

STAT575  
Large Sample Theory

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## Abstract

This is a graduate-level theoretical statistics course taught by [Georgios Fellouris](#) at University of Illinois Urbana-Champaign, aiming to provide an introduction to asymptotic analysis of various statistical methods, including weak convergence, Lindeberg-Feller CLT, asymptotic relative efficiency, etc.

We list some references of this course, although we will not follow any particular book page by page: *Asymptotic Statistics* [[Vaa98](#)], *Asymptotic Theory of Statistics and Probability* [[Das08](#)], *A course in Large Sample Theory* [[Fer17](#)], *Approximation Theorems of Mathematical Statistics* [[Ser09](#)], and *Elements of Large-Sample Theory* [[Leh04](#)].



This course is taken in Spring 2024, and the date on the cover page is the last updated time.

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# Chapter 1

## Introduction

### Lecture 1: Introduction to Large Sample Theory

Say we first collect  $n$  data points  $x_1, \dots, x_n \in \mathbb{R}^d$ , large sample theory concerns with the limiting theory as  $n \rightarrow \infty$ . We may treat  $x_i$  as a realization of a random vector  $X_i$  on a probability space  $(\Omega, \mathcal{F}, \mathbb{P})$ . In this course, we will primarily consider the case that  $X_i$ 's are i.i.d., i.e., independent and identically distributed from a distribution function, or the *cumulative density function* (CDF)  $F$  such that

$$X = (X^1, \dots, X^d) \sim F(x_1, \dots, x_d) \equiv \mathbb{P}(X^1 \leq x_1, \dots, X^d \leq x_d)$$

for all  $x_i \in \mathbb{R}$ . If we have access to  $F$ , we can compute the corresponding *probability density function* (PDF)  $\mathbb{P}$ , and then have access to  $\mathbb{P}(X \in A)$  for all (measurable)  $A \subseteq \mathbb{R}^d$  of interest.

**Remark.** If we know any of the above, we know every thing about the population.

Hence, the goal is to compute this by collecting data  $x_i$ 's, which is a statistical inference problem.

### 1.1 Parametrized Approach

There are various ways of doing this task, one way is the so-called parametrized approach. By postulating a family of CDFs  $\{F_\theta, \theta \in \Theta\}$  where  $\Theta$  is often a subset of  $\mathbb{R}^m$  for some  $m$  (generally  $\neq n$ ), the goal is to select a member of this family that is the “closest”, or the “best fit” to the truth, i.e.,  $F$ , based on the data.

**Note.** To emphasize that this depends on the data, we sometimes write the function we found as  $\hat{\theta}_n(x_1, \dots, x_n)$  so that  $F_{\hat{\theta}_n(x_1, \dots, x_n)}$  is our proxy for  $F$ .

Now, assume that the family is initially given, the problem is then how to select  $\hat{\theta}_n$ .

**Example.** Fisher suggested that we should look at the maximum likelihood estimator (MLE).

The justification for MLE is not about finite  $n$ , but about its asymptotic behavior when  $n \rightarrow \infty$ . Specifically, we have the following theorem due to Fisher (informally stated).

**Theorem 1.1.1 (Fisher).** If  $F \in \{F_\theta: \theta \in \Theta\}$ , i.e., if  $F = F_{\theta^*}$  for some  $\theta^* \in \Theta$ , then under certain conditions,  $\hat{\theta}_n$  will be “close” to  $\theta^*$  as  $n \rightarrow \infty$ . Under some other conditions,  $\sqrt{n}(\hat{\theta}_n - \theta)$  is approximately Gaussian with variance being the “best possible” in some sense.

On the other hand, in the misspecified case, i.e.,  $F \notin \{F_\theta, \theta \in \Theta\}$ , we can still compute the MLE, which leads to another justification for MLE since even in this case,  $\hat{\theta}_n$  will still be “close” to  $\theta^*$  such that  $F_{\hat{\theta}_n}$  is, in some sense, the “closest” to  $F$  among all possible  $F_\theta$  (minimizing divergence, to be precise).

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## 1.2 Hypothesis Testing

We will also develop theory for hypothesis testing for some hypothesis we're interested in, e.g., whether the data we collect is really i.i.d., or whether our proposed family is reasonable enough. Say now  $X_i$ 's are scalar random variable with  $\mathbb{E}[X] = \mu$ , and we want to test the null hypothesis  $H_0: \mu = 0$ .

**Example.** Consider a controlled group  $Z$  and a treatment group  $Y$ , and we observe  $Z_1, \dots, Z_n$ , and  $Y_1, \dots, Y_n$ , respectively, and compute  $X_i = Z_i - Y_i$  for all  $i$ . Testing  $H_0$  on the distribution of  $X$  will show the effect of the treatment.

To do this, a well-known method is the so-called  $t$ -test. Let  $s_n$  to be the sample standard derivation, then we can compute

$$T_n = \frac{\bar{X}_n}{s_n/\sqrt{n}} \sim t_{n-1}$$

as long as  $X$  is Gaussian, i.e., the  $t$ -statistics for  $H_0$ . What if  $X$  is not an Gaussian? We will show that even if  $X$  is not Gaussian, this result is “approximately valid” when  $n$  is “large enough” as long as  $\text{Var}[X] < \infty$ .

**Remark (Sample Size).** When we say  $n$  is “large enough”, what we mean really depends on how fast the underlying distribution will approach Gaussian as  $n$  grows. Hence, if we can say more about the underlying population, we can say more about when does  $n$  is “large enough”; otherwise such a limiting theory might be completely useless in practice.

What if now  $\text{Var}[X]$  doesn't exit? When the population has a heavy tail distribution, then second moment may not exit.

**Example (Cauchy distribution).** The Cauchy distribution doesn't have finite moment of order greater than 1.

In this case, some other test is needed. A simple test would be looking at the sign of  $X_i$ , i.e., the sign test.

**Example (Sign test).** We might reject  $H_0$  if  $\sum_{i=1}^n \mathbb{1}_{X_i > 0}$  is large. Note that under  $H_0$ ,  $\sum_{i=1}^n \mathbb{1}_{X_i > 0} \sim \text{Bin}(n, 1/2)$ , and this test is valid even if expectation doesn't exist.

We see that without saying anything about  $F$ , the sign test is valid even for  $n = 3$  or  $5$  as the sum is exactly binomial distribution under  $H_0$ . Although simple and have good property, only looking at the sign of  $X_i$  might be too weak. A natural idea is to look at the absolute value of  $X_i$ .

**Example (Wilcoxon's rank-sum test).** Let  $R_{i,n}$  to be the rank of  $|X_i|$ , then consider the so-called *Wilcoxon's rank-sum test*

$$\sum_{i=1}^n \mathbb{1}_{X_i > 0} R_{i,n}.$$

As one can imagine, the closed form of the above sum will be complicated; however, asymptotically, the above statics will follow Gaussian again, such that the rate of convergence doesn't depend on the underlying population.

Finally, we also ask how can we compare these different tests? This will also be addressed in this course.

# Chapter 2

## Modes of Convergence

### Lecture 2: Modes of Convergence

#### 2.1 Different Modes of Convergence

18 Jan. 9:30

Given a probability space  $(\Omega, \mathcal{F}, \mathbb{P})$ , consider a sequence of  $d$ -dimensional random vectors  $(X_n)$  and a random vector  $X$ , i.e.,  $X_n, X: \Omega \rightarrow \mathbb{R}^d$ . We now discuss different modes of convergence for  $(X_n)$ .

**Definition 2.1.1 (Point-wise converge).**  $(X_n)$  *point-wise converges* to  $X$ , denoted as  $X_n \rightarrow X$ , if  $X_n(\omega) \rightarrow X(\omega)$  for all  $\omega \in \Omega$ .<sup>a</sup>

<sup>a</sup>I.e., for every  $\epsilon > 0$ , there exists  $n_0(\omega) \in \mathbb{N}$  such that for every  $n \geq n_0$ ,  $\|X_n(\omega) - X(\omega)\|_2 < \epsilon$ .

Since we don't care about measure zero sets, we may instead consider the following.

**Definition 2.1.2 (Converge almost-surely).**  $(X_n)$  *converges almost-surely* to  $X$ , denoted as  $X_n \xrightarrow{\text{a.s.}} X$ , if  $\mathbb{P}(X_n \rightarrow X) = 1$ .<sup>a</sup>

<sup>a</sup>I.e.,  $X_n(\omega) \rightarrow X(\omega)$  for all  $\omega \in \Omega \setminus N$  where  $\mathbb{P}(N) = 0$ .

However, this might still be too strong.

**Definition 2.1.3 (Converge in probability).**  $(X_n)$  *converges in probability* to  $X$ , denoted as  $X_n \xrightarrow{p} X$ , if for every  $\epsilon > 0$ ,  $\mathbb{P}(\|X_n - X\| > \epsilon) \rightarrow 0$  as  $n \rightarrow \infty$ .

**Remark.**  $X_n \rightarrow X$  if and only if  $\|X_n - X\| \rightarrow 0$ . The same also holds for  $\xrightarrow{p}$  and  $\xrightarrow{\text{a.s.}}$ .

A related notion is the following, where we now sum over  $n$ .

