=1}^N \|f_n\|_p \leq \sum_{n=1}^{\infty} \|f_n\|_p := B < \infty.$$

Thus,

$$\int G(x)^p = \lim_{N \rightarrow \infty} \int G_N^p = \lim_{N \rightarrow \infty} \|G_N\|_p^p \leq B^p < \infty.$$

We see that  $G$  is finite [a.e.](#) as desired. This implies that  $\sum_{n=1}^{\infty} |f_n(x)| < \infty$  [a.e.](#), so  $\sum_{n=1}^{\infty} f_n(x)$  converges [a.e.](#) Now, we simply let

$$F(x) = \begin{cases} \sum_{n=1}^{\infty} f_n(x), & \text{if it converges;} \\ 0, & \text{otherwise.} \end{cases}$$

---

<sup>27</sup>The proof can be found in [here](#).



- (b)  $F \in L^p$ , where  $F(x) := \sum_{n=1}^{\infty} f_n(x)$  **a.e.** and say is zero elsewhere.

This is clear since

$$|F(x)| \leq G(x) \implies \int |F|^p \leq \int G^p < \infty,$$

hence  $F \in L^p$ .

- (c)  $\left\| \sum_{n=1}^N f_n - F \right\|_p \rightarrow 0$  as  $N \rightarrow \infty$ .

We now see that

$$\left| \sum_{n=1}^N f_n(x) - F(x) \right|^p \leq \left( \sum_{n=1}^{\infty} |f_n(x)| + |F(x)| \right)^p \leq (2G(x))^p.$$

Since  $2G \in L^p$ , so  $2G^p \in L^1$ . Thus, by **dominated convergence theorem**, we have

$$\lim_{N \rightarrow \infty} \int \left| \sum_{n=1}^N f_n(x) - F(x) \right|^p dx = 0.$$

This implies

$$\left\| \sum_{n=1}^N f_n - F \right\|_p \rightarrow 0$$

as  $N \rightarrow \infty$ .

2. The case that  $1 \leq p \leq \infty$  is left as an exercise.

DIY

■

## Lecture 26: Bounded Linear Transformations

16 Mar. 11:00

We now prove **Theorem 5.4**, completing the proof of **Theorem 5.5** since the latter relies on this result.

*Proof.* We prove it by proving two directions.

( $\implies$ ) Suppose  $V$  is **complete**, and fix an absolutely convergent series  $\sum_n v_n$ . Define  $s_N = \sum_{n=1}^N v_n$ . It suffices to show the partial sums are a **Cauchy Sequence**.

Fix  $\epsilon > 0$ , then because  $\sum_{n=1}^{\infty} \|v_n\| < \infty$ , there is a  $K \in \mathbb{N}$  so that

$$\sum_{n=K}^{\infty} \|v_n\| < \epsilon.$$

Now let  $M > N > K$ , we see that

$$\|s_M - s_N\| = \left\| \sum_{n=N+1}^M v_n \right\| \leq \sum_{n=N+1}^M \|v_n\| \leq \sum_{n=N}^{\infty} \|v_n\| < \epsilon,$$

so this is **Cauchy**.

( $\Leftarrow$ ) Now suppose  $v_n, n \in \mathbb{N}$  is a **Cauchy sequence**. For all  $j \in \mathbb{N}$ , there exists an  $N_j \in \mathbb{N}$  such that

$$\|v_n - v_m\| < \frac{1}{2^j}$$

for all  $n, m \geq N_j$ . Without loss of generality, we may assume  $N_1 < N_2 < \dots$

Let  $w_1 = v_{N_1}$ ,  $w_j = v_{N_j} - v_{N_{j-1}}$  for  $j \geq 2$ . Therefore,

$$\sum_{j=1}^{\infty} \|w_j\| \leq \|v_{N_1}\| + \sum_{j=2}^{\infty} \frac{1}{2^{j-1}} < \infty.$$

Thus,  $\sum_{j=1}^k w_j \rightarrow s \in V$  as  $k \rightarrow \infty$ . But by telescoping, we have

$$v_{N_k} = \sum_{j=1}^k w_j \rightarrow s.$$

Now we claim that since  $v_n$  is **Cauchy**, so  $v_n \rightarrow s$ .

Explicitly, take  $\epsilon > 0$ , and let  $k$  be large enough so that  $\|v_{N_k} - s\| < \epsilon$  and  $1/2^k < \epsilon$ . Then if  $n > N_k$  then

$$\|v_n - s\| \leq \|v_n - v_{N_k}\| + \|v_{N_k} - s\| < \epsilon + \epsilon = 2\epsilon.$$

Thus,  $v_n \rightarrow s$ . ■

## 5.5 Bounded Linear Transformations

**Definition 5.11 (Bounded linear transformation).** Given two **normed** vector spaces  $(V, \|\cdot\|)$ ,  $(W, \|\cdot\|')$ , a linear map  $T: V \rightarrow W$  is called a *bounded map* if there exists  $c \geq 0$  such that

$$\|Tv\|' \leq c\|v\|$$

for all  $v \in V$ .

