

# Notes on Probability Theory

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Fall 2025

The notes are based on the lecture of Prof. David Anderson at University of Wisconsin-Madison in fall 2025. The course structure mainly follows Durrett.

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# 1. Probability Space

## 1.1. Probability Space

### Definition 1.1

Let  $\Omega$  be a set. A collection of subsets  $\mathcal{F}$  forms a  **$\sigma$ -algebra** if

- (a)  $\emptyset \in \mathcal{F}$ .
- (b)  $A \in \mathcal{F}$  implies  $A^c \in \mathcal{F}$ .
- (c) If  $A_i \in \mathcal{F}$  are countably many sets,  $\cup_i A_i \in \mathcal{F}$ .

The dual  $(\Omega, \mathcal{F})$  is called a **measurable space** and the sets falling in  $\mathcal{F}$  are said to be **measurable**.

### Definition 1.2

Let  $(\Omega, \mathcal{F})$  be a measurable space. A set function  $\mu : \mathcal{F} \rightarrow [0, \infty]$  is a **measure** if

- (a)  $\mu(\emptyset) = 0$ .
- (b) For countably many disjoint  $A_i \in \mathcal{F}$ ,  $\mu(\cup_i A_i) = \sum_i \mu(A_i)$ .

The triple  $(\Omega, \mathcal{F}, \mu)$  is called a **measure space**.

### Definition 1.3

A **probability space** is a measure space  $(\Omega, \mathcal{F}, P)$  such that  $P(\Omega) = 1$ .

### Lemma 1.4

Let  $S$  be a collection of sets. Then there exists the smallest  $\sigma$ -algebra containing  $S$ .

*Proof.* Let  $\mathcal{F}$  be the intersection of all  $\sigma$ -algebra containing  $S$ .  $\mathcal{F}$  is non-empty since the power set is a  $\sigma$ -algebra containing  $S$ . Now it is clear that  $\emptyset \in \mathcal{F}$  since  $\emptyset \in \mathcal{A}$  for every  $\sigma$ -algebra  $\mathcal{A}$  containing  $S$ . If  $A \in \mathcal{F}$ ,  $A \in \mathcal{A}$  for all  $\mathcal{A}$  containing  $S$  and  $A^c \in \mathcal{A}$  for all  $\mathcal{A}$ . Thus  $A^c \in \mathcal{F}$ . Finally, if  $A_i \in \mathcal{F}$  are countably many sets, then each  $A_i$  lies in every  $\mathcal{A}$  containing  $S$ ; so does  $\cup_i A_i$  and thus  $\cup_i A_i \in \mathcal{F}$ . The minimality follows by the construction of  $\mathcal{F}$ . ■

### Definition 1.5

For any collection of sets  $S$ , the smallest  $\sigma$ -algebra is denoted as  $\sigma(S)$ .

### Theorem 1.6

Let  $(\Omega, \mathcal{F}, P)$  be a probability space. Then

- (a) If  $A, B \in \mathcal{F}$  and  $A \subset B$ , then  $P(A) \leq P(B)$ .
- (b) For countably many  $A_i \in \mathcal{F}$ ,  $P(\cup_i A_i) \leq \sum_i P(A_i)$ .
- (c) If  $A_i \nearrow A$ ,  $P(A_i) \rightarrow P(A)$ .
- (d) If  $A_i \searrow A$ ,  $P(A_i) \rightarrow P(A)$ .

*Proof.* (a) and (b) are clear. For (c), write  $E_i = A_i - A_{i-1}$  and  $A_0 = \emptyset$ . Then since  $E_i$  are disjoint and  $A_n = \cup_{i=1}^n E_i$ ,

$$P(A_n) = P(\cup_{i=1}^n E_i) = \sum_{i=1}^n P(E_i) \rightarrow \sum_i P(E_i) = P(\cup_i E_i) = P(A)$$

as  $n \rightarrow \infty$ .

For (d), note that  $A_i^c \nearrow A^c$ . Thus  $1 - P(A_i) = P(A_i^c) \rightarrow P(A^c) = 1 - P(A)$ . Thus  $P(A_i) \rightarrow P(A)$ . ■

### Definition 1.7

The **Borel  $\sigma$ -algebra** is the  $\sigma$ -algebra generated by all open sets.

### Definition 1.8

Let  $P$  be a probability measure on  $(\mathbb{R}, \mathcal{B})$ . The **distribution function**  $F$  is defined as

$$F(x) = P((-\infty, x])$$

for  $x \in \mathbb{R}$ .

### Proposition 1.9

The distribution function in  $(\mathbb{R}, \mathcal{B})$  satisfies that

- (a)  $F(x) \leq F(y)$  for all  $x \leq y$ .
- (b)  $F(x) \rightarrow F(y)$  as  $x \rightarrow y^+$ .
- (c)  $F(-\infty) = 0$  and  $F(\infty) = 1$ .

*Proof.* For (a), note that  $(-\infty, x] \subset (-\infty, y]$  and

$$F(x) = P((-\infty, x]) \leq P((-\infty, y]) = F(y).$$

For (b), notice that for  $x_n \rightarrow y^+$ ,  $(-\infty, x_n] \searrow (-\infty, y]$ . Hence

$$F(x_n) = P((-\infty, x_n]) \rightarrow P((-\infty, y]) = F(y).$$

Similarly, taking  $x_n \rightarrow \pm\infty$  gives (c). ■

### Definition 1.10

A collection  $\mathcal{S}$  of sets is called an **algebra** if

- (a)  $\emptyset \in \mathcal{S}$ .
- (b) If  $A \in \mathcal{S}$ , then  $A^c \in \mathcal{S}$ .
- (c) If  $A, B \in \mathcal{S}$ , then  $A \cup B \in \mathcal{S}$ .

### Remark

An algebra is closed under finite unions. It is also clear that a  $\sigma$ -algebra is an algebra, while the converse is not true. An example is the collection of all finite unions of intervals in  $\mathbb{R}$ .

**Definition 1.11**

A collection  $\mathcal{S}$  of sets is called a **semi-algebra** if

- (a) If  $A, B \in \mathcal{S}$ , then  $A \cap B \in \mathcal{S}$ .
- (b) If  $A \in \mathcal{S}$ , then  $A^c$  can be written as a finite disjoint union of sets in  $\mathcal{S}$ .

**Remark**

A semi-algebra must contain  $\emptyset$  since for any  $A \in \mathcal{S}$ ,  $A^c = \cup_i A_i$ , where  $A_i \in \mathcal{S}$  are disjoint. Then  $A \cap A_1 = \emptyset \in \mathcal{S}$ .

**Remark**

An example of being a semi-algebra but not an algebra is the collection of all intervals of the form  $(a_i, b_i]$  for  $-\infty \leq a_i < b_i \leq \infty$  with the empty set.

**Lemma 1.12**

If  $\mathcal{S}$  is a semi-algebra, then  $\overline{\mathcal{S}} = \{\text{finite disjoint unions of sets in } \mathcal{S}\}$  forms an algebra.

*Proof.* It has been shown that  $\emptyset \in \mathcal{S}$ . For  $A, B \in \overline{\mathcal{S}}$ , write  $A = \cup_{i=1}^n A_i$  and  $B = \cup_{j=1}^m B_j$  for disjoint  $A_i, B_j \in \mathcal{S}$ , respectively. Then  $A \cap B = \cup_{i,j} (A_i \cap B_j) \in \overline{\mathcal{S}}$ . Thus  $\overline{\mathcal{S}}$  is closed under intersection. Now if  $A \in \overline{\mathcal{S}}$ ,  $A = \cup_{i=1}^n A_i$  for disjoint  $A_i \in \mathcal{S}$ . Then  $A^c = \cap_{i=1}^n A_i^c$ . By the definition of semi-algebra,  $A_i^c$  can be written as a finite disjoint union of sets in  $\mathcal{S}$  and thus  $A_i^c \in \overline{\mathcal{S}}$ . Since  $\overline{\mathcal{S}}$  is closed under finite intersection,  $A^c = \cap_{i=1}^n A_i^c \in \overline{\mathcal{S}}$ . Finally, for  $A, B \in \overline{\mathcal{S}}$ ,  $A \cup B = (A^c \cap B^c)^c \in \overline{\mathcal{S}}$ . We conclude that  $\overline{\mathcal{S}}$  is indeed an algebra. ■

**Definition 1.13**

Suppose  $\mathcal{S}$  is a semi-algebra.  $\overline{\mathcal{S}} = \{\text{finite disjoint unions of sets in } \mathcal{S}\}$  is called the **algebra generated by  $\mathcal{S}$** .

**Definition 1.14**

Let  $\mathcal{S}$  be an algebra. A set function  $\mu_0 : \mathcal{S} \rightarrow [0, \infty]$  is called a **premeasure** if

- (a)  $\mu_0(\emptyset) = 0$ .
- (b) For countable disjoint  $A_i \in \mathcal{S}$  such that  $\cup_i A_i \in \mathcal{S}$ ,

$$\mu_0(\cup_i A_i) = \sum_i \mu_0(A_i).$$

**Theorem 1.15**

Let  $\nu$  be a set function on a semi-algebra  $\mathcal{S}$  such that  $\nu(\emptyset) = 0$ . Suppose that

- (a) if  $A \in \mathcal{S}$  and  $A = \cup_{i=1}^n A_i$  for disjoint  $A_i \in \mathcal{S}$ , then  $\nu(A) = \sum_{i=1}^n \nu(A_i)$ ;
- (b) if  $A_i \in \mathcal{S}$  are countably many sets and  $A = \cup_i A_i \in \mathcal{S}$ , then  $\nu(A) \leq \sum_i \nu(A_i)$ .

Then  $\nu$  can be extended to a unique premeasure  $\mu_0$  on the algebra generated by  $\mathcal{S}$ .

*Proof.* We first show the existence. From lemma 1.12 we know that  $\mathcal{S}$  generates an algebra  $\mathcal{A} = \{\text{finite disjoint union of sets in } \mathcal{S}\}$ . Define our candidate  $\mu_0$  by  $\mu_0(A) = \sum_i \nu(A_i)$  for

$A = \cup_i A_i$  where  $A_i \in \mathcal{S}$  are disjoint. To see that  $\mu_0$  is well-defined, suppose  $A = \cup_i B_i$  for disjoint  $B_i \in \mathcal{S}$ . Observe that

$$A_i = \cup_j (A_i \cap B_j) \quad \text{and} \quad B_j = \cup_i (A_i \cap B_j)$$

are finite disjoint unions. Then

$$\sum_i \nu(A_i) = \sum_i \sum_j \nu(A_i \cap B_j) = \sum_j \sum_i \nu(A_i \cap B_j) = \sum_j \nu(B_j)$$

by (a). Thus  $\mu_0$  is well-defined.