**Definition 2.1.4 (Converge completely).**  $(X_n)$  *converges completely* to  $X$ , denoted as  $X_n \xrightarrow{\text{comp}} X$ , if for every  $\epsilon > 0$ ,  $\sum_{n=1}^{\infty} \mathbb{P}(\|X_n - X\| > \epsilon) < \infty$ .

Finally, we have the following.

**Definition 2.1.5 (Converge in  $L^p$ ).**  $(X_n)$  *converges in  $L^p$*  to  $X$  for some  $p > 0$ , denoted as  $X_n \xrightarrow{L^p} X$ , if  $\mathbb{E}[\|X_n - X\|^p] \rightarrow 0$  as  $n \rightarrow \infty$ .

##### 2.1.1 Connection Between Modes of Convergence

We have the following connections between different modes of convergence.

$$\text{completely} \implies \text{almost-surely} \implies \text{in probability} \longleftarrow \text{in } L^p$$

To show the above, the following characterization for [almost-surely convergence](#) is useful.

**Proposition 2.1.1.** For a sequence of random vectors  $(X_n)$  and a random vector  $X$ , we have

$$\begin{aligned} X_n \xrightarrow{\text{a.s.}} X &\Leftrightarrow \mathbb{P}(\|X_k - X\| > \epsilon \text{ for some } k \geq n) \xrightarrow{n \rightarrow \infty} 0 \\ &\Leftrightarrow \mathbb{P}(\|X_n - X\| > \epsilon \text{ for infinitely many } n\text{'s}) = 0 \\ &\Leftrightarrow \mathbb{P}(\limsup_{n \rightarrow \infty} \|X_n - X\| > \epsilon) = 0, \end{aligned}$$

where the above holds for every  $\epsilon > 0$ .

From [Proposition 2.1.1](#), it's clear that  $\xrightarrow{\text{a.s.}}$  implies  $\xrightarrow{P}$  since

$$\mathbb{P}(\|X_k - X\| > \epsilon \text{ for some } k \geq n) \geq \mathbb{P}(\|X_n - X\| > \epsilon),$$

hence if the former goes to 0, so does the latter. On the other hand,  $\xrightarrow{\text{comp}}$  implies  $\xrightarrow{\text{a.s.}}$  follows from the third equivalence. Lastly, the [convergence in  \$L^p\$](#)  implies the [convergence in probability](#) since

$$\mathbb{P}(\|X_n - X\| > \epsilon) \leq \frac{1}{\epsilon^p} \mathbb{E}[\|X_n - X\|^p]$$

from Markov's inequality. However, the converse is not always true.

**Theorem 2.1.1 (Dominated convergence theorem).** If  $X_n \xrightarrow{P} X$  and  $\|X_n - X\| \leq Z$  for all  $n \geq 1$  where  $\mathbb{E}[\|Z\|^p] < \infty$ , then  $X_n \xrightarrow{L^p} X$ .

**Theorem 2.1.2 (Scheffé's theorem).** If  $X_n \xrightarrow{P} X$  and  $\limsup_{n \rightarrow \infty} \mathbb{E}[\|X_n\|^p] \leq \mathbb{E}[\|X\|^p] < \infty$ , then  $X_n \xrightarrow{L^p} X$ .

## 2.1.2 Applications to Statistics

Let  $(X_n) \stackrel{\text{i.i.d.}}{\sim} F$  where  $F$  is a distribution function. Say we're interested in some aspect of  $F$ , for example, some parameter  $\theta = T(F) \in \mathbb{R}^m$ . By collecting data  $X_1, \dots, X_n$ , we estimate  $\theta$  by computing an estimator  $\hat{\theta}_n$  of  $\theta$ .<sup>1</sup> There are some properties we might want for  $\hat{\theta}_n$ .

**Definition 2.1.6 (Consistent).**  $\hat{\theta}_n$  is *consistent* of  $\theta$  if  $\hat{\theta}_n \xrightarrow{P} \theta$  as  $n \rightarrow \infty$ .

**Definition 2.1.7 (Strongly consistent).**  $\hat{\theta}_n$  is *strongly consistent* of  $\theta$  if  $\hat{\theta}_n \xrightarrow{\text{a.s.}} \theta$  as  $n \rightarrow \infty$ .

**Definition 2.1.8 (Converge in mean squared error).**  $\hat{\theta}_n$  converges to  $\theta$  in mean squared error if  $\hat{\theta}_n \xrightarrow{L^2} \theta$ .

**Remark.** When  $d = 1$ ,  $\mathbb{E}[(\hat{\theta}_n - \theta)^2] = \text{Var}[\hat{\theta}_n] + (\mathbb{E}[\hat{\theta}_n - \theta])^2$ . Therefore,  $\hat{\theta}_n$  [converges in mean squared error](#) to  $\theta$  if and only if  $\mathbb{E}[\hat{\theta}_n] \rightarrow \theta$  and  $\text{Var}[\hat{\theta}_n] \rightarrow 0$ .

Let's first see the most well-known estimation problem, the mean estimation.

**Example (Mean estimation).** Suppose  $d = 1$ , and let  $X$  be non-negative. Say we're interested in  $\theta = \mathbb{E}[X]$ . It's standard that in this case, we can compute  $\mathbb{E}[X]$  by

$$\theta = \mathbb{E}[X] = \int_0^\infty \mathbb{P}(X > t) dt = \int_0^\infty (1 - F(t)) dt.$$

If  $X$  has a PMF  $f$ , then  $\mathbb{E}[X] = \sum_x x f(x) = \sum_x x \Delta F(x)$  where  $f(x) = \Delta F(x) \equiv F(x) - F(x^-)$ ;

<sup>1</sup> $\hat{\theta}_n$  is a function of  $X_i$ 's.

if  $X$  has a PDF  $f$ , then

$$\mathbb{E}[X] = \int_0^\infty x f(x) dx = \int_0^\infty x F(dx)$$

where  $F(dx) := f(x)dx$  in a measure-theoretical sense.

Now, let  $\hat{\theta}_n$  to be the sample mean, i.e.,  $\hat{\theta}_n = \bar{X}_n = \frac{1}{n} \sum_{i=1}^n X_i$ . From the strong law of large number,  $\bar{X}_n \xrightarrow{\text{a.s.}} \mathbb{E}[X]$ , which implies that  $\hat{\theta}_n$  is a **strongly consistent estimator** of  $\theta$ .

On the other hand, if  $\text{Var}[X] < \infty$ , then  $\bar{X}_n \xrightarrow{L^2} \mathbb{E}[X]$ , which further implies  $\bar{X}_n \xrightarrow{p} \mathbb{E}[X]$ , hence  $\hat{\theta}_n$  is **consistent**.<sup>a</sup>

<sup>a</sup>The latter is true even without  $\text{Var}[X] < \infty$  as we expect.

**Proof.** We show the last statement. Since  $\text{Var}[X] < \infty$ , then

$$\frac{\text{Var}[X]}{n} = \text{Var}[\bar{X}_n] = \mathbb{E}[(\bar{X}_n - \mathbb{E}[X])^2] \rightarrow 0$$

as  $n \rightarrow \infty$ , which implies  $\bar{X}_n \xrightarrow{p} \mathbb{E}[X]$ . ⊛

Another interesting problem is the supremum estimation.

**Example (Supremum estimation).** Suppose there is a  $\theta \in \mathbb{R}$  where distribution function  $F$  such that  $F(\theta - \epsilon) < 1 = F(\theta)$  for all  $\epsilon > 0$ , i.e.,  $\theta = \sup_{\omega} X(\omega)$  since  $\mathbb{P}(X \leq \theta - \epsilon) = F(\theta - \epsilon)$  and  $F(\theta) = \mathbb{P}(X \leq \theta)$ .<sup>a</sup> Then  $\hat{\theta}_n = \max_{1 \leq i \leq n} X_i$  is indeed a **strongly consistent estimator** of  $\theta$ .

<sup>a</sup>Such a distribution exists, for example,  $\mathcal{U}(0, \theta)$ .

**Proof.** We see that for any  $\epsilon > 0$ ,

$$\begin{aligned} \mathbb{P}(|\hat{\theta}_n - \theta| > \epsilon) &= \mathbb{P}(\hat{\theta}_n > \theta + \epsilon) + \mathbb{P}(\hat{\theta}_n < \theta - \epsilon) \\ &= \mathbb{P}\left(\bigcup_{i=1}^n \{X_i > \theta + \epsilon\}\right) + \mathbb{P}\left(\bigcap_{i=1}^n \{X_i < \theta - \epsilon\}\right) \\ &\leq \sum_{i=1}^n \underbrace{\mathbb{P}(X > \theta + \epsilon)}_0 + \prod_{i=1}^n \mathbb{P}(X_i < \theta - \epsilon) = (\mathbb{P}(X_1 < \theta - \epsilon))^n \leq (F(\theta - \epsilon))^n \rightarrow 0 \end{aligned}$$

as  $n \rightarrow \infty$  since  $F(\theta - \epsilon) < 1$ . This shows that  $\hat{\theta}_n$  is indeed **consistent**. Moreover, since  $\mathbb{P}(|\hat{\theta}_n - \theta| > \epsilon)$  decays exponentially, so this is absolutely summable, hence it's also **strongly consistency**. ⊛

Proving convergence of  $\hat{\theta}_n$  is useful, but this might not be enough.