**Proposition 5.5.** Suppose  $T: (V, \|\cdot\|) \rightarrow (W, \|\cdot\|')$  is a linear map. Then the followings are equivalent.

1.  $T$  is continuous.
2.  $T$  is continuous at 0.
3.  $T$  is a **bounded map**.

*Proof.* 1.  $\implies$  2. is clear. For 2.  $\implies$  3., take  $\epsilon = 1$ , then there exists a  $\delta > 0$  such that  $\|Tu\|' < 1$  if  $\|u\| < \delta$ .

Now take an arbitrary  $\|v\| \in V$ ,  $v \neq 0$ . Let  $u = \frac{\delta}{2\|v\|}v$ . Then  $\|u\| < \delta$ . Therefore,

$$\|Tu\|' < 1 \implies \frac{\delta}{2\|v\|} \|Tv\|' < 1 \implies \|Tv\|' < \frac{2}{\delta} \|v\|.$$

Then  $2/\delta$  is our constant.

For 3.  $\implies$  1., fix  $v_0 \in V$ . Then for some constant  $c$

$$\|Tv - Tv_0\|' = \|T(v - v_0)\|' \leq c \|v - v_0\|.$$

Thus,  $T$  is continuous, as when  $v \rightarrow v_0$  the right-hand side goes to zero, and so  $Tv \rightarrow Tv_0$ . ■

**Example.** Let's see some examples.

1. We can look at

$$\begin{aligned} T: \ell^1 &\rightarrow \ell^1 \\ (a_1, a_2, \dots) &\mapsto (a_2, a_3, \dots). \end{aligned}$$

Then clearly  $\|Ta\|_1 \leq \|a\|_1$ , so  $T$  is a **bounded linear transformation**.

2. We can also look at  $S: (C([-1, 1]), \|\cdot\|_1) \rightarrow \mathbb{C}$ , where  $Sf = f(0)$ .  $S$  is not a **bounded linear transformation**, because we can make

$$\begin{cases} \|Sf\| &= |f(0)| = n \\ \|f\|_1 &= 1 \end{cases}$$

for every  $n \in \mathbb{N}$  (take  $f$ 's graph to be a skinny triangle shooting up to  $n$  at 0).

3. But  $U: (C([-1, 1]), \|\cdot\|_\infty) \rightarrow \mathbb{C}$  defined by  $Uf = f(0)$  is a **bounded linear transformation**, because  $|f(0)| \leq \|f\|_\infty$ .
4. Let  $A$  be an  $n \times m$  matrix. Then  $T: \mathbb{R}^m \rightarrow \mathbb{R}^n$  defined by  $v \mapsto Av$  is a **bounded linear transformation**.

Explicitly this is

$$(Tv)_i = (Av)_i = \sum_{j=1}^m A_{ij}v_j.$$

5. Let  $K(x, y)$  be a continuous function on  $[0, 1] \times [0, 1]$ . We'll define

$$T: (C[0, 1], \|\cdot\|_\infty) \rightarrow (C[0, 1], \|\cdot\|_\infty)$$

by

$$(Tf)(x) = \int_0^1 K(x, y)f(y) \, dy.$$

This is an analogue of matrix multiplication ( $K$  is like a continuous matrix). This is a **bounded linear transformation**.

6. Let us look at  $T: L^1(\mathbb{R}) \rightarrow (C(\mathbb{R}), \|\cdot\|_\infty)$  defined by

$$(Tf)(t) = \int_{-\infty}^{\infty} e^{-itx} f(x) \, dx$$

that is the Fourier transform of  $f$ .

7.  $T: (C^\infty[0, 1], \|\cdot\|_\infty) \rightarrow (C^\infty[0, 1], \|\cdot\|_\infty)$ . Define

$$(Tf)(x) = f'(x).$$

This is not a **bounded linear transformation**. In contrast,  $S$ , defined on the same spaces

$$(Sf)(x) = \int_0^x f(t) dt$$

is bounded.

**Definition 5.12 (Operator norm).** Let  $L(V, W)$  be defined as a vector space such that

$$L(V, W) := \{T: V \rightarrow W \mid T \text{ is a bounded linear transformation}\}.$$

Then for  $T \in L(V, W)$ , the *operator norm* of  $T$  is

$$\begin{aligned} \|T\| &:= \inf\{c \geq 0 \mid \|Tv\|'' \leq c\|v\|' \text{ for all } v \in V\} \\ &= \sup\left\{\frac{\|Tv\|''}{\|v\|'} \mid v \neq 0, v \in V\right\} \\ &= \sup\{\|Tv\|'' \mid \|v\|' = 1, v \in V\}. \end{aligned}$$