Now we check that  $\mu_0$  is a premeasure. Clearly  $\mu_0(\emptyset) = 0$ . For finitely many disjoint  $A_i \in \mathcal{A}$  such that  $\cup_i A_i \in \mathcal{A}$ , we can write  $A_i = \cup_j B_{ij}$  for disjoint  $B_{ij} \in \mathcal{S}$ . Then (a) implies that

$$\mu_0(\cup_i A_i) = \mu_0(\cup_{i,j} B_{ij}) = \sum_{i,j} \nu(B_{ij}) = \sum_i \sum_j \mu_0(B_{ij}) = \sum_i \mu_0(A_i).$$

Next, for countably many disjoint  $A_i \in \mathcal{A}$  such that  $A = \cup_i A_i \in \mathcal{A}$ , write  $A_i = \cup_j B_{ij}$ , where  $B_{ij} \in \mathcal{S}$  are finite disjoint for each  $i$ . Then  $\mu_0(A_i) = \sum_j \nu(B_{ij})$  and

$$\sum_i \mu_0(A_i) = \sum_i \sum_j \nu(B_{ij}).$$

Without loss of generality, we may choose  $A_i$  to be those in  $\mathcal{S}$  since otherwise we can replace  $A_i$  by  $B_{ij}$ . We assume that  $A_i \in \mathcal{S}$  from now on. Since  $A \in \mathcal{A}$ ,  $A = \cup_i C_i$  for finite disjoint  $C_i \in \mathcal{S}$ .  $C_i = \cup_j (C_i \cap A_j)$ . Thus (b) gives that

$$\nu(C_i) \leq \sum_j \nu(C_i \cap A_j).$$

Then

$$\mu_0(A) = \sum_i \nu(C_i) \leq \sum_i \sum_j \nu(C_i \cap A_j) = \sum_j \sum_i \nu(C_i \cap A_j) = \sum_j \nu(A_j) = \sum_j \mu_0(A_j).$$

For the opposite inequality, set  $B_n = \cup_{i=1}^n A_i$  and  $C_n = A - B_n$ . Since  $\mathcal{A}$  is an algebra,  $C_n \in \mathcal{A}$  and the finite additivity shows that

$$\mu_0(A) = \sum_{i=1}^n \mu_0(A_i) + \mu_0(C_n) \geq \sum_{i=1}^n \mu_0(A_i).$$

Taking  $n \rightarrow \infty$  gives the desired inequality and thus  $\mu_0$  is  $\sigma$ -additive on  $\mathcal{A}$ .

Finally, if  $\mu_1$  is another premeasure on  $\mathcal{A}$  extending  $\nu$ , then for  $A = \cup_i A_i$  for disjoint  $A_i \in \mathcal{S}$ ,

$$\mu_1(A) = \sum_i \nu(A_i) = \mu_0(A).$$

■

**Definition 1.16**

A collection of sets  $\mathcal{P}$  is called a  $\pi$ -**system** if  $A, B \in \mathcal{P}$  implies  $A \cap B \in \mathcal{P}$ .

**Definition 1.17**

A collection of sets  $\mathcal{L}$  is called a  $\lambda$ -**system** if

- (a)  $\Omega \in \mathcal{L}$ .
- (b) If  $A, B \in \mathcal{L}$  and  $A \subset B$ , then  $B - A \in \mathcal{L}$ .
- (c) If  $A_i \in \mathcal{L}$  and  $A_i \nearrow A$ , then  $A \in \mathcal{L}$ .

**Theorem 1.18** (Sierpiński-Dynkin  $\pi$ - $\lambda$ )

If  $\mathcal{P}$  is a  $\pi$ -system and  $\mathcal{L}$  is a  $\lambda$ -system containing  $\mathcal{P}$ , then  $\sigma(\mathcal{P}) \subset \mathcal{L}$ .

*Proof.* First we show that a collection  $\mathcal{S}$  is a  $\sigma$ -algebra if and only if it is both a  $\pi$ -system and a  $\lambda$ -system. Suppose first that  $\mathcal{S}$  is a  $\pi$ -system and a  $\lambda$ -system.  $\emptyset = \Omega - \Omega \in \mathcal{S}$ . If  $A \in \mathcal{S}$ , then  $A^c = \Omega - A \in \mathcal{S}$ . For  $A, B \in \mathcal{S}$ ,  $A \cup B = (A^c \cap B^c)^c \in \mathcal{S}$  since we have shown that  $\mathcal{S}$  is closed under complement and intersection by being a  $\pi$ -system. Thus  $\mathcal{S}$  is also closed under finite unions. If  $A_i \in \mathcal{S}$  are countably many sets, let  $B_n = \cup_{i=1}^n A_i \in \mathcal{S}$ . Then  $B_n \nearrow \cup_i A_i$  and thus  $\cup_i A_i \in \mathcal{S}$ .

Conversely, if  $\mathcal{S}$  is a  $\sigma$ -algebra, then for  $A, B \in \mathcal{S}$ ,  $A \cap B = (A^c \cup B^c)^c \in \mathcal{S}$ . Thus  $\mathcal{S}$  is a  $\pi$ -system. If  $A, B \in \mathcal{S}$  and  $A \subset B$ , then  $B - A = B \cap A^c \in \mathcal{S}$ . Finally, if  $A_i \in \mathcal{S}$  and  $A_i \nearrow A$ , then  $A = \cup_i (A_i - A_{i-1}) \in \mathcal{S}$  with  $A_0 = \emptyset$ . Thus  $\mathcal{S}$  is a  $\lambda$ -system.

Now set  $\mathcal{L}$  to be the smallest  $\lambda$ -system containing  $\mathcal{P}$ . It suffices to show that  $\mathcal{L}$  is also a  $\pi$ -system and thus by the above conclusion,  $\mathcal{L}$  is a  $\sigma$ -algebra containing  $\mathcal{P}$ ; hence  $\sigma(\mathcal{P}) \subset \mathcal{L}$ .

To show that  $\mathcal{L}$  is a  $\pi$ -system, let  $A, B \in \mathcal{L}$ . If  $A, B \in \mathcal{P}$ ,  $A \cap B \in \mathcal{P} \subset \mathcal{L}$ . To extend the result for general  $A, B \in \mathcal{L}$ , we first fix  $B \in \mathcal{P}$  and define

$$\mathcal{L}_B = \{A \mid A \cap B \in \mathcal{L}\}.$$

We claim that  $\mathcal{L}_B$  is a  $\lambda$ -system containing  $\mathcal{P}$ . For  $A \in \mathcal{P}$ ,  $A \cap B \in \mathcal{L}$ . Thus  $\mathcal{P} \subset \mathcal{L}_B$ . Clearly  $\Omega \in \mathcal{L}_B$ . If  $E, F \in \mathcal{L}_B$  and  $E \subset F$ , then

$$(F - E) \cap B = (F \cap B) - (E \cap B) \in \mathcal{L}.$$

Thus  $F - E \in \mathcal{L}_B$ . Finally, if  $E_i \in \mathcal{L}_B$  and  $E_i \nearrow E$ , then

$$E \cap B = \cup_i (E_i \cap B) \in \mathcal{L}.$$

Hence  $E \in \mathcal{L}_B$  and we conclude that  $\mathcal{L}_B$  is a  $\lambda$ -system. Since it is a  $\lambda$ -system containing  $\mathcal{P}$ , it also contains the smallest  $\lambda$ -system  $\mathcal{L}$  with the intersection property. Thus  $A \cap B \in \mathcal{L}$  whenever  $A \in \mathcal{L}$  and  $B \in \mathcal{P}$ .

Next, fix  $A \in \mathcal{L}$  and define  $\mathcal{L}_A = \{B \mid A \cap B \in \mathcal{L}\}$ . Clearly  $\mathcal{L}_A$  contains  $\mathcal{L}$  and  $\Omega \in \mathcal{L}_A$ . If  $E, F \in \mathcal{L}_A$  and  $E \subset F$ , then

$$(F - E) \cap A = (F \cap A) - (E \cap A) \in \mathcal{L}.$$

Thus  $F - E \in \mathcal{L}_A$ . Finally, if  $E_i \in \mathcal{L}_A$  and  $E_i \nearrow E$ , then

$$E \cap A = \cup_i (E_i \cap A) \in \mathcal{L}.$$

Hence  $E \in \mathcal{L}_A$  and we conclude that  $\mathcal{L}_A$  is a  $\lambda$ -system. Since it contains  $\mathcal{L}$ ,  $A, B \in \mathcal{L}$  implies  $A \cap B \in \mathcal{L}$ ; in other words,  $\mathcal{L}$  is a  $\pi$ -system and the proof is complete. ■

### Corollary 1.19

Let  $\mu$  and  $\nu$  be two probability measures agreeing on a  $\pi$ -system  $\mathcal{P}$ , i.e.,  $\mu(A) = \nu(A)$  for all  $A \in \mathcal{P}$ . Then  $\mu(A) = \nu(A)$  for all  $A \in \sigma(\mathcal{P})$ .

*Proof.* Put

$$\mathcal{L} = \{A \mid \mu(A) = \nu(A)\}.$$

We claim that  $\mathcal{L}$  is a  $\lambda$ -system containing  $\mathcal{P}$ . It is clear that by our assumption,  $\mathcal{P} \subset \mathcal{L}$  and  $\Omega \in \mathcal{L}$ . If  $A, B \in \mathcal{L}$  and  $A \subset B$ , then

$$\mu(B - A) = \mu(B) - \mu(A) = \nu(B) - \nu(A) = \nu(B - A).$$

Thus  $B - A \in \mathcal{L}$ . Finally, if  $A_i \in \mathcal{L}$  and  $A_i \nearrow A$ , then

$$\mu(A) = \lim_{i \rightarrow \infty} \mu(A_i) = \lim_{i \rightarrow \infty} \nu(A_i) = \nu(A).$$

Hence  $A \in \mathcal{L}$  and we conclude that  $\mathcal{L}$  is a  $\lambda$ -system. By the Sierpiński-Dynkin  $\pi$ - $\lambda$  theorem,  $\sigma(\mathcal{P}) \subset \mathcal{L}$ ; in other words,  $\mu$  and  $\nu$  agree on  $\sigma(\mathcal{P})$ . ■

### Definition 1.20

A measure  $\mu$  on a measurable space  $(\Omega, \mathcal{F})$  is called  **$\sigma$ -finite** if there exists countable  $A_i \in \mathcal{F}$  such that  $\cup_i A_i = \Omega$  and  $\mu(A_i) < \infty$ .

### Definition 1.21

A set function  $\mu^* : 2^\Omega \rightarrow [0, \infty]$  is called an **outer measure** if

- (a)  $\mu^*(\emptyset) = 0$ .
- (b) If  $A \subset B$ , then  $\mu^*(A) \leq \mu^*(B)$ .
- (c) For countably many  $A_i \subset \Omega$ ,  $\mu^*(\cup_i A_i) \leq \sum_i \mu^*(A_i)$ .