**Example.** Consider any deterministic sequence  $(a_n)$  in  $\mathbb{R}$  which converges to 0. Adding  $a_n$  to  $\hat{\theta}_n$  will not change the convergence of  $\hat{\theta}_n$ .

The above suggests that we should look at the *distribution* of  $\hat{\theta}_n - \theta$  in order to say how does  $\hat{\theta}_n \rightarrow \theta$ .

**Example (Mean estimation for Gaussian).** Suppose  $X \sim \mathcal{N}(\theta, 1)$ . Then  $\hat{\theta}_n = \bar{X}_n \sim \mathcal{N}(\theta, 1/n)$ , i.e.,  $\sqrt{n}(\hat{\theta}_n - \theta) \sim \mathcal{N}(0, 1)$ . This implies that we can write down a confidence interval (CI) such that  $\hat{\theta}_n \pm 1.96/\sqrt{n}$  with 95% CI for  $\hat{\theta}_n$ .

Doing this for other kind of estimators and  $F$  is not that straightforward and will be challenging.

**Remark.** Let  $(X_n)$  and  $X$  be  $d$ -dimensional random vectors,  $h: \mathbb{R}^d \rightarrow \mathbb{R}^m$ , and  $c \in \mathbb{R}^d$  constant.

- (a) If  $X_n \rightarrow c$ , then  $h(X_n) \rightarrow h(c)$  if  $h$  is continuous at  $c$ .<sup>a</sup> This also holds for  $\xrightarrow{\text{a.s.}}$  and  $\xrightarrow{p}$ .
- (b) If  $X_n \rightarrow X$ , then  $h(X_n) \rightarrow h(X)$  if  $h$  is continuous. This also holds for  $\xrightarrow{\text{a.s.}}$  and  $\xrightarrow{p}$ .

<sup>a</sup>This is an if and only if condition if this holds for any  $h$ .



Let's see some examples.

**Example.** If  $d = 1$ , and  $X_n \rightarrow \theta \neq 0$ . Then  $1/X_n \rightarrow 1/\theta$  where

$$h(x) = \begin{cases} \frac{1}{x}, & \text{if } x \neq 0; \\ c, & \text{if } x = 0 \end{cases}$$

for any  $c \in \mathbb{R}$ . The same holds for  $\xrightarrow{\text{a.s.}}$  and  $\xrightarrow{P}$ .

**Example.** If  $X_n \rightarrow X$  and  $Y_n \rightarrow Y$ , then  $(X_n Y_n) \rightarrow (X, Y)$ .<sup>a</sup> The same holds for  $\xrightarrow{\text{a.s.}}$  and  $\xrightarrow{P}$ .

<sup>a</sup>The converse is also true since projections are continuous.

**Proof.**  $\|(X_n, Y_n) - (X, Y)\| \rightarrow 0$  since  $\|(X_n, Y_n) - (X, Y)\| \leq \|X_n - X\| + \|Y_n - Y\|$  for all  $n \geq 1$ .<sup>a</sup> The latter two terms goes to 0 (in whatever sense) by assumption.  $\otimes$

<sup>a</sup>This can be seen from  $\sqrt{x+y} \leq \sqrt{x} + \sqrt{y}$ .

## Lecture 3: Weak Convergence Portmanteau Theorem

### 2.2 Weak Convergence

25 Jan. 9:30

All convergences we have discussed are in some senses “point-wise” but not “distribution-wise”, and the latter is more powerful. Consider working with a probability space  $(\Omega, \mathcal{F}, \mathbb{P})$  and the following.

**Definition 2.2.1 (Total variation).** The *total variation* distance between  $X$  and  $Y$  in  $\Omega$  is defined as

$$\text{TV}(X, Y) = \sup_{B \in \mathcal{F}} |\mathbb{P}(X \in B) - \mathbb{P}(Y \in B)|$$

Returning to our situation, consider a sequence of random variables  $(X_n)$  and a random variable  $X$ .

**Remark.** If  $X_n$  has density  $f_n$  and  $X$  has density  $f$ , then  $\text{TV}(X_n, X) = \frac{1}{2} \int |f_n - f|$ .

**Definition 2.2.2 (Converge in total variation).**  $(X_n)$  *converges in total variation* to  $X$ , denoted as  $X_n \xrightarrow{\text{TV}} X$ , if  $\text{TV}(X_n, X) \rightarrow 0$  as  $n \rightarrow \infty$ .

**Remark.** If  $X_n$  and  $X$  have densities  $f_n$  and  $f$ ,  $f_n \rightarrow f$  implies  $X_n \xrightarrow{\text{TV}} X$  from [Scheffé's theorem](#).

**Note.** The above could make sense even if  $X_n$  is defined on different  $(\Omega_n, \mathcal{F}_n, \mathbb{P}_n)$  for every  $n$ .

Let's see some examples.

**Example.** Consider  $X_n \sim \text{Bin}(n, p_n)$  such that  $np_n \rightarrow \lambda \in \mathbb{R}$ . As this happens,

$$X_n \sim \text{Bin}(n, p_n) \xrightarrow{\text{TV}} X \sim \text{Pois}(\lambda).$$

**Example.** Let  $X_n \sim f_{\theta_n}$  where  $f_{\theta}(x) = f(x)e^{\theta x - \psi(\theta)}$  for some  $\theta \in \Theta$ . If  $\theta_n \rightarrow \theta$ , then  $X_n \xrightarrow{\text{TV}} X \sim f_{\theta}$ . For example, if  $X_n \sim \text{Pois}(\theta_n)$  and  $\theta_n \rightarrow \theta$ , then  $X_n \xrightarrow{\text{TV}} X \sim \text{Pois}(\theta)$ .

However, [convergence in total variation](#) might be too strong to work with.

**Example.** Let  $X_n \sim \mathcal{U}\{0, 1/n, \dots, (n-1)/n\}$ , which should be converging to  $X \sim \mathcal{U}(0, 1)$ . However, this doesn't happen in total variation distance as we can take  $B$  to be  $\mathbb{Q}$ .

This suggests that we should look at something weaker.

**Definition 2.2.3 (Converge weakly).**  $(X_n)$  converges weakly to  $X$ , denoted as  $X_n \xrightarrow{w} X$ , if for all bounded continuous  $g: \mathbb{R}^d \rightarrow \mathbb{R}$ ,  $\mathbb{E}[g(X_n)] \rightarrow \mathbb{E}[g(X)]$ .

To see how is [weak convergence](#) compared to [convergence in total variation](#), we revisit the above.

**Example.** Let  $X_n \sim \mathcal{U}\{0, 1/n, \dots, (n-1)/n\}$ , which should be converging to  $X \sim \mathcal{U}(0, 1)$ . We have

$$\mathbb{E}[g(X_n)] = \sum_{k=0}^{n-1} g(k/n) \left( \frac{k+1}{n} - \frac{k}{n} \right) \rightarrow \int_0^1 g(x) dx = \mathbb{E}[g(X)]$$

as  $g$  is bounded and continuous on  $[0, 1]$ , hence Riemann integrable.

### 2.2.1 Portmanteau Theorem

The following is our main tool of proving [weak convergence](#).

**Theorem 2.2.1 (Portmanteau theorem).** The following are equivalent.

- (a)  $X_n \xrightarrow{w} X$ .
- (b)  $\mathbb{E}[g(X_n)] \rightarrow \mathbb{E}[g(X)]$  for all bounded Lipschitz  $g: \mathbb{R}^d \rightarrow \mathbb{R}$ .
- (c)  $\mathbb{P}(X \in A) \leq \liminf_{n \rightarrow \infty} \mathbb{P}(X_n \in A)$  for all  $A \subseteq \mathbb{R}^d$  open.
- (d)  $\mathbb{P}(X \in A) \geq \limsup_{n \rightarrow \infty} \mathbb{P}(X_n \in A)$  for all  $A \subseteq \mathbb{R}^d$  closed.
- (e)  $\mathbb{P}(X_n \in A) \rightarrow \mathbb{P}(X \in A)$  for all  $A$  such that  $\mathbb{P}(X \in \partial A) = 0$ .

Before we prove [Portmanteau theorem](#), we should note that all our discussion can be extended to metric spaces from Euclidean spaces. Let's first recall some basic results for metric spaces.

**Claim.** Given a metric space  $(S, \rho)$ ,  $\rho(\cdot, A)$  is Lipschitz for any  $A \subseteq S$ , i.e., for any  $x, y \in S$ ,

$$|\rho(x, A) - \rho(y, A)| \leq \rho(x, y).$$

**Proof.** Since for any  $z \in S$ ,  $\rho(x, z) \leq \rho(x, y) + \rho(y, z)$ , hence  $\rho(x, A) - \rho(y, A) \leq \rho(x, y)$  by taking the infimum over  $z \in A$ . Interchanging  $x$  and  $y$  gives another inequality.  $\circledast$

**Claim.** Given a metric space  $(S, \rho)$ , for any  $A \subseteq S$ ,  $x \in \overline{A} \Leftrightarrow \rho(x, A) = 0$ .