**Lemma 5.3.** We have that

1. The **three definitions** of  $\|T\|$  above are all equal.
2.  $(L(V, W), \|\cdot\|)$  is indeed a **normed** space.

*Proof.*



DIY

## Lecture 27: Dual Space

18 Mar. 11:00

As previously seen. From **Definition 5.12**, we have that

$$\|Tv\|'' \leq \|T\| \|v\|'.$$

**Remark.** Notice that this **Definition 5.12** is only for **bounded linear transformation**.

**Theorem 5.6.** If  $W$  is **complete**, then  $L(V, W)$  is **complete**.

*Proof.* Suppose  $T_n$  is a **Cauchy sequence** in  $L(V, W)$ . Fix  $v \in V$  and let  $w_n := T_n v \in W$ , we then have

$$\|w_n - w_m\| = \|T_n v - T_m v\| = \|(T_n - T_m)v\| \leq \underbrace{\|T_n - T_m\|}_{\rightarrow 0} \underbrace{\|v\|}_{\text{fixed value}}.$$

Thus,  $w_n$  is **Cauchy**, so it converges since  $W$  is **complete**. We call its unique limit  $Tv$ . This makes  $T: V \rightarrow W$  into a function. We must show it is a **bounded linear transformation** and that  $\|T_n - T\| \rightarrow 0$ .



DIY

## 5.6 Dual of $L^p$ Spaces

**Example.** Let  $w \in \mathbb{R}^d$ , and denote the inner product between  $w$  and  $v \in \mathbb{R}^d$  by

$$v \cdot w := \langle v, w \rangle.$$

Then we can consider

$$\max\{v \cdot w \mid \|v\|_2 = 1\} = \|w\|_2.$$

If  $w \in \mathbb{C}^d$ , this is similar since

$$\max\{|v \cdot w| \mid \|v\|_2 = 1\} = \|w\|_2.$$

These maximums are achieved by  $v = \frac{\bar{w}}{\|w\|}$  if  $w \neq 0$ .

**Proposition 5.6.** Let  $1/p + 1/q = 1$  with  $1 \leq q < \infty$ . For every  $g \in L^q$ ,

$$\|g\|_q = \sup \left\{ \left| \int fg \right| \mid \|f\|_p = 1 \right\}.$$

Suppose  $\mu$  is  $\sigma$ -finite. Then the result also holds for  $q = \infty$ ,  $p = 1$ .

**As previously seen.** For  $\alpha \in \mathbb{C}$ ,  $\text{sgn}(\alpha) := e^{i\theta}$  where  $\alpha = |\alpha| e^{i\theta}$ .

*Proof.* By Hölder's inequality, we know that

$$\left| \int fg \right| \leq \int |fg| = \|fg\|_1 \leq \|f\|_p \|g\|_q = \|g\|_q.$$

Thus, the supremum is less or equal to  $\|g\|_q$ .

1. Let

$$f(x) = \frac{|g(x)|^{q-1} \cdot \overline{\text{sgn}(g(x))}}{\|g\|_q^{q-1}}$$

Then  $\int |f|^p = 1$ , and  $\int fg = \|g\|_q$ .

2. The case that  $\mu$  is  $\sigma$ -finite and  $q = \infty$ ,  $p = 1$  can be shown.

Check

DIY

■

**Remark.** One could use the above to prove Minkowski's inequality (as it only uses Hölder's inequality).

**Definition 5.13 (Dual space).** For a normed space  $(V, \|\cdot\|)$ , its dual space is  $V^* = L(V, \mathbb{R})$  or  $V^* = L(V, \mathbb{C})$ .

**Remark.** Namely, the dual space of  $V$  contains bounded linear transformations with codomain being the scalar field.

**Definition 5.14 (Linear functional).** Given a **normed** space  $(V, \|\cdot\|)$ ,  $\ell \in V^*$  is called a *linear functional* on  $V$ . i.e.,

- $\ell: V \rightarrow \mathbb{R}$  (or  $\mathbb{C}$ ).
- $\ell$  is linear.
- There exists a  $c \geq 0$  such that  $|\ell(v)| = c \|v\|$ .

**Note.**  $V^*$  is always a **Banach space** (even if  $V$  is not **complete**).

**Corollary 5.1.** We have the followings.

1. Let  $1/p + 1/q = 1, 1 \leq q < \infty$ . For  $g \in L^q$  define  $\ell_g \in L^p \rightarrow \mathbb{C}$  by

$$\ell_g(f) = \int fg.$$

Then  $\ell_g \in (L^p)^*$ . Furthermore,  $\|\ell_g\| = \|g\|_q$ .

2. If  $\mu$  is  **$\sigma$ -finite** then this also holds for  $q = \infty, p = 1$ .

*Proof.*  $\ell_g$  is clearly linear in  $f$  because the integral is linear. Then **Proposition 5.6** gives in both 1. and 2. that

$$\|g\|_q = \sup\{|\ell_g(f)| \mid \|g\|_p = 1\} = \|\ell_g\|$$

and so  $\ell_g$  is a **bounded linear transformation** with the desired properties. ■

**Theorem 5.7.** We have the followings.

1. Let  $1/p + 1/q = 1, 1 \leq q < \infty$ . The map  $T: L^q \rightarrow (L^p)^*$  given by  $Tg = \ell_g$  is an isometric<sup>a</sup> linear isomorphism.