### Definition 1.22

Let  $\mu^*$  be an outer measure. A set  $A \subset \Omega$  is said to be **Carathéodory measurable** or  $\mu^*$ -



**measurable** if for all  $E \subset \Omega$ ,

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

**Lemma 1.23**

Let  $\mu^*$  be an outer measure on  $\Omega$ . Then the collection of all  $\mu^*$ -measurable sets forms a  $\sigma$ -algebra  $\mathcal{F}$  and  $\mu^*|_{\mathcal{F}}$  is a measure.

*Proof.* Put

$$\mathcal{F} = \{A \subset \Omega \mid \mu^*(E) = \mu^*(E \cap A) + \mu^*(E \cap A^c) \text{ for all } E \subset \Omega\}.$$

We first show that  $\mathcal{F}$  is a  $\sigma$ -algebra. Clearly  $\emptyset \in \mathcal{F}$  and if  $A \in \mathcal{F}$ , then  $A^c \in \mathcal{F}$ . For  $A, B \in \mathcal{F}$ , let  $C = A \cup B$ . The property of outer measure gives that  $\mu^*(E) \leq \mu^*(E \cap C) + \mu^*(E \cap C^c)$ . To see the opposite inequality, note that  $C = A \cup (B \cap A^c)$  and

$$\begin{aligned} \mu^*(E \cap C) + \mu^*(E \cap C^c) &\leq \mu^*(E \cap A) + \mu^*(E \cap B \cap A^c) + \mu^*(E \cap A^c \cap B^c) \\ &= \mu^*(E \cap A) + \mu^*(E \cap A^c) = \mu^*(E). \end{aligned}$$

Hence  $C \in \mathcal{F}$  and  $\mathcal{F}$  is closed under finite unions. For countable disjoint  $A_i \in \mathcal{F}$  with  $A = \cup_i A_i$ , let  $B_n = \cup_{i=1}^n A_i \in \mathcal{F}$ . Then

$$\mu^*(E \cap A) = \mu^*(E \cap B_n) + \mu^*(E \cap B_n^c) \geq \mu^*(E \cap B_n) = \sum_{i=1}^n \mu^*(E \cap A_i).$$

Taking  $n \rightarrow \infty$  gives that

$$\mu^*(E \cap A) \geq \sum_i \mu^*(E \cap A_i) \geq \mu^*(E \cap A)$$

by the  $\sigma$ -subadditivity of outer measure. Hence  $\mu^*(E \cap A) = \sum_i \mu^*(E \cap A_i)$ . Note also that  $E \cap A^c \subset E \cap B_n^c$  so  $\mu^*(E \cap A^c) \leq \mu^*(E \cap B_n^c)$ . Thus

$$\mu^*(E) = \mu^*(E \cap B_n) + \mu^*(E \cap B_n^c) \geq \sum_{i=1}^n \mu^*(E \cap A_i) + \mu^*(E \cap A^c) \rightarrow \mu^*(E \cap A) + \mu^*(E \cap A^c) \geq \mu^*(E)$$

by the  $\sigma$ -subadditivity of outer measure. We conclude that  $\mathcal{F}$  is a  $\sigma$ -algebra.

Finally, denote  $\mu^*|_{\mathcal{F}}$  by  $\mu$ . Clearly  $\mu(\emptyset) = 0$ . For countably many disjoint  $A_i \in \mathcal{F}$  such that  $A = \cup_i A_i \in \mathcal{F}$ , let  $B_n = \cup_{i=1}^n A_i \in \mathcal{F}$ . Then

$$\mu(A) = \mu(B_n) + \mu(A \cap B_n^c) \geq \mu(B_n) = \sum_{i=1}^n \mu(A_i) \rightarrow \sum_i \mu(A_i) \geq \mu(A).$$

Hence  $\mu(A) = \sum_i \mu(A_i)$  and  $\mu$  is a measure on  $\mathcal{F}$ . ■

**Theorem 1.24** (Carathéodory Extension)

Let  $\nu$  be a finitely additive,  $\sigma$ -subadditive set function on a semi-algebra  $\mathcal{S}$  such that  $\nu(\emptyset) = 0$ . Then  $\nu$  can be extended to a measure on  $\sigma(\mathcal{S})$ .

*Proof.* By [theorem 1.15](#),  $\nu$  can be extended to a premeasure  $\mu_0$  on the algebra  $\mathcal{A}$  generated by  $\mathcal{S}$ . Define the outer measure by

$$\mu^*(A) = \inf \left\{ \sum_i \mu_0(E_i) \mid A \subset \cup_i E_i, E_i \in \mathcal{A} \right\}$$

for all  $A \subset \Omega$  with the convention that  $\inf \emptyset = \infty$ . We check that  $\mu^*$  is indeed an outer measure. Clearly  $\mu^*(\emptyset) = 0$ . If  $A \subset B$ , then any cover of  $B$  by sets in  $\mathcal{A}$  is also a cover of  $A$  and hence  $\mu^*(A) \leq \mu^*(B)$ . For countably many  $A_i \subset \Omega$ , we can find  $\{E_{ij}\}_j$  covering  $A_i$  such that

$$\sum_j \mu_0(E_{ij}) \leq \mu^*(A_i) + 2^{-i}\epsilon$$

for some  $\epsilon > 0$ . Then  $\cup_{i,j} E_{ij}$  covers  $\cup_i A_i$  and

$$\mu^*(\cup_i A_i) \leq \sum_i \sum_j \mu_0(E_{ij}) \leq \sum_i \mu^*(A_i) + \epsilon.$$

Since  $\epsilon$  is arbitrary, we conclude that  $\mu^*(\cup_i A_i) \leq \sum_i \mu^*(A_i)$  and  $\mu^*$  is indeed an outer measure.

It follows from [lemma 1.23](#) that the collection of all  $\mu^*$ -measurable sets forms a  $\sigma$ -algebra  $\mathcal{F}$  and  $\mu^*$  restricted on  $\mathcal{F}$  is a measure. It is clear that  $\mathcal{A} \subset \mathcal{F}$  and  $\sigma(\mathcal{S}) \subset \sigma(\mathcal{A}) \subset \mathcal{F}$  and  $\mu = \mu^*|_{\sigma(\mathcal{S})}$  is also a measure. Finally, for  $A, A_i \in \mathcal{S}$  where  $A_i$  covers  $A$ ,

$$\mu(A) = \mu^*(A) \leq \nu(A) \leq \sum_i \nu(A \cap A_i) \leq \sum_i \nu(A_i).$$

Taking the infimum over all such covers, we get  $\nu(A) = \mu^*(A)$  and  $\mu$  is indeed an extension of  $\nu$ . ■

**Remark**

If the measures are probability measures, then we have that the extension is unique by [corollary 1.19](#).

**Theorem 1.25**

If  $F$  is non-decreasing, right-continuous and satisfies that  $F(-\infty) = 0$ ,  $F(\infty) = 1$ , then there is a unique probability measure such that

$$P((-\infty, x]) = F(x).$$

*Proof.* Define

$$\mathcal{S} = \{(a, b] \mid -\infty \leq a < b \leq \infty\} \cup \{\emptyset\}.$$

It is clear that  $\mathcal{S}$  is a semi-algebra. Define the set function  $P : \mathcal{S} \rightarrow [0, 1]$  by

$$P((a, b]) = F(b) - F(a)$$

and  $P(\emptyset) = 0$ . For disjoint, at most countable  $(a_i, b_i] \in \mathcal{S}$ , we define

$$P(\cup_i (a_i, b_i]) = \sum_i P((a_i, b_i]) = \sum_i F(b_i) - F(a_i).$$

It is clear that  $P$  is finitely additive. If  $(a, b] = \cup_i (a_i, b_i]$  for disjoint  $(a_i, b_i] \in \mathcal{S}$ , we may assume without loss of generality that  $a = a_1 < b_1 < b_2 < \cdots < b_n = b$  and

$$P((a, b]) = F(b) - F(a) = \sum_i F(b_i) - F(a_i) = \sum_i P((a_i, b_i]).$$

Hence  $P$  is  $\sigma$ -additive. It now follows from the Carathéodory extension theorem that  $P$  can be extended uniquely to a probability measure on  $\sigma(\mathcal{S}) = \mathcal{B}$ . ■

**Remark**

*This theorem shows that the distribution function completely characterizes the probability measure. In other words, the term “distribution function” can refer to either the CDF or the probability measure.*

## 1.2. Random Variable

### Definition 1.26

Let  $\Omega$  be a probability space. A **random variable**  $X$  is a measurable function  $X : \Omega \rightarrow (S, \mathcal{S})$ , where  $(S, \mathcal{S})$  is a measurable space.

### Remark

The codomain is often taken to be  $(\mathbb{R}, \mathcal{B})$  or  $(\mathbb{R}^d, \mathcal{B}(\mathbb{R}^d))$ , but it is also possible to define random functions, i.e.,  $(S, \mathcal{S})$  is a function space.

### Definition 1.27

Let  $X : (\Omega, \mathcal{F}) \rightarrow (S, \mathcal{S})$  be a random variable. The **distribution** of  $X$  is the pushforward measure of  $\mathbb{P}$  under  $X$ , i.e.,

$$\mu_X(A) = \mathbb{P}(X \in A) = \mathbb{P}(X^{-1}(A)), \quad A \in \mathcal{S}.$$

### Definition 1.28

Let  $X : (\Omega, \mathcal{F}) \rightarrow (\mathbb{R}^d, \mathcal{B})$  be a random variable. The **cumulative distribution function** of  $X$  is defined as

$$F_X(x) = \mathbb{P}(X \leq x) = \mathbb{P}(X_1 \leq x_1, \dots, X_d \leq x_d), \quad x = (x_1, \dots, x_d) \in \mathbb{R}^d.$$

### Proposition 1.29

Let  $X : (\Omega, \mathcal{F}) \rightarrow (\mathbb{R}, \mathcal{B})$  be a random variable and  $F$  be its cumulative distribution function. Then,

- (a)  $F$  is non-decreasing, i.e.,  $x \leq y$  implies  $F(x) \leq F(y)$ ;
- (b)  $F(-\infty) = 0$  and  $F(\infty) = 1$ ;
- (c)  $F$  is right-continuous, i.e.,  $\lim_{y \rightarrow x^+} F(y) = F(x)$ ;
- (d)  $F(x^-) = \mathbb{P}(X < x)$ ;
- (e)  $\mathbb{P}(X = x) = F(x) - F(x^-)$ .

*Proof.* (a) comes from that  $\{X \leq x\} \subset \{X \leq y\}$  for  $x \leq y$ .