**Proof.** If  $x \in \overline{A}$ , there exists  $(x_n)$  in  $A$  such that  $\rho(x_n, x) \rightarrow 0$ . Then for any  $z \in A$ ,  $\rho(x, z) \leq \rho(x, x_n) + \rho(x_n, z)$ , implying

$$\rho(x, A) \leq \rho(x, x_n) + \rho(x_n, A) \rightarrow 0,$$

hence  $\rho(x, A) = 0$ . On the other hand, suppose  $\rho(x, A) = 0$ . As  $\rho(x, A) = \inf_{y \in A} \rho(x, y)$ , there exists  $(y_n)$  in  $A$  such that  $\rho(x, y_n) \rightarrow \rho(x, A) = 0$ , i.e.,  $x \in \overline{A}$ .  $\circledast$

The crucial lemma we're going to use to prove [Portmanteau theorem](#) is the following.

**Lemma 2.2.1.** Given a metric space  $(S, \rho)$  and let  $A \subseteq S$  be a closed subset. Then there exists bounded Lipschitz  $g_k: S \rightarrow \mathbb{R}$ , decreasing in  $k$  such that  $g_k(x) \searrow \mathbb{1}_A(x)$ .

**Proof.** Since  $A$  is closed,  $A = \overline{A}$  and

$$\mathbb{1}_A(x) = \begin{cases} 1, & \text{if } x \in A \Leftrightarrow \rho(x, A) = 0; \\ 0, & \text{if } x \notin A \Leftrightarrow \rho(x, A) > 0. \end{cases}$$

Now, we let

$$g_k(x) = \begin{cases} 0, & \text{if } \rho(x, A) > \frac{1}{k}; \\ 1 - k\rho(x, A), & \text{otherwise;} \end{cases} = 1 - (k\rho(x, A) \wedge 1).$$

We see that

- if  $x \in A$ :  $\mathbb{1}_A(x) = 1$ , and  $g_k(x) = 1$  since  $\rho(x, A) = 0$ ;
- if  $x \notin A$ :  $\mathbb{1}_A(x) = 0$ , and  $\rho(x, A) > 0$  since  $A$  closed, and  $g_k(x) = 0$  for all large enough  $k$ .

Finally, it's clear that  $g_k(x)$  takes values in  $[0, 1]$ , and we now show it's Lipschitz. We have

$$|g_k(x) - g_k(y)| = |(k\rho(x, A) \wedge 1) - (k\rho(y, A) \wedge 1)| \leq k\rho(x, y)$$

for all  $x, y \in S$ . ■

Then we can prove the [Portmanteau theorem](#).

**Proof of Theorem 2.2.1.** (a)  $\Rightarrow$  (b) is clear. And we start by proving (c)  $\Leftrightarrow$  (d).

**Claim.** (c)  $\Leftrightarrow$  (d).

**Proof.** We first prove that (d)  $\Rightarrow$  (c). Since when  $A$  is open,

$$\begin{aligned} \mathbb{P}(X \in A) &= 1 - \mathbb{P}(X \in A^c) \leq 1 - \limsup_{n \rightarrow \infty} \mathbb{P}(X_n \in A^c) \\ &= 1 - \limsup_{n \rightarrow \infty} (1 - \mathbb{P}(X_n \in A)) = \liminf_{n \rightarrow \infty} \mathbb{P}(X_n \in A). \end{aligned} \tag{d}$$

(c)  $\Rightarrow$  (d) is exactly the same, hence (c)  $\Leftrightarrow$  (d). ⊗

Next, we prove (b)  $\Rightarrow$  (d), which gives us (a)  $\Rightarrow$  (b)  $\Rightarrow$  (d)  $\Leftrightarrow$  (c).

**Claim.** (b)  $\Rightarrow$  (d).

**Proof.** From [Lemma 2.2.1](#), there exists bounded Lipschitz  $g_k \searrow \mathbb{1}_A$  such that for all closed  $A$ ,

$$\mathbb{P}(X_n \in A) = \mathbb{E}[\mathbb{1}_A(X_n)] \leq \mathbb{E}[g_k(X_n)].$$

This is true for every  $k$  and  $n$  since  $g_k \geq \mathbb{1}_A$ , and by taking the limit as  $n \rightarrow \infty$ ,

$$\limsup_{n \rightarrow \infty} \mathbb{P}(X_n \in A) \leq \limsup_{n \rightarrow \infty} \mathbb{E}[g_k(X_n)] = \mathbb{E}[g_k(X)]$$

from our assumption (b). Finally, as  $k \rightarrow \infty$ , it goes to  $\mathbb{E}[\mathbb{1}_A(X)] = \mathbb{P}(X \in A)$  as desired. ⊗

*The proof will be continued...*

## Lecture 4: Continuous Mapping Theorem

Before finishing the proof of [Portmanteau theorem](#), we need one additional tool.

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**Lemma 2.2.2.** If  $\{A_i\}_{i \in I}$  are pairwise disjoint events, then  $\{i \in I : \mathbb{P}(A_i) > 0\}$  is countable.<sup>a</sup>

<sup>a</sup>Note that  $I$  can be uncountable.

**Proof.** Since we can write

$$\{i \in I: \mathbb{P}(A_i) > 0\} = \bigcup_{k=1}^{\infty} \left\{i \in I: \mathbb{P}(A_i) \geq \frac{1}{k}\right\} =: \bigcup_{k=1}^{\infty} I_k,$$

hence it suffices to show  $|I_k| < \infty$  for any  $k \geq 1$ . Indeed, for any  $k$ ,  $|I_k| \leq k$ . Suppose not. Then there exists a countable  $J_k \subseteq I_k$  such that  $|J_k| > k$ , implying

$$\mathbb{P}\left(\bigcup_{i \in J_k} A_i\right) = \sum_{i \in J_k} \mathbb{P}(A_i) \geq \frac{|J_k|}{k} > 1,$$

which is a contradiction. ■

We now finish the proof of [Portmanteau theorem](#).

**Proof of Theorem 2.2.1 (cont.)** We already proved (a)  $\Rightarrow$  (b)  $\Rightarrow$  (d)  $\Leftrightarrow$  (c).

**Claim.** (c) + (d)  $\Rightarrow$  (e).

**Proof.** We see that for any  $A$ ,  $A^o \subseteq A \subseteq \overline{A}$ , and from (c),

$$\begin{aligned} \mathbb{P}(X \in A^o) &\leq \liminf_{n \rightarrow \infty} \mathbb{P}(X_n \in A^o) \leq \liminf_{n \rightarrow \infty} \mathbb{P}(X_n \in A) \\ &\leq \limsup_{n \rightarrow \infty} \mathbb{P}(X_n \in A) \leq \limsup_{n \rightarrow \infty} \mathbb{P}(X_n \in \overline{A}) \leq \mathbb{P}(X \in \overline{A}) \end{aligned}$$

where the last step follows from (d). Finally, since

$$\mathbb{P}(X \in \overline{A}) - \mathbb{P}(X \in A^o) = \mathbb{P}(\{X \in \overline{A}\} \setminus \{X \in A^o\}) = \mathbb{P}(X \in (\overline{A} \setminus A^o)) = \mathbb{P}(X \in \partial A),$$

which is 0 by our assumption, i.e., inequalities above are all equalities. In particular, since

$$\liminf_{n \rightarrow \infty} \mathbb{P}(X_n \in A) \leq \lim_{n \rightarrow \infty} \mathbb{P}(X_n \in A) \leq \limsup_{n \rightarrow \infty} \mathbb{P}(X_n \in A)$$

$$\text{and } \mathbb{P}(X \in A^o) \leq \mathbb{P}(X \in A) \leq \mathbb{P}(X \in \overline{A}), \quad \mathbb{P}(X \in A) = \lim_{n \rightarrow \infty} \mathbb{P}(X_n \in A). \quad \textcircled{*}$$

Finally, we prove the following.

**Claim.** (e)  $\Rightarrow$  (a).

**Proof.** For every  $g: \mathbb{R}^d \rightarrow \mathbb{R}$  bounded and continuous, we want to show  $\mathbb{E}[g(X_n)] \rightarrow \mathbb{E}[g(X)]$ . Suppose  $g \geq 0$ ,<sup>a</sup> and let  $K \geq g(x)$  for every  $x \in \mathbb{R}^d$  (which exists since  $g$  is bounded), then

$$\mathbb{E}[g(X_n)] = \int_0^K \mathbb{P}(g(X_n) > t) dt, \quad \mathbb{E}[g(X)] = \int_0^K \mathbb{P}(g(X) > t) dt,$$

so we just need to prove the convergence of the above two integrals. From bounded convergence theorem, it suffices to show that for almost every  $t \in [0, K]$ ,

$$\mathbb{P}(g(X_n) > t) \rightarrow \mathbb{P}(g(X) > t).$$

Observe that  $\mathbb{P}(g(X_n) > t) = \mathbb{P}(X_n \in \{g > t\})$  and  $\mathbb{P}(g(X) > t) = \mathbb{P}(X \in \{g > t\})$ , so from (e) with  $A := \{g > t\}$ , it suffices to show  $\mathbb{P}(X \in \partial\{g > t\}) = 0$  for almost all  $t$ . Firstly,

$$\mathbb{P}(X \in \partial\{g > t\}) = \mathbb{P}(X \in \overline{\{g > t\}} \setminus \{g > t\}^o) = \mathbb{P}(X \in \overline{\{g \geq t\}} \setminus \{g > t\}) = \mathbb{P}(g(X) = t).$$

Moreover, consider the events  $\{g(X) = t\}_{t \in [0, K]}$ , which are pairwise disjoint, hence [Lemma 2.2.2](#) implies  $\mathbb{P}(g(X) = t) = 0$  for all but countably many  $t$ 's, exactly what we want to show. ⊗

<sup>a</sup>Otherwise, we consider  $g = g^+ - g^-$  where  $g^+ = \max(g, 0)$  and  $g^- = \max(-g, 0)$ , and everything follows.