This means that

- $T$  is a **bounded linear transformation**.
- $T$  is bijective.
- $T$  is **norm-preserving**.

2. If  $\mu$  is  **$\sigma$ -finite** then this also holds for  $q = \infty, p = 1$ .

<sup>a</sup>A map  $T$  is called isometric if for a given  $g$ ,  $\|Tg\| = \|g\|$ .

**Note.** Even if  $\mu$  is  **$\sigma$ -finite** we might not have  $L^1 \cong (L^\infty)^*$ .

Also note that  $L^2 \cong (L^2)^*$ , and for all  $1 < p < \infty$  we have  $(L^p)^{**} \cong L^p$ .

*Proof.* We have already proved this is isometric in **Corollary 5.1**, it is clearly linear, and isometry implies injectivity.

We will prove that it is surjective later. ■

Fix!!!

## Lecture 28: Signed Measure

21 Mar. 11:00

## 6 Signed and Complex Measures

**As previously seen.** Suppose  $f: X \rightarrow [0, \infty]$  is a measurable function on  $(X, \mathcal{A}, \mu)$ .

We can define  $\nu(E) = \int_E f \, d\mu$  for  $E \in \mathcal{A}$ , and  $\nu$  is a measure on  $(X, \mathcal{A})$ .

This gives a map from the set of non-negative measurable functions on  $X$  to measures on  $X$ . This is injective if we identify functions which are equal almost everywhere. But it is not necessarily surjective. We can then think of measures as a generalization of functions.

For an example, think of a Dirac-Delta measure on  $\mathbb{R}$ . This is not the Lebesgue integral of any non-negative measurable function.

What if instead we took  $f: X \rightarrow \mathbb{R}, \bar{\mathbb{R}}$  or  $\mathbb{C}$ . We could take the same construction to get  $\nu(E) = \int_E f \, d\mu$ , but this is no longer a measure as it can take  $\mathbb{R}, \bar{\mathbb{R}}$  or  $\mathbb{C}$  values.

## 6.1 Signed Measures

**Definition 6.1.** Let  $(X, \mathcal{A})$  be a measurable space. A signed measure is  $\nu: \mathcal{A} \rightarrow [-\infty, \infty]$  or  $\nu: \mathcal{A} \rightarrow (-\infty, \infty]$  such that

- $\nu(\emptyset) = 0$ .
- If  $A_1, A_2, \dots \in \mathcal{A}$  are disjoint then

$$\nu\left(\bigcup_{i=1}^{\infty} A_i\right) = \sum_{i=1}^{\infty} \nu(A_i)$$

where the series on the right-hand side converges absolutely if

$$\nu\left(\bigcup_{i=1}^{\infty} A_i\right) \in (-\infty, \infty).$$

This means the series does not depend on rearrangement.

**Example.** Consider

1.  $\nu$  is a positive measure (i.e., measure), then  $\nu$  is a signed measure.
2. If we have positive measures  $\mu_1, \mu_2$  such that either  $\mu_1(X) < \infty$  or  $\mu_2(X) < \infty$ , then  $\nu = \mu_1 - \mu_2$  is a signed measure.
3. If  $f: X \rightarrow \bar{\mathbb{R}}$  on a measure space  $(X, \mathcal{A}, \mu)$  such that  $\int_X f^+ \, d\mu < \infty$  or  $\int_X f^- \, d\mu < \infty$ , we can define

$$\nu(E) = \int_E f \, d\mu$$

and this will be a signed measure.

**Note.** The following weird things happen with [signed measures](#).

1.  $A \subseteq B$  does not imply  $\nu(A) \leq \nu(B)$ , as  $\nu(B) = \nu(A) + \nu(B \setminus A)$ , and  $\nu(B \setminus A)$  may be negative.
2. If  $A \subseteq B$  and  $\nu(A) = \infty$ , then  $\nu(B) = \infty$ , because  $\nu(B \setminus A) \in (-\infty, \infty]$ .
3. Similarly, if  $A \subseteq B$  and  $\nu(A) = -\infty$  then  $\nu(B) = -\infty$ .