Take  $a_n \rightarrow \infty$ . Then  $\{X \leq a_n\} \nearrow \Omega$  and  $\{X \leq -a_n\} \searrow \emptyset$ . By [theorem 1.6](#), we have that

$$F(a_n) = \mathbb{P}(X \leq a_n) \rightarrow \mathbb{P}(\Omega) = 1, \quad F(-a_n) = \mathbb{P}(X \leq -a_n) \rightarrow \mathbb{P}(\emptyset) = 0.$$

(c) is similar to (b). Take  $y_n \rightarrow x^+$ , then  $\{X \leq y_n\} \searrow \{X \leq x\}$ . By [theorem 1.6](#), we have that

$$F(y_n) = \mathbb{P}(X \leq y_n) \rightarrow \mathbb{P}(X \leq x) = F(x).$$

For (d), take  $x_n \rightarrow x^-$ , then  $\{X \leq x_n\} \nearrow \{X < x\}$ . By [theorem 1.6](#), we have that

$$F(x_n) = \mathbb{P}(X \leq x_n) \rightarrow \mathbb{P}(X < x).$$

For (e),  $P(X = x) = P(X \leq x) - P(X < x) = F(x) - F(x^-)$ . ■

**Theorem 1.30**

Let  $F$  be a non-decreasing, right-continuous function satisfying that  $F(-\infty) = 0$  and  $F(\infty) = 1$ . Then there is a random variable  $X$  such that

$$F(x) = \mu_X((-\infty, x]).$$

*Proof.* Put  $\Omega = (0, 1)$ ,  $\mathcal{F} = \mathcal{B}$ ,  $P$  be the Lebesgue measure and  $X(\omega) = \sup \{x \mid F(x) < \omega\}$ . Notice that

$$\begin{aligned} \{X \leq x\} &= \{\omega \in \Omega \mid \sup \{y \mid F(y) < \omega\} \leq x\} \\ &= \{\omega \in \Omega \mid \text{for all } y > x, F(y) \geq \omega\} \\ &= \{\omega \in \Omega \mid F(x) \geq \omega\}. \end{aligned}$$

Hence  $P(X \leq x) = P(\{\omega \in \Omega \mid \omega \leq F(x)\}) = F(x)$ . ■

**Definition 1.31**

If  $X$  and  $Y$  are random variables mapping to some measurable space  $(S, \mathcal{S})$ , then  $X$  and  $Y$  are said to be **equal in distribution** if  $\mu_X = \mu_Y$ , denoted by  $X \stackrel{d}{=} Y$ .

**Definition 1.32**

Let  $X : \Omega \rightarrow \mathbb{R}$  be a random variable with distribution  $F$ .  $f : \mathbb{R} \rightarrow \mathbb{R}$  is said to be the **density** of  $X$  if

$$F(x) = \int_{-\infty}^x f(y) dy$$

for all  $x \in \mathbb{R}$ .

**Remark**

If  $f$  and  $g$  are both densities of  $X$ , then  $f = g$  a.e.

**Remark**

If  $\mu_X \ll \lambda$ , where  $\lambda$  is the Lebesgue measure, then by Radon-Nikodym theorem, there is a density  $f$  such that

$$\mu_X(A) = \int_A f(x) d\lambda(x)$$

for all  $A \in \mathcal{B}$ . Or equivalently,  $F$  is absolutely continuous.

**Example**

Not all random variables have densities, even when its CDF is continuous. Consider the

*Cantor function*

$$F(x) = \begin{cases} \sum_n \frac{a_n}{2^n}, & x = \sum_n \frac{2a_n}{3^n} \in C \text{ for some } \{a_n\} \in \{0, 1\}^{\mathbb{N}} \\ \sup_{y \leq x, y \in C} F(y), & x \in [0, 1] - C \\ 0, & x < 0 \\ 1, & x > 1 \end{cases}$$

where  $C$  is the Cantor set. Then  $F$  is a valid CDF, but has no density.

**Definition 1.33**

A probability measure  $P$  is said to be **discrete** if there is a countable set  $S$  such that  $P(S^c) = 0$ . A random variable  $X$  is said to be **discrete** if its distribution is.

**Theorem 1.34**

Suppose  $X : (\Omega, \mathcal{F}) \rightarrow (S, \sigma(\mathcal{A}))$  and  $\mathcal{A}$  is a collection of subsets in  $S$ . If  $X^{-1}(A) \in \mathcal{F}$  for all  $A \in \mathcal{A}$ , then  $X$  is a random variable.

*Proof.* Set  $\mathcal{G} = \{A \subset S \mid X^{-1}(A) \in \mathcal{F}\}$ . Clearly  $\emptyset \in \mathcal{G}$  and if  $A \in \mathcal{G}$ ,  $X^{-1}(A^c) = (X^{-1}(A))^c \in \mathcal{F}$ , so  $A^c \in \mathcal{G}$ . If  $A_n \in \mathcal{G}$ , then  $X^{-1}(\cup_n A_n) = \cup_n X^{-1}(A_n) \in \mathcal{F}$ , so  $\cup_n A_n \in \mathcal{G}$ . Hence  $\mathcal{G}$  is a  $\sigma$ -algebra containing  $\mathcal{A}$ , so  $\sigma(\mathcal{A}) \subset \mathcal{G}$ . It follows that  $X^{-1}(B) \in \mathcal{F}$  for all  $B \in \sigma(\mathcal{A})$ , so  $X$  is a random variable. ■

**Corollary 1.35**

If  $X_i$  are random variables, then

$$\inf_i X_i, \quad \sup_i X_i, \quad \liminf_{i \rightarrow \infty} X_i, \quad \limsup_{i \rightarrow \infty} X_i$$

are all random variables.

*Proof.* Since the sets of the form  $(-\infty, x]$  generate  $\mathcal{B}$ , it suffices to check that the inverse images of these sets are in  $\mathcal{F}$ . For  $\inf_i X_i$ ,

$$\left\{ \inf_i X_i \leq x \right\} = \cup_i \{X_i \leq x\} \in \mathcal{F}.$$

For  $\sup_i X_i$ , since  $\sup_i X_i = -\inf_i (-X_i)$ , it is also a random variable. Finally, write

$$\liminf_i X_i = \sup_n \inf_{i \geq n} X_i, \quad \limsup_i X_i = \inf_n \sup_{i \geq n} X_i.$$

The results follow from the measurability of  $\inf_i X_i$  and  $\sup_i X_i$ . ■

**Definition 1.36**

Let  $X$  be a random variable.  $\sigma(X)$  is the smallest  $\sigma$ -algebra such that  $X$  is measurable.

**Remark**

If  $X : \Omega \rightarrow (S, \mathcal{S})$ , then  $\sigma(X) = X^{-1}(\mathcal{S})$ .

**Definition 1.37**

Let  $X$  be a random variable. The **expectation** of  $X$  is defined as

$$\mathbf{E}[X] = \int X d\mathbf{P}.$$

**Theorem 1.38** (Jensen's Inequality)

Let  $X : \Omega \rightarrow \mathbb{R}^d$  be a random variable such that  $\mathbf{E}[\|X\|_1] < \infty$  and  $\phi : \mathbb{R}^d \rightarrow \mathbb{R}$  be a convex function. Then

$$\phi(\mathbf{E}[X]) \leq \mathbf{E}[\phi(X)].$$

*Proof.* For any given  $y \in \mathbb{R}^d$ , note that  $\{x \in \mathbb{R}^d \mid \phi(x) > \phi(y)\}$  is a open convex set. By the Hahn-Banach separation theorem, there is a hyperplane  $\{f(x) = a + \langle b, x \rangle\}$  separating  $\{(x, \phi(x)) \in \mathbb{R}^{d+1} \mid \phi(x) > \phi(y)\}$  and  $\{(y, \phi(y))\}$ . Note that  $\phi(y) = f(y)$  and  $\phi(x) \geq f(x)$  for all  $x \in \mathbb{R}^d$ . Take  $y = \mathbf{E}[X]$ , then

$$\phi(\mathbf{E}[X]) = f(\mathbf{E}[X]) = \mathbf{E}[f(X)] \leq \mathbf{E}[\phi(X)].$$

■

**Theorem 1.39** (Hölder's Inequality)

Let  $X, Y$  be random variables and  $p, q \in [1, \infty]$  such that  $\frac{1}{p} + \frac{1}{q} = 1$ . Then

$$\mathbf{E}[|XY|] \leq \mathbf{E}[|X|^p]^{1/p} \mathbf{E}[|Y|^q]^{1/q}.$$

*Proof.* If  $\mathbf{E}[|X|^p]$  and  $\mathbf{E}[|Y|^q]$  are zero or infinite, the result is trivial. We assume that  $\mathbf{E}[|X|^p] = \mathbf{E}[|Y|^q] = 1$ . For fixed  $y \geq 0$ , set  $\phi(x) = x^p/p + y^p/p - xy$  for  $x \geq 0$ .

$$\phi'(x) = x^{p-1} - y, \quad \phi''(x) = (p-1)x^{p-2} \geq 0.$$

Thus  $\phi$  is convex and minimized at  $x = y^{1/(p-1)}$  with minimum  $\phi(y^{1/(p-1)}) = 0$ . Hence  $x^p/p + y^q/q \geq xy$  for all  $x, y \geq 0$ .

$$\mathbf{E}[|XY|] \leq \mathbf{E}\left[\frac{|X|^p}{p} + \frac{|Y|^q}{q}\right] = \frac{1}{p} + \frac{1}{q} = 1 = \mathbf{E}[|X|^p]^{1/p} \mathbf{E}[|Y|^q]^{1/q}.$$

■

**Theorem 1.40** (Markov's Inequality)

If  $X \geq 0$  is a random variable, then for any  $c > 0$ ,

$$\mathbf{P}(X \geq c) \leq \frac{1}{c} \mathbf{E}[X].$$

*Proof.*

$$\mathbf{P}(X \geq c) = \int \mathbf{1}_{\{X \geq c\}} d\mathbf{P} \leq \int \frac{X}{c} d\mathbf{P} = \frac{1}{c} \mathbf{E}[X].$$

■

**Example**

Suppose  $\phi : \mathbb{R} \rightarrow \mathbb{R}$  is a non-negative function. Put

$$I_A = \inf_{y \in A} \phi(y),$$

where  $A$  is some measurable set. Then for any random variable  $X$ ,

$$I_A \mathbf{1}_{\{X \in A\}} \leq \phi(X) \mathbf{1}_{\{X \in A\}} \leq \phi(X).$$

Thus

$$I_A \mathbb{P}(X \in A) \leq \mathbb{E}[\phi(X)].$$

**Corollary 1.41** (Chebyshev's Inequality)

Let  $X$  be a random variable. Then for any  $c > 0$  and  $\alpha \in \mathbb{R}$ ,

$$\mathbb{P}(|X - \alpha| \geq c) \leq \frac{1}{c^2} \mathbb{E}[(X - \alpha)^2].$$

*Proof.* By the Markov's inequality,

$$\mathbb{P}(|X - \alpha| \geq c) = \mathbb{P}((X - \alpha)^2 \geq c^2) \leq \frac{1}{c^2} \mathbb{E}[(X - \alpha)^2].$$

■

**Theorem 1.42**

Suppose  $X$  is a random variable of  $(S, \mathcal{S})$  with distribution  $\mu$  and  $f : (S, \mathcal{S}) \rightarrow (\mathbb{R}, \mathcal{B})$  is measurable. If either

- (a)  $f \geq 0$ , or
- (b)  $\mathbb{E}[|f(X)|] < \infty$ ,

then

$$\mathbb{E}[f(X)] = \int f(x) d\mu(x).$$

*Proof.* Suppose first that  $f = \mathbf{1}_A$  for some  $A \in \mathcal{S}$ . Then

$$\mathbb{E}[f(X)] = \mathbb{P}(X \in A) = \mathbb{P}(X^{-1}(A)) = \mu(A) = \int \mathbf{1}_A d\mu.$$

By linearity we can extend this result to simple functions. Now suppose first that (a) holds. For such  $f$ , there is a sequence of simple functions  $s_n \nearrow f$  and  $s_n \circ X \nearrow f \circ X$ . By LMCT,

$$\mathbb{E}[f(X)] = \mathbb{E}\left[\lim_n s_n(X)\right] = \lim_n \mathbb{E}[s_n(X)] = \lim_n \int s_n d\mu = \int f d\mu.$$



Suppose that (b) is the case. Write  $f = f^+ - f^-$  and apply the previous result.

$$\mathbb{E}[f(X)] = \mathbb{E}[f^+(X)] - \mathbb{E}[f^-(X)] = \int f^+ d\mu - \int f^- d\mu = \int f d\mu.$$

■

**Definition 1.43**

The ***k-th moment*** of a random variable  $X$  is  $\mathbb{E}[X^k]$ .