This finishes the proof. ■

### 2.2.2 Continuous Mapping Theorem

A common scenario is that given a nice function  $h$  (in terms of continuity), if  $X_n \xrightarrow{w} X$ , we want to know when will  $h(X_n) \xrightarrow{w} h(X)$ . To develop the theorem of this, we need some more facts about metric spaces.

**As previously seen.** Given two metric spaces  $(S, \rho)$ ,  $(S', \rho')$ ,  $g: S \rightarrow S'$  is continuous if  $x_n \xrightarrow{\rho} x$  implies  $g(x_n) \xrightarrow{\rho'} g(x)$ , or for open  $A \subseteq S'$ ,  $g^{-1}(A) \subseteq S$  is open.

**Notation.** We sometimes write  $g^{-1}(A) =: \{g \in A\}$ .

It's clear that the following holds.

**Note.** If  $g: S \rightarrow S'$  is continuous and  $A \subseteq S'$  is closed, then  $\overline{\{g \in A\}} = \{g \in \overline{A}\}$ .

However, when  $g$  is not continuous and  $A$  is not closed, the situation is a bit more complicated. But at least we can first look at the set where  $g$  is continuous.

**Notation** (Continuous set). For any  $g: S \rightarrow S'$ , we denote the *continuous set* as  $C_g := \{x \in S: g \text{ is continuous at } x\}$ .

Then we have the following.

**Proposition 2.2.1.** Given  $g: S \rightarrow S'$  between metric spaces and  $A \subseteq S'$ ,

$$C_g \cap \overline{\{g \in A\}} \subseteq \{g \in \overline{A}\}.$$

**Proof.** Let  $x \in C_g \cap \overline{\{g \in A\}}$ . Since  $x \in \overline{\{g \in A\}}$ , there exists  $(x_n) \in \{g \in A\}$  such that  $x_n \xrightarrow{\rho} x$ . Moreover,  $x \in C_g$  implies  $g$  is continuous at  $x$ , hence  $g(x_n) \xrightarrow{\rho'} g(x)$ , i.e.,  $g(x) \in \overline{A}$ . ■

This allows us to prove the following theorem, which answers our main question in this section.

**Theorem 2.2.2** (Continuous mapping theorem). Consider  $X_n \xrightarrow{w} X$  and  $h: \mathbb{R}^d \rightarrow \mathbb{R}^m$ . If  $\mathbb{P}(X \in C_h) = 1$ , then  $h(X_n) \xrightarrow{w} h(X)$ .

**Proof.** Let  $A \subseteq \mathbb{R}^m$  be a closed set. Then from [Portmanteau theorem \(d\)](#), we need to show

$$\limsup_{n \rightarrow \infty} \mathbb{P}(h(X_n) \in A) \leq \mathbb{P}(h(X) \in A).$$

Since  $\limsup_{n \rightarrow \infty} \mathbb{P}(h(X_n) \in A) = \limsup_{n \rightarrow \infty} \mathbb{P}(X_n \in \{h \in A\})$ , implying

$$\limsup_{n \rightarrow \infty} \mathbb{P}(h(X_n) \in A) \leq \limsup_{n \rightarrow \infty} \mathbb{P}(X_n \in \overline{\{h \in A\}}) \leq \mathbb{P}(X \in \overline{\{h \in A\}}),$$

where the last inequality follows again from [Portmanteau theorem \(d\)](#) since  $\overline{\{h \in A\}}$  is clearly closed and  $X_n \xrightarrow{w} X$ . Finally, as  $\mathbb{P}(X \in C_h) = 1$ ,

$$\mathbb{P}(X \in \overline{\{h \in A\}}) = \mathbb{P}(X \in \overline{\{h \in A\}} \cap C_h) \leq \mathbb{P}(X \in \{h \in \overline{A}\})$$

from [Proposition 2.2.1](#), i.e.,

$$\limsup_{n \rightarrow \infty} \mathbb{P}(h(X_n) \in A) \leq \mathbb{P}(X \in \{h \in \overline{A}\}) = \mathbb{P}(X \in \{h \in A\}) = \mathbb{P}(h(X) \in A)$$

since  $A$  is closed, hence we're done. ■

**Example.** Let  $d = 1$  and  $X_n \xrightarrow{w} X$  where  $X$  is continuous. Then  $1/X_n \xrightarrow{w} 1/X$  and  $X_n^2 \xrightarrow{w} X^2$ .

**Proof.** For the case of  $X^2 \xrightarrow{w} X^2$ , [continuous mapping theorem](#) clearly applies with  $h(x) = x^2$ . For the first case, consider

$$h(x) = \begin{cases} \frac{1}{x}, & \text{if } x \neq 0; \\ 0, & \text{if } x = 0. \end{cases}$$

This means  $C_h = \mathbb{R} \setminus \{0\}$ . Then, we just need to show  $\mathbb{P}(X \in C_h) = 1$  and apply [continuous mapping theorem](#). Observe that this is the same as asking  $\mathbb{P}(X = 0) = 0$ , which is true when  $X$  is continuous.<sup>a</sup> ⊛

<sup>a</sup>Even if  $X$  is not continuous, as long as this is true we can conclude the same thing.

Another useful theorem for proving [weak convergence](#) is the following.

**Theorem 2.2.3 (Converging together).** Let  $X_n \xrightarrow{w} X$ , and if  $Y_n$  on the same probability space as  $X_n$  such that  $\|X_n - Y_n\| \xrightarrow{p} 0$ , i.e., for all  $\epsilon > 0$ ,  $\mathbb{P}(\|X_n - Y_n\| > \epsilon) \rightarrow 0$  as  $n \rightarrow \infty$ . Then,  $Y_n \xrightarrow{w} X$ .

We first see some applications.

**Corollary 2.2.1.** If  $Y_n \xrightarrow{p} X$ , then  $Y_n \xrightarrow{w} X$ . The converse holds as long as  $\mathbb{P}(X = c) = 1$  for some constant  $c$ .

**Proof.** By considering  $X_n = X$  for all  $n$ , [Theorem 2.2.3](#) implies that if  $Y_n \xrightarrow{p} X$ ,  $Y_n \xrightarrow{w} X$ . Conversely, if  $Y_n \xrightarrow{w} c$ , from [Portmanteau theorem \(c\)](#), for any fixed  $\epsilon > 0$ ,<sup>a</sup>

$$\underbrace{\mathbb{P}(c \in B(c, \epsilon))}_1 \leq \liminf_{n \rightarrow \infty} \mathbb{P}(Y_n \in B(c, \epsilon)),$$

implying  $\mathbb{P}(Y_n \in B(c, \epsilon)) \rightarrow 1$ , i.e.,  $\mathbb{P}(\|Y_n - c\| < \epsilon) \rightarrow 1$ . ■

<sup>a</sup>Recall that  $B(c, \epsilon)$  is the open ball centered at  $c$  with radius  $\epsilon$ .

## Lecture 5: Convergence in Distribution and Weak Convergence

Now we prove [Theorem 2.2.3](#).

**Proof.** From [Portmanteau theorem \(b\)](#), we want to prove that  $\mathbb{E}[g(Y_n)] \rightarrow \mathbb{E}[g(X)]$  for all bounded and Lipschitz  $g: \mathbb{R}^d \rightarrow \mathbb{R}$ . Specifically, let  $|g(x)| \leq C$  for all  $x \in \mathbb{R}^d$  and  $|g(x) - g(y)| \leq K\|x - y\|$  for all  $x, y \in \mathbb{R}^d$ . From triangle inequality,

$$|\mathbb{E}[g(Y_n)] - \mathbb{E}[g(X)]| \leq |\mathbb{E}[g(Y_n)] - \mathbb{E}[g(X_n)]| + |\mathbb{E}[g(X_n)] - \mathbb{E}[g(X)]|.$$

Since  $X_n \xrightarrow{w} X$ , the second term goes to 0. As for the first term, since  $Y_n$  and  $X_n$  are in the same probability space, we see that

$$\begin{aligned} |\mathbb{E}[g(Y_n)] - \mathbb{E}[g(X_n)]| &= |\mathbb{E}[g(Y_n) - g(X_n)]| \\ &\leq \mathbb{E}[|g(Y_n) - g(X_n)|] \\ &= \mathbb{E}[|g(Y_n) - g(X_n)| \cdot \mathbb{1}_{\|X_n - Y_n\| > \epsilon}] + \mathbb{E}[|g(Y_n) - g(X_n)| \cdot \mathbb{1}_{\|X_n - Y_n\| \leq \epsilon}] \\ &\leq 2C\mathbb{P}(\|X_n - Y_n\| > \epsilon) + K\epsilon\mathbb{P}(\|X_n - Y_n\| \leq \epsilon) \\ &\leq 2C\mathbb{P}(\|X_n - Y_n\| > \epsilon) + K\epsilon. \end{aligned}$$

As  $n \rightarrow \infty$ , we finally have

$$\limsup_{n \rightarrow \infty} |\mathbb{E}[g(Y_n)] - \mathbb{E}[g(X)]| \leq K\epsilon$$

for all  $\epsilon > 0$ , by letting  $\epsilon \rightarrow 0$ , we're done. ■

We can now apply [Theorem 2.2.3](#) to prove something similar as we have seen before in the case of [convergence in probability](#).