**Lemma 6.1.** If  $\nu$  is a [signed measure](#) on  $(X, \mathcal{A})$ , then we have

1. Continuity from below. If  $E_n \in \mathcal{A}$  and  $E_1 \subseteq E_2 \subseteq \dots$  then

$$\nu\left(\bigcup_{n=1}^{\infty} E_n\right) = \lim_{N \rightarrow \infty} \nu(E_N).$$

2. Continuity from above. If  $E_n \in \mathcal{A}$ ,  $E_1 \supseteq E_2 \supseteq \dots$ , and  $-\infty < \nu(E_1) < \infty$  then

$$\nu\left(\bigcap_{n=1}^{\infty} E_n\right) = \lim_{N \rightarrow \infty} \nu(E_N).$$

*Proof.* Read [FF99]. ■

**Definition 6.2 (Positive, negative, null set for a signed measure).**

Let  $\nu$  be a [signed measure](#) on  $(X, \mathcal{A})$ . Let  $E \in \mathcal{A}$ , then we say that

1.  $E$  is *positive* for  $\nu$  if for all  $F \subseteq E$ ,  $\nu(F) \geq 0$ .
2.  $E$  is *negative* for  $\nu$  if for all  $F \subseteq E$ ,  $\nu(F) \leq 0$ .
3.  $E$  is *null* for  $\nu$  if for all  $F \subseteq E$ ,  $\nu(F) = 0$ .

**Note.** We see that

1. If  $E$  is a [positive set](#),  $F \subseteq E$ , then  $\nu(F) \leq \nu(E)$ .
2. If  $E$  is a [negative set](#),  $F \subseteq E$ , then  $\nu(F) \geq \nu(E)$ .

**Lemma 6.2.** Let  $\nu$  be a [signed measure](#) on  $(X, \mathcal{A})$ , then

1. If  $E$  is [positive](#),  $G \subseteq E$  is [measurable](#), then  $G$  is [positive](#).
2. If  $E$  is [negative](#),  $G \subseteq E$  is [measurable](#), then  $G$  is [negative](#).
3. If  $E$  is [null](#),  $G \subseteq E$  is [measurable](#), then  $G$  is [positive](#).
4.  $E_1, E_2, \dots$  are [positive](#) sets, then  $\bigcup_{i=1}^{\infty} E_i$  is [positive](#).

*Proof.* ■

DIY



**Lemma 6.3.** Suppose that  $\nu$  is a signed measure with  $\nu: \mathcal{A} \rightarrow [-\infty, \infty)$ . Suppose  $E \in \mathcal{A}$  and  $0 < \nu(E) < \infty$ , then there exists a measurable  $A \subseteq E$  such  $A$  is a positive set and  $\nu(A) > 0$ .

*Proof.* If  $E$  is positive, we're done. Otherwise, there exist measurable subsets with negative measure. Let  $n_1 \in \mathbb{N}$  be the least such  $n_1$  such that there exists  $E_1 \subseteq E$  with  $\nu(E_1) < -1/n_1$ .

If  $E \setminus E_1$  is positive, we're done. Else we can inductively define  $n_2, n_3, \dots$  as well as  $E_2, E_3, \dots$

Explicitly, if  $E \setminus \bigcup_{i=1}^{k-1} E_i$  is not positive, let  $n_k$  be the least such that there exists  $E_k \subseteq E \setminus \bigcup_{i=1}^{k-1} E_i$  with  $\nu(E_k) < -1/n_k$ .

Note then that if  $n_k \geq 2$ , for all  $B \subseteq E \setminus \bigcup_{i=1}^{k-1} E_i$  we have that  $\nu(B) \geq -\frac{1}{n_k-1}$ .

Now let  $A = E \setminus \bigcup_{i=1}^{\infty} E_i$ . Since  $E = A \cup (\bigcup_i E_i)$  we have by countable additivity that

$$0 < \nu(E) = \nu(A) + \sum_{k=1}^{\infty} \nu(E_k) < \nu(A).$$

Furthermore,  $\nu(E), \nu(A)$  are both in  $(0, \infty)$ , and we see that

$$0 < \nu(E) \leq \nu(A) - \sum_{k=1}^{\infty} \frac{1}{n_k}.$$

Therefore, the sum on the right-hand side must converge, meaning that  $1/n_k \rightarrow 0$  as  $k \rightarrow \infty$ . That is  $\lim_{k \rightarrow \infty} n_k = \infty$ .

Now if  $B \subseteq A$ , then  $B \subseteq E \setminus \bigcup_{i=1}^{\infty} E_i$ . Therefore,  $B \subseteq E \setminus \bigcup_{i=1}^{k-1} E_i$ . By the note above, for large enough  $k$  such that  $n_k \geq 2$  we have

$$\nu(B) \geq \frac{-1}{n_k - 1},$$

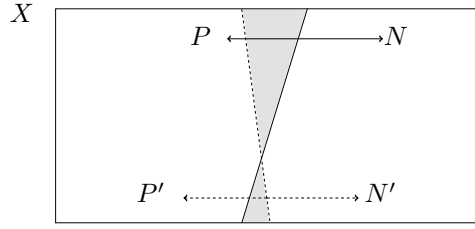
then taking  $k \rightarrow \infty$  we have  $\nu(B) \geq 0$ , and so  $A$  is a positive set as desired. ■

**Theorem 6.1 (Hahn decomposition theorem).** If  $\nu$  is a signed measure on  $(X, \mathcal{A})$ , then there exist  $P, N \in \mathcal{A}$  such that

$$P \cap N = \emptyset, \quad P \cup N = X,$$

where  $P$  is positive for  $\nu$ ,  $N$  is negative for  $\nu$ .