**Definition 1.44**

The ***variance*** of a random variable  $X$  is  $\text{Var } \mathbb{E}[(X - \mathbb{E}[X])^2]$ .

**Definition 1.45**

The ***covariance*** of two integrable random variables  $X, Y$  is

$$\text{Cov}(X, Y) = \mathbb{E}[(X - \mathbb{E}[X])(Y - \mathbb{E}[Y])].$$

**Definition 1.46**

For  $1 \leq p < \infty$ , the  $\mathcal{L}^p(\Omega, \mathbb{P})$  space is defined as

$$\mathcal{L}^p(\Omega, \mathbb{P}) = \{X : \Omega \rightarrow S \mid X \text{ measurable and } \mathbb{E}[|X|^p] < \infty\}.$$

For  $p = \infty$ ,

$$\mathcal{L}^\infty(\Omega, \mathbb{P}) = \{X : \Omega \rightarrow S \mid X \text{ measurable and } \text{ess sup}_{\omega \in \Omega} X(\omega) < \infty\}.$$

**Proposition 1.47**

Let  $1 \leq p < q \leq \infty$ . Then  $\mathcal{L}^q(\mathbb{P}) \subset \mathcal{L}^p(\mathbb{P})$ .

*Proof.* Suppose first that  $q < \infty$ . If  $X \in \mathcal{L}^q(\mathbb{P})$ , then

$$\mathbb{E}[|X|^p] \leq \mathbb{E}[|X|^q \mathbf{1}_{\{|X| \geq 1\}}] + \mathbb{E}[|X|^p \mathbf{1}_{\{|X| < 1\}}] \leq \mathbb{E}[|X|^q] + 1 < \infty.$$

Hence  $X \in \mathcal{L}^p(\mathbb{P})$ . If  $q = \infty$ ,  $X$  is essentially bounded, i.e.,  $X \leq M$  for some  $M \in \mathbb{R}$  almost surely. Hence  $X \in \mathcal{L}^p$ . ■

### 1.3. Independence

#### Definition 1.48

Let  $(\Omega, \mathcal{F}, P)$  be a probability space. Suppose  $\mathcal{F}_\beta \subset \mathcal{F}$ ,  $\beta \in B$  are a collection of sub- $\sigma$ -algebras. Then  $\{\mathcal{F}_\beta\}$  are **independent** if for all finite  $\{\mathcal{F}_i\}_{i=1}^n \subset \{\mathcal{F}_\beta\}$ ,

$$P(\cap_{i=1}^n A_i) = \prod_{i=1}^n P(A_i)$$

where  $A_i \in \mathcal{F}_i$ .

#### Definition 1.49

A collection of random variables  $\{X_\beta \mid \beta \in B\}$  on  $(\Omega, \mathcal{F}, P)$  is **independent** if the collection of the generating  $\sigma$ -algebras  $\{\sigma(X_\beta) \mid \beta \in B\}$  is.

#### Remark

In other words,

$$P(\cap_i \{X_{\beta_i} \in A_i\}) = \prod_i P(X_{\beta_i} \in A_i).$$

Note that these random variables can map into different measurable space.

#### Definition 1.50

A collection of events  $\mathcal{S}$  is **independent** if  $\{1_A \mid A \in \mathcal{S}\}$  is.

#### Proposition 1.51

Let  $X_1, \dots, X_n$  be independent random variables and  $g_1, \dots, g_n$  are measurable functions. Then  $g_1(X_1), \dots, g_n(X_n)$  are independent.

*Proof.* Suppose  $g_i : (S_i, \mathcal{S}_i) \rightarrow (T_i, \mathcal{T}_i)$ . For  $A_i \in \mathcal{T}_i$ ,  $g_i^{-1}(A_i) \in \mathcal{S}_i$  and

$$P(\cap_i \{g_i(X_i) \in A_i\}) = P(\cap_i \{X_i \in g_i^{-1}(A_i)\}) = \prod_i P(X_i \in g_i^{-1}(A_i)) = \prod_i P(g_i(X_i) \in A_i).$$

$g_1(X_1), \dots, g_n(X_n)$  are independent. ■

#### Theorem 1.52

Let  $\mathcal{S}_1, \dots, \mathcal{S}_n$  be a collection of  $\pi$ -system. If  $\Omega \in \mathcal{S}_i$  for all  $i = 1, \dots, n$  and for all  $A_i \in \mathcal{S}_i$ ,

$$P(\cap_i A_i) = \prod_i P(A_i),$$

then  $\sigma(\mathcal{S}_1), \dots, \sigma(\mathcal{S}_n)$  are independent.

*Proof.* Fix  $\mathcal{S}_2, \dots, \mathcal{S}_n$ . Put

$$\mathcal{L} = \left\{ A \in \mathcal{F} \mid P(A \cap (\cap_{i=2}^n A_i)) = P(A) \prod_{i=2}^n P(A_i), A_i \in \mathcal{S}_i \text{ for } i = 2, \dots, n \right\}.$$

We claim that  $\mathcal{L}$  forms a  $\lambda$ -system. First, by assumption we can pick  $A_i = \Omega$  for  $i = 2, \dots, n$  to see that  $\Omega \in \mathcal{L}$ . Suppose that  $A \subset B$ ,  $A, B \in \mathcal{L}$ ,

$$\begin{aligned} P((B - A) \cap (\cap_{i=2}^n A_i)) &= P((B \cap (\cap_{i=2}^n A_i)) - (A \cap (\cap_{i=2}^n A_i))) \\ &= P(B) \prod_{i=2}^n P(A_i) - P(A) \prod_{i=2}^n P(A_i) = P(B - A) \prod_{i=2}^n P(A_i). \end{aligned}$$

Hence  $B - A \in \mathcal{L}$ . Let  $S_j \nearrow S$ ,  $S_j \in \mathcal{L}$ . Then

$$P(S \cap (\cap_{i=2}^n A_i)) = \lim_{j \rightarrow \infty} P(S_j \cap (\cap_{i=2}^n A_i)) = \lim_{j \rightarrow \infty} P(S_j) \prod_{i=2}^n P(A_i) = P(S) \prod_{i=2}^n P(A_i).$$

Thus  $S \in \mathcal{L}$  and  $\mathcal{L}$  is a  $\lambda$ -system. By Dynkin's  $\pi$ - $\lambda$ ,  $\sigma(S_1), S_2, \dots, S_n$  satisfies the product property. Repeat the procedure for  $S_2, \dots, S_n$ . We have that  $\sigma(S_1), \dots, \sigma(S_n)$  satisfies the product property. That is, they are independent. ■

### Corollary 1.53

Let  $X_1, \dots, X_n$  be  $\mathbb{R}$ -valued random variables. Then they are independent if and only if

$$P(X_1 \leq s_1, \dots, X_n \leq s_n) = \prod_{i=1}^n P(X_i \leq s_i)$$

for all  $s_i \in \mathbb{R}$ ,  $1 \leq i \leq n$ .

*Proof.* The sufficient part is trivial. For the converse, put  $\mathcal{S}_i = \{\{X_i \leq t\} \mid t \in \mathbb{R}\} \cup \{\Omega\}$ . Clearly  $\mathcal{S}_i$  are  $\pi$ -system and  $\Omega \in \mathcal{S}_i$  for all  $i$ .  $\sigma(\mathcal{S}_i)$  are independent and  $\mathcal{S}_i$  generates  $\sigma(X_i)$ . Applying [theorem 1.52](#) shows that  $X_i$  are independent. ■

### Corollary 1.54

If  $\mathcal{F}_{ij}$ ,  $1 \leq i \leq n$ ,  $1 \leq j \leq m(i)$  are independent  $\sigma$ -algebras, then  $\mathcal{G}_i = \sigma(\cup_j \mathcal{F}_{ij})$  are independent.

*Proof.* Put  $\mathcal{H}_i = \{\cap_j A_j \mid A_j \in \mathcal{F}_{ij}\}$ . We claim that  $\sigma(\mathcal{H}_i) = \mathcal{G}_i$ . Indeed, by choosing sets of the form

$$(\Omega, \dots, \Omega, A_j, \Omega, \dots, \Omega) \in \mathcal{F}_{i1} \times \dots \times \mathcal{F}_{im(i)},$$

it is clear that  $\cup_j \mathcal{F}_{ij} \subset \mathcal{H}_i$ . Also, if  $A \in \mathcal{H}_i$ , then

$$A = \cap_j A_j = (\cup_j (A_j^c))^c \in \sigma(\cup_j \mathcal{F}_{ij}).$$

Thus  $\cup_j \mathcal{F}_{ij} \subset \mathcal{H}_i \subset \sigma(\cup_j \mathcal{F}_{ij})$  and  $\sigma(\mathcal{H}_i) = \sigma(\cup_j \mathcal{F}_{ij}) = \mathcal{G}_i$ . Also notice that  $\mathcal{H}_i$  contain  $\Omega$  and form  $\pi$ -systems. For  $A_i \in \mathcal{H}_i$ , write  $A_i = \cap_j A_{ij}$ . Then

$$P(\cap_i A_i) = P(\cap_{ij} A_{ij}) = \prod_{ij} P(A_{ij}) = \prod_i P(\cap_j A_{ij}) = \prod_i P(A_i).$$

From [theorem 1.52](#) we know that  $\mathcal{G}_i = \sigma(\mathcal{H}_i)$  are independent. ■

**Corollary 1.55**

If  $X_{ij}, 1 \leq i \leq n, 1 \leq j \leq m(i)$  are independent random variables, then  $Y_i = h_i(X_{i1}, \dots, X_{im(i)})$  are independent provided that  $h_i$  are measurable.