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**As previously seen.**  $X_n \xrightarrow{p} X$  and  $Y_n \xrightarrow{p} Y$  if and only if  $(X_n, Y_n) \xrightarrow{p} (X, Y)$ .

Now, in the case of **weak convergence**, from **continuous mapping theorem**, we see that if  $(X_n, Y_n) \xrightarrow{w} (X, Y)$ , then  $X_n \xrightarrow{w} X$  and  $Y_n \xrightarrow{w} Y$ . However, the converse needs not be true.

**Example.** Consider a random variable  $X$  on  $(\Omega, \mathcal{F}, \mathbb{P})$ , and let  $X_n = X$ ,  $Y_n = -X$  for all  $n \geq 1$ . If  $X \sim \mathcal{N}(0, 1)$ , we see that  $\mathbb{P}(X \in A) = \mathbb{P}(-X \in A)$  for all  $A \subseteq \mathbb{R}^d$ , implying  $X_n \xrightarrow{w} X$  and  $Y_n \xrightarrow{w} X$ . However, this does not imply  $(X_n, Y_n) \xrightarrow{w} (X, X)$  since otherwise, by **continuous mapping theorem**,  $X_n + Y_n \xrightarrow{w} X + X = 2X$ , which is not true since  $X_n + Y_n = 0$ .

But in the case of  $Y$  is a constant, the converse is actually true, and the result is quite useful.

**Theorem 2.2.4 (Slutsky's theorem).** If  $X_n \xrightarrow{w} X$  in  $\mathbb{R}^d$  and  $Y_n \xrightarrow{p} c$  in  $\mathbb{R}^m$ ,<sup>a</sup> then  $(X_n, Y_n) \xrightarrow{w} (X, c)$ .

<sup>a</sup>Recall that from **Corollary 2.2.1**, for a constant  $c$ , **weak convergence** is equivalent to **convergence in probability**.

**Proof.** Firstly, we show that  $(X_n, c) \xrightarrow{w} (X, c)$ . Indeed, since for every continuous and bounded  $g: \mathbb{R}^{d+m} \rightarrow \mathbb{R}$ ,  $\mathbb{E}[g(X_n, c)] \rightarrow \mathbb{E}[g(X, c)]$  follows directly from  $X_n \xrightarrow{w} X$  with  $g(\cdot, c)$  being continuous and bounded.

Secondly, we show that  $\|(X_n, Y_n) - (X_n, c)\| \xrightarrow{p} 0$ . This is easy since

$$\|(X_n, Y_n) - (X_n, c)\| \leq \|X_n - X_n\| + \|Y_n - c\| = \|Y_n - c\|,$$

which goes to 0 in probability as we wish. Combining both with **Theorem 2.2.3** gives the result. ■

Revisiting the **counter-example**, we see that now it's not the case when  $Y$  is a constant.

**Corollary 2.2.2.** If  $X_n \xrightarrow{w} X$  and  $Y_n \xrightarrow{p} c$  in  $\mathbb{R}^d$ ,  $X_n \pm Y_n \xrightarrow{w} X \pm c$ ,  $X_n \cdot Y_n \xrightarrow{w} X \cdot c$ . If  $d = 1$  and  $c \neq 0$ , then  $X_n/Y_n \xrightarrow{w} X/c$ .

**Proof.** This follows directly from **Slutsky's theorem** and **continuous mapping theorem**. ■

### 2.2.3 Convergence in Distribution

So far, the notions of convergence we have talked about applies to general probability space, which needs not to be in  $\mathbb{R}^d$  in general. However, traditionally, the case in  $\mathbb{R}^d$  is considered first.

**Intuition.** There's a conical ordering available in  $\mathbb{R}^d$  to define  $F_X$  and  $F_{X_n}$ .

This allows us to define the following.

**Definition 2.2.4 (Converge in distribution).** Let  $(X_n)$  and  $X$  be random variables in  $\mathbb{R}^d$ . Then  $(X_n)$  converges in distribution to  $X$ , denoted as  $X_n \xrightarrow{D} X$ , if for all  $(t_1, \dots, t_d) \in C_{F_X}$ ,

$$F_{X_n}(t_1, \dots, t_d) \rightarrow F_X(t_1, \dots, t_d).$$

**Note.**  $X_n$  and  $X$  (in  $\mathbb{R}^d$ ) do not have to be on the same probability space.

Specifically, to see how this relates to what we have seen, recall that

$$F_{X_n}(t_1, \dots, t_d) = \mathbb{P}(X_n^i \leq t_i, \forall 1 \leq i \leq d) = \mathbb{P}(X_n \in (-\infty, t_1] \times \dots \times (-\infty, t_d]),$$

same for  $F_X$ . So this reduces to the form we're familiar with, i.e.,  $\mathbb{P}(X_n \in A)$  for some  $A$ .

**Remark.**  $X_n \xrightarrow{TY} X$  implies  $X_n \xrightarrow{D} X$ .

**Proof.** Since  $X_n \xrightarrow{\text{TV}} X$  means  $\mathbb{P}(X_n \in A) \rightarrow \mathbb{P}(X \in A)$  uniformly in  $A$ , but  $X_n \xrightarrow{D} X$  only requires the above holds for  $A$  in the form of  $(-\infty, t_1] \times \cdots \times (-\infty, t_d]$ , which is weaker.  $\circledast$

There are more classical results that are worth mentioning.

**Remark (De Moivre central limit theorem).** Let  $X_n \sim \text{Bin}(n, p)$ , then for every  $t \in \mathbb{R}$ , as  $n \rightarrow \infty$ ,

$$\mathbb{P}\left(\frac{X_n - np}{\sqrt{np(1-p)}} \leq t\right) \rightarrow \frac{1}{\sqrt{2\pi}} \int_{-\infty}^t e^{-u^2/2} du = \Phi(t).$$

**Proposition 2.2.2.** Let  $X_n$  and  $X$  be in  $\mathbb{Z}$  such that  $f_n$  and  $f$  are their corresponding PMF's, then

$$f_n \rightarrow f \Leftrightarrow X_n \xrightarrow{\text{TV}} X \Leftrightarrow X_n \xrightarrow{D} X.$$

**Proof.** The forward implications are clear, so we just need to show  $X_n \xrightarrow{D} X$  implies  $f_n \rightarrow f$ . Since for every  $t \in \mathbb{Z}$ , since  $X_n$  and  $X$  are discrete in  $\mathbb{Z}$ ,

$$f_n(t) = \mathbb{P}(X_n = t) = \mathbb{P}(X_n \leq t + \epsilon) - \mathbb{P}(X_n \leq t - \epsilon)$$

for some  $\epsilon > 0$  small enough. Now, as  $t \pm \epsilon$  are in  $C_X$  clearly,  $X_n \xrightarrow{D} X$  implies

$$\mathbb{P}(X_n \leq t + \epsilon) \rightarrow \mathbb{P}(X \leq t + \epsilon),$$

and the same holds for  $t - \epsilon$ , hence

$$f_n(t) = \mathbb{P}(X_n = t) = \mathbb{P}(X_n \leq t + \epsilon) - \mathbb{P}(X_n \leq t - \epsilon) \rightarrow \mathbb{P}(X \leq t + \epsilon) - \mathbb{P}(X \leq t - \epsilon) = \mathbb{P}(X = t) = f(t).$$

As this holds for every  $t \in \mathbb{Z}$ , we're done.  $\blacksquare$

Now, the problem one might have is the following.

**Problem.** Why not defined for all  $t \in \mathbb{R}^d$ , rather than  $t \in C_{F_X}$ ?

**Answer.** Consider for  $d = 1$  with  $X = c \in \mathbb{R}$ , i.e.,  $F_X$  is the step function at  $c$ . To show  $X_n \xrightarrow{D} c$ , we don't have to show  $\mathbb{P}(X_n \leq c) \rightarrow \mathbb{P}(X \leq c) = 1$ . Otherwise, if we need to show this for all  $t$ , in particular,  $c$ ,  $X_n = c + 1/n$  would not satisfy this.  $\circledast$

If  $X_n \xrightarrow{D} X$  and  $X$  is continuous, then  $F_{X_n}$  converges to  $F_X$  not only point-wise, but uniformly.

**Remark (Polya's theorem).** If  $F_X$  is continuous,  $X_n \xrightarrow{D} X$  is equivalent as

$$\sup_{t \in \mathbb{R}^d} |F_{X_n}(t) - F_X(t)| \rightarrow 0.$$

Now we have seen various remarks and clarifications about [convergence in distribution](#), the upshot is that, it is actually just a renaming of [weak convergence](#) in  $\mathbb{R}^d$ !