Furthermore, if  $P', N'$  are another such pair, then  $P \Delta P' (= N \Delta N')$  is null for  $\nu$ .



## Lecture 29: Hahn and Jordan Decomposition Theorem

23 Mar. 11:00

We now prove Theorem 6.1.

*Proof.* We first show the uniqueness. We see that  $P \setminus P' \subseteq P, P \setminus P' \subseteq N'$ . Thus,  $P \setminus P' \subseteq P \cap N'$  is both positive and negative, hence  $P \setminus P'$  is null.

Similarly, for  $P' \setminus P$ , and then their union  $P \Delta P'$  is null as well.

To show the existence, without loss of generality suppose  $\nu: \mathcal{A} \rightarrow [-\infty, \infty)$ . If not, consider  $-\nu$ . Let

$$s := \sup\{\nu(E) \mid E \in \mathcal{A} \text{ is a positive set}\},$$

which is a nonempty supremum because  $\emptyset$  is positive. Then there exist  $P_1, P_2, \dots$  positive sets such that  $\lim_{n \rightarrow \infty} \nu(P_n) = s$ .

Then we have that  $P = \bigcup_n P_n$  is positive by Lemma 6.2. We then have  $\nu(P) \leq s$  and  $\nu(P) = \nu(P_n) + \nu(P \setminus P_n) \geq \nu(P_n)$ . Thus,

$$\nu(P) \geq \lim_{n \rightarrow \infty} \nu(P_n) = s.$$

Hence,  $\nu(P) = s$  and the supremum is in fact a max. We then know that  $s = \nu(P) < \infty$  because  $\nu$  does not attain the value infinity.

Now let  $N = X \setminus P$ . We claim that  $N$  is negative. If not then there exists a measurable  $E \subseteq N$  with  $\nu(E) > 0$ . By assumption,  $\nu(E) < \infty$ . Then  $0 < \nu(E) < \infty$ , so by Lemma 6.3 there exists a measurable  $A \subseteq E$  such that  $A$  is positive and  $\nu(A) > 0$ .

But we then know that

$$\nu(P \cup A) = \nu(P) + \nu(A) > \nu(P)$$

which is a contradiction since  $P \cup A$  is a positive set, and  $\nu(P)$  is maximal.

Therefore,  $N$  is **negative**, and the theorem holds. ■

**Definition 6.3 (Singular).** If  $\mu, \nu$  are **signed measures** on  $(X, \mathcal{A})$ , then we say  $\mu$  and  $\nu$  are *singular to each other*, denoted as  $\mu \perp \nu$ , if there exists  $E, F \in \mathcal{A}$  such that  $E \cap F = \emptyset, E \cup F = X$ ,  $F$  is **null** for  $\mu$ ,  $E$  is **null** for  $\nu$ .

**Example.** Consider  $(\mathbb{R}, \mathcal{B}(\mathbb{R}))$  with

1. The **Lebesgue measure**  $m$ .
2. The **Cantor measure**  $\mu_C$  defined by the **Cantor function**.
3. The **discrete measure**  $\mu_D = \delta_1 + 2\delta_{-1}$ .

We then see that

1. Take  $E = \mathbb{R} \setminus \{-1, 1\}, F = \{1, -1\}$  to see that  $m \perp \mu_D$ .
2. Take  $E = \mathbb{R} \setminus K$  and  $F = K$  where  $K$  is the **Cantor set** to see that  $m \perp \mu_C$ .
3. We can also see that  $\mu_C \perp \mu_D$ .

**Theorem 6.2 (Jordan decomposition theorem).** Let  $\nu$  be a **signed measure** on  $(X, \mathcal{A})$ . Then there exists unique **positive measures**  $\nu^+, \nu^-$  on  $(X, \mathcal{A})$  such that for all  $E \in \mathcal{A}$  we have

$$\nu(E) = \nu^+(E) - \nu^-(E)$$

and

$$\nu^+ \perp \nu^-.$$

*Proof.* For existence, we take  $\nu^+(E) := \nu(E \cap P), \nu^-(E) := -\nu(E \cap N)$ . ■

DIY for  
uniqueness

**Lecture 30**

25 Mar. 11:00

**Lecture 31**

28 Mar. 11:00

# Appendix

## A Additional Proofs

### A.1 Measure

This section gives all additional proofs in [Section 1](#).

**Theorem A.1** ([Theorem 1.2 3.](#)). Under the setup of [Theorem 1.2](#),  $(X, \mathcal{A}, \mu)$  is a [complete measure space](#).

*Proof.* We see this in two parts.

1. **Claim:** If  $A \subset X$  satisfies  $\mu^*(A) = 0$ , then  $A$  is [Carathéodory measurable](#) with respect to  $\mu^*$ .