*Proof.* Write  $\mathcal{F}_{ij} = \sigma(X_{ij})$ . We claim that  $\sigma(Y_i) \subset \sigma(\cup_j \mathcal{F}_{ij})$ . Indeed, if  $B_i$  is a measurable set,  $h_i^{-1}(B_i)$  is measurable. Write  $h_i^{-1}(B_i) = C_{i1} \times \dots \times C_{im(i)}$  and since each  $X_{ij}^{-1}(C_{ij}) \in \mathcal{F}_{ij}$ , we see that  $\sigma(Y_i) \subset \sigma(\cup_j \mathcal{F}_{ij})$ . It then follows from [corollary 1.54](#) that  $\sigma(Y_i)$  are independent and  $Y_i$  are independent. ■

**Theorem 1.56**

If  $X_1, \dots, X_n$  are independent  $\mathbb{R}$ -valued random variables and the distribution of  $X_i$  is  $\mu_i$ . Then the joint distribution of  $(X_1, \dots, X_n)$  is  $\mu_1 \times \dots \times \mu_n$ .

*Proof.* Let  $\mu$  be the distribution of  $(X_1, \dots, X_n)$ . By definition,

$$\begin{aligned} \mu((X_1, \dots) \in A_1 \times \dots \times A_n) &= \mu(X_1 \in A_1, \dots, X_n \in A_n) \\ &= \prod_{i=1}^n \mu_i(X_i \in A_i) = (\mu_1 \times \dots \times \mu_n)(A_1 \times \dots \times A_n). \end{aligned}$$

Now the sets of the forms  $A = A_1 \times \dots \times A_n$  is a  $\pi$ -system generating the product  $\sigma$ -algebra. By [corollary 1.19](#), the joint distribution is exactly  $\mu_1 \times \dots \times \mu_n$ . ■

**Theorem 1.57**

Let  $X, Y$  be two independent random variables. If  $h(x, y)$  satisfies either

- (a)  $\mathbb{E}[|h(X, Y)|] < \infty$ , or
- (b)  $h$  is non-negative,

then

$$\mathbb{E}[h(X, Y)] = \int \int h d\mu_X d\mu_Y,$$

where  $\mu_X, \mu_Y$  are the distributions of  $X$  and  $Y$ , respectively.

*Proof.* The proof follows directly from Fubini-Tonelli theorem. If one of the assumptions is true, then

$$\mathbb{E}[h(X, Y)] = \int_{\mathbb{R}^2} h d(\mu_X \times \mu_Y) = \int \int h d\mu_X d\mu_Y.$$

■

**Remark**

If  $h(x, y) = h_1(x)h_2(y)$ , then

$$\mathbb{E}[h_1(X)h_2(Y)] = \mathbb{E}[h(X, Y)] = \int \int h_1 h_2 d\mu_X d\mu_Y = \mathbb{E}[h_1(X)] \mathbb{E}[h_2(Y)].$$

**Corollary 1.58**

If  $X_1, \dots, X_n$  are independent random variables and

- (a)  $E[|X_1 \cdots X_n|] < \infty$  or
- (b)  $X_i \geq 0$  for all  $i$ ,

then

$$E[X_1 \cdots X_n] = \prod_{i=1}^n E[X_i].$$

*Proof.* Let  $h(x, y) = xy$ . By assumptions, we have either  $E[|h(X_1, X_2)|] < \infty$  or  $h(X_1, X_2) \geq 0$ . By **theorem 1.57**,  $E[X_1 X_2] = E[X_1] E[X_2]$ . Substitute  $X_1$  by  $X_1 X_2$  and  $X_2$  by  $X_3$ , we see that  $E[X_1 X_2 X_3] = E[X_1] E[X_2] E[X_3]$ . Repeat the procedure  $n$  times and the result follows. ■

**Definition 1.59**

Let  $X, Y$  be independent random variables with CDF  $F$  and  $G$ , respectively. The **convolution** of two CDF is defined as

$$(F * G)(z) = \int F(z - y) dG(y).$$

**Remark**

If  $F$  and  $G$  are absolutely continuous with respect to the Lebesgue measure, then they have Radon-Nikodym derivatives  $f$  and  $g$ . The definition of convolution becomes

$$(F * G)(z) = \int F(z - y) dG(y) = \int_{-\infty}^{\infty} \int_{-\infty}^{z-y} f(x) g(y) dx dy.$$

Then

$$(F * G)'(z) = \int f(z - y) g(y) dy = (f * g)(z),$$

which is exactly the definition of convolution of two functions.

**Proposition 1.60**

Let  $X$  and  $Y$  be independent random variables. Then

$$P(X + Y \leq z) = (F * G)(z).$$

*Proof.* By **theorem 1.57**,

$$\begin{aligned} P(X + Y \leq z) &= E[\mathbf{1}\{X + Y \leq z\}] = \int \int \mathbf{1}\{x + y \leq z\} dF(x) dG(y) \\ &= \int F(z - y) dG(y) = (F * G)(z). \end{aligned}$$

■

**Remark**

Note that the convolution is commutative since

$$(F * G)(z) = P(X + Y \leq z) = P(Y + X \leq z) = (G * F)(z).$$

**Remark**

For discrete  $X$  and  $Y$ , the convolution becomes

$$P(X + Y = z) = \sum_y P(X = z - y) P(Y = y).$$

**Example**

Consider  $X \sim \Gamma(\alpha_1, \beta)$  and  $Y \sim \Gamma(\alpha_2, \beta)$ . Then the density for  $X + Y$  is

$$\begin{aligned} f_{X+Y}(z) &= \int f_X(z-y) f_Y(y) dy \\ &= \int_0^z \frac{1}{\Gamma(\alpha_1)} \beta^{\alpha_1} (z-y)^{\alpha_1-1} e^{-\beta(z-y)} \frac{1}{\Gamma(\alpha_2)} \beta^{\alpha_2} y^{\alpha_2-1} e^{-\beta y} dy \\ &= \frac{1}{\Gamma(\alpha_1)\Gamma(\alpha_2)} \beta^{\alpha_1+\alpha_2} e^{-\beta z} \int_0^z (z-y)^{\alpha_1-1} y^{\alpha_2-1} dy \\ &= \frac{1}{\Gamma(\alpha_1)\Gamma(\alpha_2)} \beta^{\alpha_1+\alpha_2} e^{-\beta z} z^{\alpha_1+\alpha_2-1} \int_0^1 (1-t)^{\alpha_1-1} t^{\alpha_2-1} dt \\ &= \frac{B(\alpha_1, \alpha_2)}{\Gamma(\alpha_1)\Gamma(\alpha_2)} \beta^{\alpha_1+\alpha_2} e^{-\beta z} z^{\alpha_1+\alpha_2-1} = \frac{1}{\Gamma(\alpha_1 + \alpha_2)} \beta^{\alpha_1+\alpha_2} e^{-\beta z} z^{\alpha_1+\alpha_2-1}. \end{aligned}$$

Hence  $X + Y \sim \Gamma(\alpha_1 + \alpha_2, \beta)$ .

## 1.4. Convergence of Random Variables

### Definition 1.61

A sequence of probability measures  $P_n$  on  $(\mathbb{R}^n, \mathcal{B}(\mathbb{R}^n))$  are **consistent** if

$$P_{n+1}((a_1, b_1] \times \cdots \times (a_n, b_n] \times \mathbb{R}) = P_n((a_1, b_1] \times \cdots \times (a_n, b_n])$$

for every  $n$ .

### Theorem 1.62 (Kolmogorov Extension)

Suppose that a sequence of probability measures  $P_n$  on  $(\mathbb{R}^n, \mathcal{B}(\mathbb{R}^n))$  are consistent. Then there is a unique probability measure  $P$  on  $(\mathbb{R}^{\mathbb{N}}, \mathcal{B})$  satisfying that

$$P(\{\omega \in \mathbb{R}^{\mathbb{N}} \mid \omega_i \in (a_i, b_i], 1 \leq i \leq n\}) = P_n((a_1, b_1] \times \cdots \times (a_n, b_n]),$$

where  $\mathcal{B}$  is generated by the collection

$$\{\omega \in \mathbb{R}^{\mathbb{N}} \mid \omega_i \in (a_i, b_i], 1 \leq i \leq n, n \in \mathbb{N}\}.$$

*Proof.* Let

$$\mathcal{S} = \{(a_1, b_1] \times \cdots \times (a_n, b_n] \times \mathbb{R} \times \cdots \mid n \in \mathbb{N}\}.$$

Define  $P$  on  $\mathcal{S}$  to be

$$P((a_1, b_1] \times \cdots \times (a_n, b_n] \times \mathbb{R} \times \cdots) = P_n((a_1, b_1] \times \cdots \times (a_n, b_n])$$

Clearly,  $\mathcal{S}$  forms a semi-algebra. From the Carathéodory extension theorem, it suffices to show that  $P$  is finitely additive,  $\sigma$ -additive on  $\mathcal{S}$  and  $P(\emptyset) = 0$ . Note that  $P(\emptyset) = P(\emptyset \times \mathbb{R} \times \cdots) = P_1(\emptyset) = 0$ . We verify the first two conditions.

First, if  $A, B \in \mathcal{S}$  are disjoint,  $m \leq n$ ,

$$A = \{\omega \in \mathbb{R}^{\mathbb{N}} \mid \omega_i \in (a_i, b_i], 1 \leq i \leq m\} \quad \text{and} \quad B = \{\omega \in \mathbb{R}^{\mathbb{N}} \mid \omega_i \in (c_i, d_i], 1 \leq i \leq n\},$$

then

$$P(A \cup B) = P_n((\pi_n A) \cup (\pi_n B)) = P_n(\pi_n A) + P_n(\pi_n B) = P(A) + P(B),$$

where  $\pi_n : \omega \rightarrow (\omega_1, \dots, \omega_n)$  is the projection onto the first  $n$  components. Hence  $P$  is finitely additive.

Next, suppose  $A_1, \dots \in \mathcal{S}$  are countably many disjoint measurable sets. Put  $A = \cup_i A_i$ . We can consider the algebra  $\tilde{\mathcal{S}} = \{\text{finite disjoint union of sets in } \mathcal{S}\}$  generated by  $\mathcal{S}$ .  $B_n = \cup_{i>n} A_i \in \tilde{\mathcal{S}}$ . Thus

$$P(A) = P(B_n) + \sum_{i=1}^n P(A_i)$$

by the previous result. It now suffices to show that  $P(B_n) \rightarrow 0$  for any  $B_n \searrow \emptyset$ . Suppose not,

then there is  $\delta > 0$  such that  $P(B_n) \rightarrow \delta$  as  $B_n \rightarrow \emptyset$  by the monotonicity of  $P$ .