**Theorem 2.2.5.** Given  $X_n$  and  $X$  in  $\mathbb{R}^d$ , then  $X_n \xrightarrow{w} X$  if and only if  $X_n \xrightarrow{D} X$ .

**Proof.** We prove for the case of  $d = 1$ , then it's easy to see the same holds for  $d \geq 1$ . For the forward direction, we want to show that for all  $t \in C_{F_X}$ ,  $\mathbb{P}(X_n \leq t) \rightarrow \mathbb{P}(X \leq t)$ . Note that  $\mathbb{P}(X \leq t) = \mathbb{P}(X \in (-\infty, t])$  and  $\mathbb{P}(X_n \leq t) = \mathbb{P}(X_n \in (-\infty, t])$ , hence, from [Portmanteau theorem \(e\)](#) with  $A = (-\infty, t]$ ,  $X_n \xrightarrow{w} X$  is equivalently as saying  $\mathbb{P}(X_n \leq t) \rightarrow \mathbb{P}(X \leq t)$  if

$$\mathbb{P}(X \in \partial(-\infty, t]) = \mathbb{P}(X \in \{t\}) = \mathbb{P}(X = t)$$

is 0. This is indeed the case since  $t \in C_{F_X}$ , hence we're done.



To show the backward direction, we need the following lemma.

**Lemma 2.2.3.**  $X_n \xrightarrow{D} X$  if and only if for all  $x \in \mathbb{R}^d$ ,

$$F_X(x^-) \leq \liminf_{n \rightarrow \infty} F_{X_n}(x^-) \leq \liminf_{n \rightarrow \infty} F_{X_n}(x) \leq \limsup_{n \rightarrow \infty} F_{X_n}(x) \leq F_X(x).$$

**Proof.** The backward direction is clear, so we prove the forward direction. When  $x \in C_{F_X}$ , we're clearly done, so consider  $x \notin C_{F_X}$ . Firstly, note that  $|C_{F_X}^c|$  is countable, so there exists  $(x_k) \nearrow x$  and  $(y_k) \searrow x$ , both in  $C_{F_X}$ . Hence, for all  $n \geq 1$  and  $k \geq 1$ ,

$$F_{X_n}(x_k) \leq F_{X_n}(x) \leq F_{X_n}(y_k)$$

as  $F_{X_n}$  is increasing. We now have for every  $k \geq 1$ ,

$$\begin{aligned} F_X(x_k) &= \lim_{n \rightarrow \infty} F_{X_n}(x_k) && x_k \in C_{F_X} \\ &\leq \liminf_{n \rightarrow \infty} F_{X_n}(x^-) \\ &\leq \liminf_{n \rightarrow \infty} F_{X_n}(x) && F_{X_n} \text{ is increasing} \\ &\leq \limsup_{n \rightarrow \infty} F_{X_n}(x) \\ &\leq \limsup_{n \rightarrow \infty} F_{X_n}(y_k) = F_X(y_k). && y_k \in C_{F_X} \end{aligned}$$

By taking  $k \rightarrow \infty$ ,  $F_X(x_k) \rightarrow F_X(x^-)$ , while  $F_X(y_k) \rightarrow F_X(x)$ ,<sup>a</sup> and we're done.

<sup>a</sup>Recall that the distribution function is always right-continuous.

The proof will be *continued*...

## Lecture 6: Stochastic Boundedness and Delta Theorem

Before we finish the proof of [Theorem 2.2.5](#), we recall one important characterization of  $\liminf$ .

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**As previously seen.** Given two real sequence  $x_n$  and  $y_n$ ,

$$\liminf_{n \rightarrow \infty} (x_n + y_n) \geq \liminf_{n \rightarrow \infty} x_n + \liminf_{n \rightarrow \infty} y_n,$$

where the equality holds when either  $x_n$  or  $y_n$  converges (not if and only if).

We can then finish the proof of [Theorem 2.2.5](#).

**Proof of Theorem 2.2.5 (cont.)** Now we can prove the backward direction. From [Portmanteau theorem \(c\)](#), it suffices to show that for every open  $A \subseteq \mathbb{R}$ , we have

$$\mathbb{P}(X \in A) \leq \liminf_{n \rightarrow \infty} \mathbb{P}(X_n \in A).$$

From the elementary analysis, we see that it suffices to show when  $A = (a, b)$  since when  $A \subseteq \mathbb{R}$  is open, one can write  $A = \bigcup_{k=1}^{\infty} (a_k, b_k)$  where  $(a_k, b_k)$ 's disjoint, and have

$$\begin{aligned} \mathbb{P}(X \in A) &= \sum_{k=1}^{\infty} \mathbb{P}(X \in (a_k, b_k)) \\ &\leq \sum_{k=1}^{\infty} \liminf_{n \rightarrow \infty} \mathbb{P}(X_n \in (a_k, b_k)) && \text{assume true for each } (a_k, b_k) \\ &\leq \liminf_{n \rightarrow \infty} \sum_{k=1}^{\infty} \mathbb{P}(X_n \in (a_k, b_k)) = \liminf_{n \rightarrow \infty} \mathbb{P}(X_n \in A), \end{aligned}$$

where the last inequality follows from an induction on  $\liminf_{n \rightarrow \infty} (x_n + y_n) \geq \liminf_{n \rightarrow \infty} x_n + \liminf_{n \rightarrow \infty} y_n$ . Now, we show that  $\mathbb{P}(X \in A) \leq \liminf_{n \rightarrow \infty} \mathbb{P}(X_n \in A)$  when  $A = (a, b)$ .

**Claim.**  $\mathbb{P}(X \in (a, b)) \leq \liminf_{n \rightarrow \infty} \mathbb{P}(X_n \in (a, b))$ .

**Proof.** Observe that  $\mathbb{P}(X \in (a, b)) = F_X(b^-) - F_X(a)$ , with [Lemma 2.2.3](#), we further have

$$\begin{aligned} \mathbb{P}(X \in (a, b)) &= F_X(b^-) - F_X(a) \\ &\leq \liminf_{n \rightarrow \infty} F_{X_n}(b^-) - \left( \limsup_{n \rightarrow \infty} F_{X_n}(a) \right) \\ &\leq \liminf_{n \rightarrow \infty} F_{X_n}(b^-) + \liminf_{n \rightarrow \infty} (-F_{X_n}(a)) \\ &\leq \liminf_{n \rightarrow \infty} (F_{X_n}(b^-) - F_{X_n}(a)) = \liminf_{n \rightarrow \infty} \mathbb{P}(X_n \in (a, b)), \end{aligned}$$

which proves the claim. ⊗

This proves the case of  $d = 1$ . ■

[Theorem 2.2.5](#) means that when talking about random vectors, we can use every result we have proved for the case of [weak convergence](#). Let's see one application, which uses [weak convergence](#)'s result but now prove something about the distribution.

**Proposition 2.2.3.** If  $X_n \xrightarrow{D} X$  and  $t_n \rightarrow t \in C_{F_X}$ , then  $\mathbb{P}(X_n \leq t_n) \rightarrow \mathbb{P}(X \leq t)$ .

**Proof.** We see that from [Corollary 2.2.2](#),  $X_n - t_n \xrightarrow{w} X - t$ , i.e.,  $X_n - t_n \xrightarrow{D} X - t$ . Hence,

$$\mathbb{P}(X_n \leq t_n) = \mathbb{P}(X_n - t_n \leq 0) = F_{X_n - t_n}(0) \rightarrow F_{X - t}(0) = \mathbb{P}(X - t \leq 0)$$

as long as  $0 \in C_{F_{X-t}}$ , i.e.,  $\mathbb{P}(X - t = 0) = \mathbb{P}(X = t) = 0$ , which is just  $t \in C_{F_X}$  as we assumed. ■

## 2.2.4 Stochastic Boundedness

So far we have been talking about the notion of convergence, now we switch the gear a bit and consider boundedness. In this section, let  $(X_i)_{i \in I}$  be a family of  $d$ -dimensional random vectors defined on probability spaces  $(\Omega_i, \mathcal{F}_i, \mathbb{P}_i)$ , with the non-empty index set  $I$ , which can be either finite or infinite.

**Definition 2.2.5 (Bounded in probability).**  $(X_i)_{i \in I}$  is said to be *bounded in probability* if for every  $\epsilon > 0$ , there exists an  $M > 0$  such that for every  $i \in I$ ,

$$\mathbb{P}(\|X_i\| \geq M) < \epsilon.$$

In other words, for every  $\epsilon > 0$ , there exists an  $M > 0$  such that  $\mathbb{P}(\|X_i\| < M) \geq 1 - \epsilon$  for every  $i \in I$ .

**Intuition.** For any arbitrary large probability close to 1 we want, one can find an upper-bound  $M$  on  $\|X_i\|$  uniformly for all  $i \in I$ .

**Note.** When  $X_i = X$  for every  $i \in I$ ,  $(X_i)_{i \in I}$  is trivially [bounded in probability](#).

**Proof.** Since if not, there exists  $\epsilon > 0$ , for every  $M > 0$ ,  $\mathbb{P}(\|X\| \geq M) \geq \epsilon$ . Then as  $M \rightarrow \infty$ ,  $\mathbb{P}(\|X\| = \infty) \geq \epsilon$ , which is a contradiction since  $\|X\| = \infty$ . ⊗

**Remark.** When  $I$  is finite,  $(X_i)_{i \in I}$  is also trivially [bounded in probability](#). On the other hand, when  $I$  is infinite, by considering  $X_n = n$  (deterministic), which is not [bounded in probability](#) anymore.