*Proof.* If  $A \subset X$  and  $\mu^*(A) = 0$ , where  $\mu^*$  is an outer measure on  $X$ , we'll show that  $A$  is [Carathéodory measurable](#) with respect to  $\mu^*$ .

Equivalently, we want to show that for any  $E \subset X$ ,

$$\mu^*(E) = \mu^*(E \cap A) + \mu^*(E \setminus A).$$

Firstly, noting that  $(E \cap A) \subset A$ , and by [monotonicity](#) of  $\mu^*$ , we see that

$$\mu^*(E \cap A) \leq \mu^*(A) = 0,$$

and since  $\mu^* \geq 0$ , hence  $\mu^*(E \cap A) = 0$ . Now, we only need to show that

$$\mu^*(E) = \mu^*(E \setminus A).$$

Since  $E \setminus A = E \cap A^c$ , and hence we have  $E \cap A^c \subset E$ , so

$$\mu^*(E) \geq \mu^*(E \setminus A).$$

To show another direction, we note that

$$\mu^*(E) \leq \mu^*(E \cup A) = \mu^*((E \setminus A) \cup A) \leq \mu^*(E \setminus A),$$

hence we conclude that  $A$  is [Carathéodory measurable](#) with respect to  $\mu^*$  if  $\mu^*(A) = 0$ . ■

2. **Claim:** If  $A$  is [μ-subnull](#), then  $A \in \mathcal{A}$ .

*Proof.* Let  $\mathcal{A}$  denotes the [Carathéodory σ-algebra](#), and  $\mu := \mu^*|_{\mathcal{A}}$ . We want to show if  $A$  is [μ-subnull](#), then  $A \in \mathcal{A}$ .

Firstly, if  $A$  is [μ-subnull](#), then there exists a  $B \in \mathcal{A}$  such that  $A \subset B$  and  $\mu(B) = 0$ . But since from the [monotonicity](#) of  $\mu^*$ , we further have

$$0 = \mu(B) = \mu^*(B) \geq \mu^*(A),$$

hence  $\mu^*(A) = 0$ .

From the first claim, we immediately see that  $A$  is [Carathéodory measurable](#) with respect to  $\mu^*$ , which implies  $A$  is in [Carathéodory σ-algebra](#), hence  $A \in \mathcal{A}$ . ■

We see that the second claim directly proves that  $(X, \mathcal{A}, \mu)$  is a [complete measure space](#). ■

**Lemma A.1.** The function  $F$  defined in [this example](#) is a [distribution function](#)

*Proof.* We define

$$F_n(x) = \begin{cases} 1, & \text{if } x \geq r_n; \\ 0, & \text{if } x < r_n \end{cases}$$

where  $\{r_1, r_2, \dots\} = \mathbb{Q}$ , and

$$F(x) = \sum_{n=1}^{\infty} \frac{F_n(x)}{2^n} = \sum_{n; r_n \leq x} \frac{1}{2^n}$$

is both increasing and right-continuous.

- Increasing. Consider  $x < y$ . We see that

$$F(x) = \sum_{n; r_n \leq x} \frac{1}{2^n} \leq \sum_{n; r_n \leq y} \frac{1}{2^n} = F(y)$$

clearly.<sup>[28](#)</sup>

- Right-continuous. We want to show  $F(x^+) = F(x)$ . Let  $x^+(\epsilon) := x + \epsilon$  with  $\epsilon > 0$ , we'll show that

$$\lim_{\epsilon \rightarrow 0} F(x^+(\epsilon)) = \lim_{\epsilon \rightarrow 0} F(x + \epsilon) = F(x).$$

Firstly, we have

$$F(x^+(\epsilon)) - F(x) = \sum_{n; r_n \leq x+\epsilon} \frac{1}{2^n} - \sum_{n; r_n \leq x} \frac{1}{2^n} = \sum_{n; x < r_n \leq x+\epsilon} \frac{1}{2^n},$$

and we want to show

$$\lim_{\epsilon \rightarrow 0} F(x^+(\epsilon)) - F(x) = \lim_{\epsilon \rightarrow 0} \sum_{n; x < r_n \leq x+\epsilon} \frac{1}{2^n} = 0.$$

Before we show how we choose  $\epsilon$ ,<sup>[30](#)</sup> we see that

$$\sum_{n=k}^{\infty} \frac{1}{2^n} = 2^{1-k}.$$

<sup>28</sup>This is trivial since we're always going to sum more strictly positive terms in  $F(y)$  than in  $F(x)$ .

<sup>29</sup>The strict is crucial to show the result, since if  $x = r_k$  for some fixed  $k$ , then we can't make the summation arbitrarily small.

<sup>30</sup>To be precise, how  $\epsilon$  depends on  $r_n$ .