For such  $\{B_n\}$ , we claim that there is a sequence of compact set  $K_n$  such that  $K_n \subset B_n$  and  $P(B_n - K_n) < 2^{-(n+1)}\delta$ . Now since  $B_1 \in \bar{S}$ , there are disjoint  $E_1^1, \dots, E_{m_1}^1$  such that  $B_1 = \cup_{i=1}^{m_1} E_i^1$ . Now since each  $E_i^1$  is of the product of  $(\cdot, \cdot]$ . We can find a compact subset  $K_i^1$  of the product of  $[\cdot, \cdot]$  such that  $P(E_i^1 - K_i^1) < m_1^{-1}2^{-2}\delta$ . Hence  $K_1 = \cup_i K_i^1 \subset B_1$  satisfies that

$$P(B_1 - K_1) = \sum_{i=1}^{m_1} P(E_i^1 - K_i^1) < 2^{-2}\delta$$

as desired. Repeat the process and find  $K_n$  inductively. The claim follows.

Now,  $\cap_{n=1}^m K_n \searrow K$  as  $m \rightarrow \infty$ . Also,

$$P(B_m - (\cap_{n=1}^m K_n)) \leq \sum_{n=1}^m P(B_n - K_n) \leq \frac{\delta}{2}.$$

Hence  $\delta/2 \leq P(B_m) - \delta/2 \leq P(\cap_{n=1}^m K_n)$ . We see that  $\cap_{n=1}^m K_n$  is non-empty for each  $m$ . But this implies that  $K \subset \cap_n B_n$  is non-empty, a contradiction. Thus  $P(B_n) \rightarrow 0$ .

Finally, the  $\sigma$ -additivity follows from that we can take  $n \rightarrow \infty$  so that

$$P(A) = \lim_{n \rightarrow \infty} P(B_n) + \sum_{i=1}^n P(A_n) = \sum_i P(A_n).$$

Applying Carathéodory extension theorem, such  $P$  can be extended on  $(\mathbb{R}^N, \mathcal{B})$ . ■

### Remark

With Kolmogorov extension theorem, we can consider a sequence of independent variable  $X_i$  on the product probability space with  $\mathcal{F} = \mathcal{B}$ ,  $\tilde{X}_i : \omega \mapsto \omega_i$  and  $P(B_1 \times \dots \times B_n) = \prod_{i=1}^n \mu_i(B_i)$ , where  $\mu_i$  is the distribution of  $X_i$ .

### Definition 1.63

Let  $X_n$  be a sequence of random variable.  $X_n$  **converges almost surely** to  $X$  if

$$P \left\{ \lim_{n \rightarrow \infty} X_n = X \right\} = 1.$$

We denote it as  $X_n \xrightarrow{a.s.} X$  or  $X_n \rightarrow X$  a.s.

### Definition 1.64

Let  $X_n$  be a sequence of random variable.  $X_n$  **converges in probability** to  $X$  if for every  $\epsilon > 0$ ,

$$P \{ |X_n - X| > \epsilon \} \rightarrow 0$$

as  $n \rightarrow \infty$ . We denote it as  $X_n \xrightarrow{p} X$ .

### Definition 1.65



A sequence of random variable  $X_n \in \mathcal{L}^p$  is said to **converge in**  $\mathcal{L}^p$  to  $X$  if

$$\mathbf{E} [|X_n - X|^p]^{1/p} \rightarrow 0$$

as  $n \rightarrow \infty$ . If  $p = \infty$ , the definition becomes

$$\text{ess sup}_{\omega \in \Omega} |X_n(\omega) - X(\omega)| \rightarrow 0.$$

We denote it as  $X_n \rightarrow X$  in  $\mathcal{L}^p$ .

**Proposition 1.66**

Let  $X_n$  be a sequence of independent and identically distributed random variables. Then

(a) If  $X_n \rightarrow X$  almost surely, then  $X_n \xrightarrow{p} X$ .

(b) If  $X_n \rightarrow X$  in  $\mathcal{L}^p$ , then  $X_n \xrightarrow{p} X$ .

*Proof.* For (a), given  $\epsilon > 0$ , put

$$E_k = \cup_{n \geq k} \{|X_n - X| > \epsilon\}.$$

Note that  $E_k \searrow E = \{|X_n - X| > \epsilon \text{ for infinitely many } n\} = \{\lim_{n \rightarrow \infty} X_n = X\}^c$ . Hence

$$\mathbf{P}\{|X_k - X| > \epsilon\} \leq \mathbf{P}(E_k) \rightarrow \mathbf{P}\left\{\lim_{n \rightarrow \infty} X_n = X\right\}^c = 0$$

Hence  $X_n \rightarrow X$  in probability.

For (b), suppose first that  $p < \infty$ . By Markov inequality,

$$\mathbf{P}\{|X_n - X| > \epsilon\} = \mathbf{P}\{|X_n - X|^p > \epsilon^p\} \leq \frac{1}{\epsilon^p} \mathbf{E} [|X_n - X|^p] \rightarrow 0.$$

Let  $p = \infty$ . Note that  $\text{ess sup} |X_n - X| = \inf \{c \mid \mathbf{P}\{|X_n - X| > c\} = 0\}$ . Convergence in  $\mathcal{L}^\infty$  implies that for  $\epsilon > 0$ , there is  $N$  such that if  $n \geq N$ ,  $\inf \{c \mid \mathbf{P}\{|X_n - X| > c\} = 0\} < \epsilon$ . That is,  $\mathbf{P}\{|X_n - X| > \epsilon\} = 0$  for  $n \geq N$ . Hence  $X_n \xrightarrow{p} X$ . ■

## 2. Law of Large Number and Central Limit Theorem

### 2.1. Weak Law of Large Number

#### Definition 2.1

Let  $X_i$  be random variables with  $E[X_i^2] < \infty$ . They are called **uncorrelated** if

$$E[X_i X_j] = E[X_i] E[X_j].$$

#### Theorem 2.2 (Weak Law of Large Number I)

Suppose that  $X_n$  are uncorrelated random variables with  $\text{Var}[X_n] \leq C$  and  $E[X_n] = \mu$  for all  $n$ . Let  $S_n = \sum_{i=1}^n X_i$ . Then

$$\frac{1}{n} S_n \rightarrow \mu$$

in  $\mathcal{L}^2$  and hence in probability.

*Proof.* Compute that

$$E\left[\left(\frac{1}{n} S_n - \mu\right)^2\right] = \frac{1}{n^2} \sum_{i=1}^n \text{Var}(X_i) \leq \frac{C}{n} \rightarrow 0.$$

Hence  $\frac{1}{n} S_n \rightarrow \mu$  in  $\mathcal{L}^2$  and thus in probability. ■

#### Theorem 2.3 (Weak Law of Large Number II, Khinchin)

Suppose that  $X_i$  is a sequence of independent and identically distributed random variables with  $E[|X_1|] < \infty$ . Let  $S_n = \sum_{i=1}^n X_i$  and  $\mu = E[X_1]$ . Then

$$\frac{1}{n} S_n \rightarrow \mu$$

in  $\mathcal{L}^1$  and hence in probability.

*Proof.* By replacing  $X_i$  with  $X_i - \mu$ , we may assume without loss of generality that  $\mu = 0$ .

Now, for  $C > 0$ ,

$$0 = E[X_i] = E[X_i \mathbf{1}\{|X_i| > C\}] + E[X_i \mathbf{1}\{|X_i| \leq C\}].$$

Also,

$$\begin{aligned} \frac{1}{n} S_n &= \frac{1}{n} \sum_{i=1}^n X_i \mathbf{1}\{|X_i| > C\} + \frac{1}{n} \sum_{i=1}^n X_i \mathbf{1}\{|X_i| \leq C\} \\ &= \frac{1}{n} \sum_{i=1}^n (X_i \mathbf{1}\{|X_i| > C\} - E[X_i \mathbf{1}\{|X_i| > C\}]) + \frac{1}{n} \sum_{i=1}^n (X_i \mathbf{1}\{|X_i| \leq C\} - E[X_i \mathbf{1}\{|X_i| \leq C\}]). \end{aligned}$$

Notice that by LDCT,

$$\mathbf{E} \left[ \left\| \frac{1}{n} \sum_{i=1}^n (X_i \mathbf{1}_{\{|X_i| > C\}} - \mathbf{E}[X_i \mathbf{1}_{\{|X_i| > C\}}]) \right\| \right] \leq 2 \mathbf{E}[|X_1| \mathbf{1}_{\{|X_1| > C\}}] \rightarrow 0$$

as  $C \rightarrow \infty$  since  $|X_1| \mathbf{1}_{\{|X_1| > C\}} \leq |X_1|$  and  $\mathbf{E}[|X_1|] < \infty$ . Also, by Hölder inequality and the independence,

$$\mathbf{E} \left[ \left\| \frac{1}{n} \sum_{i=1}^n (X_i \mathbf{1}_{\{|X_i| \leq C\}} - \mathbf{E}[X_i \mathbf{1}_{\{|X_i| \leq C\}}]) \right\| \right] \leq \sqrt{\frac{1}{n} \text{Var}(X_1 \mathbf{1}_{\{|X_1| \leq C\}})} \leq \frac{C}{\sqrt{n}}$$

For any given  $\epsilon > 0$ , there is  $C$  such that  $2 \mathbf{E}[|X_1| \mathbf{1}_{\{|X_1| > C\}}] < \epsilon$  and

$$\begin{aligned} \mathbf{E} \left[ \left\| \frac{1}{n} S_n \right\| \right] &\leq \mathbf{E} \left[ \left\| \frac{1}{n} \sum_{i=1}^n (X_i \mathbf{1}_{\{|X_i| > C\}} - \mathbf{E}[X_i \mathbf{1}_{\{|X_i| > C\}}]) \right\| \right] \\ &\quad + \mathbf{E} \left[ \left\| \frac{1}{n} \sum_{i=1}^n (X_i \mathbf{1}_{\{|X_i| \leq C\}} - \mathbf{E}[X_i \mathbf{1}_{\{|X_i| \leq C\}}]) \right\| \right] \\ &\leq \epsilon + \frac{C}{\sqrt{n}} \rightarrow \epsilon \end{aligned}$$

as  $n \rightarrow \infty$ . Since  $\epsilon$  can be arbitrarily small, we conclude that  $\frac{1}{n} S_n \rightarrow 0$  in  $\mathcal{L}^1$  and hence in probability. ■

## 2.2. Strong Law of Large Number

### Definition 2.4

Let  $A_n$  be a sequence of events.

$$\limsup_{n \rightarrow \infty} A_n = \bigcap_{m=1}^{\infty} \bigcup_{n=m}^{\infty} A_n$$

and

$$\liminf_{n \rightarrow \infty} A_n = \bigcup_{m=1}^{\infty} \bigcap_{n=m}^{\infty} A_n.$$

### Remark

Observe that

$$\limsup_{n \rightarrow \infty} A_n = \{\omega \in \Omega \mid \omega \in A_n \text{ for infinitely many } n\}$$

and

$$\liminf_{n \rightarrow \infty} A_n = \{\omega \in \Omega \mid \omega \in A_n \text{ for all but finitely many } n\}.$$

### Theorem 2.5 (Borel-Cantelli I)

Let  $A_n$  be a sequence of events. If  $\sum_n P(A_n) < \infty$ , then

$$P\left(\limsup_{n \rightarrow \infty} A_n\right) = 0.$$

*Proof.* Let  $\epsilon > 0$  be given. By assumption, there is  $n_0$  such that  $\sum_{n \geq n_0} P(A_n) < \epsilon$ . Then

$$P\left(\limsup_{n \rightarrow \infty} A_n\right) = P\left(\bigcap_{m=1}^{\infty} \bigcup_{n=m}^{\infty} A_n\right) \leq P\left(\bigcup_{n=n_0}^{\infty} A_n\right) \leq \sum_{n=n_0}^{\infty} P(A_n) < \epsilon.$$

Since  $\epsilon$  can be arbitrarily small,  $P(\limsup_{n \rightarrow \infty} A_n) = 0$ . ■

### Corollary 2.6

Suppose for  $\epsilon > 0$ ,  $\sum_n P(|X_n - X| > \epsilon) < \infty$ . Then  $X_n \rightarrow X$  almost surely.

*Proof.* Let  $E_k = \{|X_n - X| > k^{-1} \text{ for finitely many } n\}$ . Note that  $E_{k+1} \subset E_k$  and  $E_k \searrow E = \{X_n \rightarrow X\}$ . Now we claim that  $P(E_k) = 1$ . Consider  $E_k^n = \{|X_n - X| > k^{-1}\}$ . For fixed  $k$ , by assumption we have  $\sum_n P(E_k^n) < \infty$ . By Borel-Cantelli,  $P(\limsup_{n \rightarrow \infty} E_k^n) = 0$ . Hence

$$P(E_k) = P(\{|X_n - X| > k^{-1} \text{ for infinitely many } n\}^c) = 1 - P(\limsup_{n \rightarrow \infty} E_k^n) = 1.$$

It now follows by the monotone convergence of measures that  $P(E) = 1$ . ■

### Remark

*Intuitively, if the convergence is sufficiently fast, the convergence in probability may recover almost sure convergence.*

**Theorem 2.7** (Strong Law of Large Number I)

Let  $X_i$  be independent and identically distributed with  $\mu = E[X_1]$  and  $E[X_1^4] < \infty$ . Let  $S_n = \sum_{i=1}^n X_i$ . Then

$$\frac{1}{n}S_n \rightarrow \mu$$

almost surely.

*Proof.* Note that

$$\begin{aligned} E \left[ \left( \frac{1}{n}S_n - \mu \right)^4 \right] &= \frac{1}{n^4} \left( \sum_i E[(X_i - \mu)^4] + \sum_{i \neq j} E[(X_i - \mu)^2(X_j - \mu)^2] \right) \\ &\leq \frac{1}{n^3} E[(X_1 - \mu)^4] + \frac{1}{n^4} \binom{n}{2} \binom{4}{2} E[(X_1 - \mu)^2]^2 \leq \frac{C}{n^2} \end{aligned}$$

for some constant  $C$ . By Chebyshev's inequality, for  $\epsilon > 0$ ,

$$P \left\{ \left| \frac{1}{n}S_n - \mu \right| > \epsilon \right\} \leq \frac{1}{\epsilon^4} E \left[ \left( \frac{1}{n}S_n - \mu \right)^4 \right] \leq \frac{C}{\epsilon^2 n^2}$$

is absolute summable. Hence by [corollary 2.6](#),

$$\frac{1}{n}S_n \rightarrow \mu$$

almost surely. ■

**Theorem 2.8**

$X_n \xrightarrow{p} X$  if and only if every subsequence of  $X_n$  has a further subsequence converging almost surely.

*Proof.* Suppose first that  $X_n \xrightarrow{p} X$ . Given a subsequence  $X_{n(k)}$ , we can choose  $n(k_1) < n(k_2) < \dots$  such that

$$P(|X_{n(k_i)} - X| > 2^{-i}) < 2^{-i}.$$

Since  $2^{-i}$  is summable, by Borel-Cantelli we have

$$P(|X_{n(k_i)} - X| > 2^{-i} \text{ for infinitely many } i) = 0.$$

In other words,

$$P\{X_{n(k_i)} \rightarrow X\} = P\{|X_{n(k_i)} - X| > 2^{-i} \text{ for infinitely many } i\}^c = 1.$$

For the converse, suppose that  $X_n \not\xrightarrow{p} X$  in probability. Then there exist  $\epsilon, \delta > 0$  and

$$P\{|X_{n(k)} - X| > \epsilon\} \geq \delta.$$

By assumption there is a further subsequence converging almost surely and thus in probability, i.e.,

$$\mathbb{P} \{ |X_{n(k_j)} - X| > \epsilon \} \rightarrow 0.$$

This is a contradiction. Hence  $X_n \rightarrow X$  in probability. ■

### Corollary 2.9

Suppose  $X_n \xrightarrow{p} X$ . Then the followings are true:

- (a) If  $f$  is continuous, then  $f(X_n) \xrightarrow{p} f(X)$ .
- (b) If  $|X_n| \leq Y$  for some  $Y \in \mathcal{L}^1$ , then  $\mathbb{E}[X_n] \rightarrow \mathbb{E}[X]$ .

*Proof.* For (a), by **theorem 2.8**, every subsequence has a further subsequence  $X_{n(k_j)} \rightarrow X$  almost surely and hence  $f(X_{n(k_j)}) \rightarrow f(X)$  almost surely. Then by **theorem 2.8** again we see that  $f(X_n) \xrightarrow{p} f(X)$ .

For (b), by **theorem 2.8**, every subsequence has a further subsequence  $X_{n(k_j)} \rightarrow X$  almost surely and LDCT gives  $\mathbb{E}[X_{n(k_j)}] \rightarrow \mathbb{E}[X]$ . This implies that  $\mathbb{E}[X_n] \rightarrow \mathbb{E}[X]$  as well. ■

### Definition 2.10

Let  $(\Omega, \mathcal{F}, \mathbb{P})$  be a probability space.

$$\mathcal{L}^0(\Omega) = \{X : \Omega \rightarrow \mathbb{R} \mid X \text{ is } \mathcal{F}\text{-measurable}\}.$$

### Remark

In general, the almost convergence notion on  $\mathcal{L}^0$  is not metrizable, i.e., there is no metric  $d$  on  $\mathcal{L}^0$  such that

$$d(X_n, X) \rightarrow 0 \iff X_n \rightarrow X \text{ a.s.}$$

To see this, suppose that the almost sure convergence is metrizable. If  $X_n \xrightarrow{p} X$ , any subsequence  $X_{n(k)}$  converges to  $X$  in probability as well. By **theorem 2.8**, we can find a further subsequence converging almost surely and hence in metric  $d$ , but this implies that  $d(X_n, X) \rightarrow 0$ . Then  $X_n \rightarrow X$  almost surely, which is absurd since convergence in probability does not imply almost sure convergence in general.

However, convergence in probability on  $\mathcal{L}^0$  can be metrized. For instance,

$$d(X, Y) = \mathbb{E}[\max\{|X - Y|, 1\}].$$

### Theorem 2.11 (Borel-Cantelli II)

Let  $A_n$  be independent events and  $\sum_{n=1}^{\infty} \mathbb{P}(A_n) = \infty$ . Then

$$\mathbb{P}\left(\limsup_{n \rightarrow \infty} A_n\right) = 1.$$

*Proof.* By assumption we have that  $\sum_{n \geq m} \mathbb{P}(A_n) = \infty$  for every  $m \in \mathbb{N}$ . Notice that  $1 + x \leq e^x$ .

Then

$$\begin{aligned}
P(\limsup_{n \rightarrow \infty} A_n) &= \lim_{m \rightarrow \infty} P(\cup_{n \geq m} A_n) = 1 - \lim_{m \rightarrow \infty} P(\cap_{n \geq m} A_n^c) \\
&= 1 - \lim_{m \rightarrow \infty} \lim_{N \rightarrow \infty} P(\cap_{n=m}^N A_n^c) = 1 - \lim_{m \rightarrow \infty} \lim_{N \rightarrow \infty} \prod_{n=m}^N P(A_n^c) \\
&= 1 - \lim_{m \rightarrow \infty} \prod_{n=m}^{\infty} (1 - P(A_n)) \geq 1 - \lim_{m \rightarrow \infty} \exp\left(-\sum_{n=m}^{\infty} P(A_n)\right) = 1.
\end{aligned}$$

Hence  $P(\limsup_{n \rightarrow \infty} A_n) = 1$ . ■

**Lemma 2.12**

Let  $X$  be a non-negative random variable and  $h : \mathbb{R} \rightarrow \mathbb{R}$  be a differentiable function with  $h(0) = 0$  and  $h' \geq 0$ . Then

$$E[h(X)] = \int_0^{\infty} h'(t) P(X > t) dt.$$

*Proof.* By Fubini-Tonelli theorem,

$$\begin{aligned}
E[h(X)] &= E\left[\int_0^X h'(t) dt\right] = E\left[\int_0^{\infty} \mathbf{1}_{\{t < X\}} h'(t) dt\right] \\
&= \int_0^{\infty} h'(t) E[\mathbf{1}_{\{t < X\}}] dt = \int_0^{\infty} h'(t) P(X > t) dt.
\end{aligned}$$
■

**Proposition 2.13**

Suppose that  $X_i$  are independent and identically distributed random variables with  $E[|X_i|] = \infty$ . Let  $S_n = \sum_{i=1}^n X_i$ . Then

- (a)  $P\{|X_n| > n \text{ for infinitely many } n\} = 1$ .
- (b)  $P\{\frac{1}{n}S_n \text{ has finite limit}\} = 0$ .

*Proof.* For (a), using [lemma 2.12](#) with  $h$  being identity,

$$\begin{aligned}
\infty &= E[|X_1|] = \int_0^{\infty} P(|X_1| > t) dt \leq \sum_{n=0}^{\infty} \int_n^{n+1} P(|X_1| > t) dt \\
&\leq \sum_{n=0}^{\infty} \int_n^{n+1} P(|X_1| > n) dt = \sum_{n=0}^{\infty} P(|X_n| > n).
\end{aligned}$$

Now by the second Borel-Cantelli,  $P\{|X_n| > n \text{ for infinitely many } n\} = 1$ .

For (b), consider  $\omega$  with  $\frac{S_n(\omega)}{n} \rightarrow Y(\omega) \in \mathbb{R}$ . Then for such  $\omega$ ,

$$\frac{X_n}{n} = \frac{S_n - S_{n-1}}{n} = \frac{S_n}{n} - \frac{n-1}{n} \frac{S_{n-1}}{n-1} \rightarrow 0$$

as  $n \rightarrow \infty$ . Thus

$$\begin{aligned} \mathbb{P} \left\{ \frac{1}{n} S_n \text{ has finite limit} \right\} &\leq \mathbb{P} \{ |X_n| > n \text{ for finitely many } n \} \\ &= 1 - \mathbb{P} \{ |X_n| > n \text{ for infinitely many } n \} = 0. \end{aligned}$$

(b) follows. ■