Now, we observe that

$$\sum_{n; x < r_n \leq x + \epsilon} \frac{1}{2^n} \leq \sum_{n = \arg \min_k x < r_k \leq x + \epsilon}^{\infty} \frac{1}{2^n} = 2^{1-k}.$$

With this observation, it should be fairly easy to see that we can choose  $\epsilon$  based on how small we want to make  $2^{1-k}$  be,<sup>31</sup> and we indeed see that

$$\lim_{k \rightarrow \infty} 2^{1-k} = 0,$$

which implies that  $F$  is right-continuous by squeeze theorem. ■

**Lemma A.2.** The function  $F$  defined in [this example](#) satisfies

- $\mu_F(\{r_i\}) > 0$  for all  $r_i \in \mathbb{Q}$ .
- $\mu_F(\mathbb{R} \setminus \mathbb{Q}) = 0$

given in [this example](#).

*Proof.* We prove them one by one. And notice that  $F$  is indeed a distribution function as we proved in [Lemma A.1](#).

1. To show  $\mu_F(\{r\}) > 0$  for every  $r \in \mathbb{Q}$ , we first note that

$$\{r\} = \bigcap_{a-1 \leq x < r} (x, r].$$

Then, we see that

$$\mu_F(\{r\}) = \mu_F \left( \bigcap_{a-1 \leq x < a} (x, r] \right),$$

where each  $(x, r] \in \mathcal{A}$  and  $(x, r] \supset (y, r]$  whenever  $r - 1 \leq x \leq y < r$ . Notice that we implicitly assign the order of the index by the order of  $x$ . Then, we see that  $\mu_F(r - 1, r] < \infty$ .<sup>32</sup> Then, from [continuity from above](#), we see that

$$\mu_F(\{r\}) = \lim_{i \rightarrow \infty} \mu_F((x_i, r]),$$

where we again implicitly assign an order to  $x$  as the usual order on  $\mathbb{R}$  by given index  $i$ . It's then clear that as  $i \rightarrow \infty$ ,  $x_i \rightarrow r$ . From the definition of  $F$ , we see that

$$F((x_i, r]) = F(r) - F(x_i) = \sum_{n; r_n \leq r} \frac{1}{2^n} - \sum_{n; r_n \leq x_i} \frac{1}{2^n} = \sum_{n; x_i < r_n \leq r} \frac{1}{2^n}.$$

<sup>31</sup>We're referring to  $\epsilon - \delta$  proof approach.

<sup>32</sup>This will be  $\mu(A_1)$  in the condition of [continuity from above](#). Furthermore, since  $\mathbb{Q}$  is countable, hence  $F(x) < \infty$  is promised.

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It's then clear that since  $r \in \mathbb{Q}$ , there exists an  $i'$  such that  $r_{i'} = r$ . Then, we immediately see that no matter how close  $x_i \rightarrow r$ , this sum is at least

$$\frac{1}{2^{i'}}$$

for a fixed  $i'$ . Hence, we conclude that  $\mu_F(\{r\}) > 0$  for every  $r \in \mathbb{Q}$ .

2. Now, we show  $\mu_F(\mathbb{R} \setminus \mathbb{Q}) = 0$ . Firstly, we claim that

$$\mu_F(\mathbb{Q}) = 1$$

and

$$\mu_F(\mathbb{R}) = 1$$

as well. Since  $\mu_F(\mathbb{Q}) = 1$  is clear, we note that the second one essentially follows from the fact that we can write

$$\mathbb{R} = \lim_{N \rightarrow \infty} \bigcup_{i=1}^N (a - i, a + i]$$

for any  $a \in \mathbb{R}$ , say 0. From [continuity from below](#), we have

$$\mu_F\left(\bigcup_{i=1}^{\infty} (-i, +i]\right) = \lim_{n \rightarrow \infty} \mu_F((-n, n]) = \sum_{n; r_n \in \mathbb{Q}} \frac{1}{2^n} = 1.$$

Given the above, from countable additivity of  $\mu_F$ , we have

$$\mu_F(\mathbb{R} \setminus \mathbb{Q}) + \underbrace{\mu_F(\mathbb{Q})}_1 = \underbrace{\mu_F(\mathbb{R})}_1 \implies \mu_F(\mathbb{R} \setminus \mathbb{Q}) = 0$$

as we desired. ■

**Lemma A.3 (Cantor set has measure 0).** Let  $C$  denotes the [middle thirds Cantor set](#), then the [Lebesgue measure](#) of  $C$  is 0. i.e.,

$$m(C) = 0.$$

*Proof.* Since we're removing  $\frac{1}{3}$  of the whole interval at each  $n$ , we see that the measure of those removing parts, denoted by  $r$ , is

$$m(r) = \sum_{n=1}^{\infty} \frac{2^{n-1}}{3^n} = \frac{1}{2} \sum_{n=1}^{\infty} \left(\frac{2}{3}\right)^n = 1.$$

Then, by [countable additivity](#) of  $m$ , we see that

$$m(C) = m([0, 1]) - m(r) = 1 - 1 = 0. \quad \blacksquare$$

## A.2 Integration

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