We now provide some sufficient conditions for being [bounded in probability](#).

**Proposition 2.2.4.** If  $(X_i)_{i \in I}$  is bounded in  $L^p$  for some  $p > 0$ , i.e.,  $\sup_{i \in I} \mathbb{E}[\|X_i\|^p] < \infty$ , then  $(X_i)_{i \in I}$  is **bounded in probability**.

**Proof.** Denote  $K := \sup_{i \in I} \mathbb{E}[\|X_i\|^p] < \infty$ . Since for any  $\epsilon > 0$ , from Markov's inequality,

$$\mathbb{P}(\|X_i\| > M) \leq \frac{\mathbb{E}[\|X_i\|^p]}{M^p} \leq \frac{K}{M^p} =: \epsilon$$

for  $M := \sqrt[p]{K/\epsilon}$ . Hence, we're done.  $\blacksquare$

We now establish some relation between convergence and boundedness. Recall the following fact in elementary analysis.

**As previously seen.** If a deterministic sequence in  $\mathbb{R}$  converges, then it's bounded.

In our context, we might expect something like “if  $X_n \xrightarrow{p} X$ , then  $(X_n)$  is **bounded in probability**.” In fact, we have the following “stronger” result where we only require **convergence in distribution**.

**Proposition 2.2.5.** If  $X_n \xrightarrow{D} X$ , then  $(X_n)$  is **bounded in probability**.

**Proof.** Fix an  $\epsilon > 0$ . There is an  $M > 0$  such that  $\mathbb{P}(\|X\| \geq M) < \epsilon$  since this is a single random vector. To relate this back to  $X_n$ , from **Portmanteau theorem (d)**,

$$\epsilon > \mathbb{P}(\|X\| \geq M) = \mathbb{P}(X \in B^c(0, M)) \geq \limsup_{n \rightarrow \infty} \mathbb{P}(X_n \in B^c(0, M)) = \limsup_{n \rightarrow \infty} \mathbb{P}(\|X_n\| \geq M).$$

In other words,

$$\liminf_{n \rightarrow \infty} \mathbb{P}(\|X_n\| < M) > 1 - \epsilon,$$

i.e., there exists an  $n_0$  such that for every  $n \geq n_0$ ,  $\mathbb{P}(\|X_n\| < M) \geq 1 - \epsilon$ . As for those  $n < n_0$ , since  $\{X_n : n < n_0\}$  is a finite family, we can find  $M' > 0$  such that  $\mathbb{P}(\|X_n\| < M') > 1 - \epsilon$  for every  $n < n_0$ . Finally, by considering  $M'' := \max(M, M')$ , we have  $\mathbb{P}(\|X_n\| < M'') > 1 - \epsilon$ , i.e.,  $\mathbb{P}(\|X_n\| \geq M'') < \epsilon$  as desired.  $\blacksquare$

A kind of converse theorem is called **Prokhorov's theorem**, but we won't prove it here right now. We now see another useful characterization that generalizes our intuition in  $\mathbb{R}$ . Recall the following.

**As previously seen.** In  $\mathbb{R}$ , if  $a_n \rightarrow 0$  and  $b_n$  is bounded,  $a_n b_n \rightarrow 0$ .

The generalization is the following.

**Proposition 2.2.6.** Let  $d = 1$  such that  $X_n$  and  $Y_n$  are defined on the same probability space. If  $X_n \xrightarrow{p} 0$  and  $Y_n$  is **bounded in probability**, then  $X_n Y_n \xrightarrow{p} 0$ .

**Proof.** Fix an  $\epsilon > 0$ . We want to show that  $\mathbb{P}(|X_n Y_n| > \epsilon) \rightarrow 0$ . This is because

$$\begin{aligned} \mathbb{P}(|X_n Y_n| > \epsilon) &= \mathbb{P}(|X_n Y_n| > \epsilon, |Y_n| > M) + \mathbb{P}(|X_n Y_n| > \epsilon, |Y_n| \leq M) \\ &\leq \mathbb{P}(|Y_n| > M) + \mathbb{P}(|X_n Y_n| > \epsilon, |Y_n| \leq M) \leq \mathbb{P}(|Y_n| > M) + \mathbb{P}(|X_n| > \epsilon/M) \end{aligned}$$

for any  $M$ . Now, we see that

- since  $Y_n$  is **bounded in probability**, there's an  $M > 0$  such that  $\mathbb{P}(|Y_n| > M) < \epsilon$  for all  $n$ ;
- since  $X_n \xrightarrow{p} 0$ , for the  $M$  (depends on the fixed  $\epsilon$ ) above,  $\mathbb{P}(|X_n| > \epsilon/M) \rightarrow 0$  as  $n \rightarrow \infty$ .

We see that the second term always goes to 0, while the first term can always be upper-bounded by  $\epsilon$ . Hence, by letting  $\epsilon \rightarrow 0$ , we're done.  $\blacksquare$

We often write the following.

**Notation.** We write  $X_n = o_p(1)$  for  $X_n \xrightarrow{p} 0$ , and  $X_n = O_p(1)$  when  $(X_n)$  is **bounded in probability**.

Let's see one important application which combines the above. Consider an estimator  $T_n$  of  $\theta$ , and a deterministic sequence  $b_n$  which goes to  $\infty$ . In this case, we often have

$$b_n(T_n - \theta) \xrightarrow{D} Y.$$

**Example.** When  $X_n \sim \text{Bin}(n, p)$ , then for  $b_n = \sqrt{n/p(1-p)} \rightarrow \infty$ ,  $T_n = X_n/n$ , and  $\theta = p$ , we have

$$\frac{X_n - np}{\sqrt{np(1-p)}} = \sqrt{\frac{n}{p(1-p)}} \left( \frac{X_n}{n} - p \right) = b_n(T_n - \theta) \rightarrow Y \sim \mathcal{N}(0, 1).$$

This allows us to compute the rate of convergence and the limiting distribution. But what can we say when we care about  $g(T_n)$  for a function  $g$ ?

**Theorem 2.2.6 (Delta method).** Let  $\theta \in \mathbb{R}^d$ ,  $(T_n)$  and  $Y$  be random vectors in  $\mathbb{R}^d$ , and  $b_n \rightarrow \infty$  be a positive deterministic sequence. If  $b_n(T_n - \theta) \xrightarrow{D} Y$ , then  $T_n \xrightarrow{P} \theta$ . Moreover, if  $g: \mathbb{R}^d \rightarrow \mathbb{R}^m$  is differentiable at  $\theta$ ,  $b_n(g(T_n) - g(\theta)) \xrightarrow{D} \nabla g(\theta)Y$ .

**Proof.** We first observe that  $\|b_n(T_n - \theta)\| \in O_p(1)$  since  $b_n(T_n - \theta) \xrightarrow{D} Y$ , with [continuous mapping theorem](#) and the fact that  $\|\cdot\|$  is continuous,  $\|b_n(T_n - \theta)\| \xrightarrow{P} \|Y\|$ , so  $\|b_n(T_n - \theta)\| \in O_p(1)$  by [Proposition 2.2.5](#). With this, as  $b_n \rightarrow \infty$ ,  $T_n \xrightarrow{P} \theta$  since

$$\|T_n - \theta\| = \frac{1}{b_n} \|b_n(T_n - \theta)\| = o(1)O_p(1) \xrightarrow{P} 0$$

as  $o(1)O_p(1) = o_p(1)$  from [Proposition 2.2.6](#). For the second claim, since  $g$  is differentiable at  $\theta$ ,

$$\frac{g(x) - g(\theta) - \nabla g(\theta)(x - \theta)}{\|x - \theta\|} \rightarrow 0$$

when  $x \rightarrow \theta$ . Let  $r(x) := g(x) - g(\theta) - \nabla g(\theta)(x - \theta)$  for  $x \in \mathbb{R}^d$  be the remainder, and consider

$$h(x) = \begin{cases} 0, & \text{if } x = \theta; \\ \frac{r(x)}{\|x - \theta\|}, & \text{if } x \neq \theta, \end{cases}$$

which is continuous at  $\theta$ . Rewriting everything, we have

$$r(x) = g(x) - g(\theta) - \nabla g(\theta)(x - \theta) = h(x)\|x - \theta\|$$

for every  $x \in \mathbb{R}^d$ . Now, let  $x = T_n$ , multiply both sides by  $b_n$ , and take the norm, we see that

$$\|b_n(g(T_n) - g(\theta)) - \nabla g(\theta)b_n(T_n - \theta)\| = \|h(T_n)\| \|b_n(T_n - \theta)\|.$$

We observe the following.

**Claim.** It suffices to show that the right-hand sides goes to 0 in probability.

**Proof.** Since it implies that  $b_n(g(T_n) - g(\theta))$  has the same weak limit as  $\nabla g(\theta)b_n(T_n - \theta)$  from [Theorem 2.2.3](#), i.e.,  $\nabla g(\theta)Y$  from our assumption with [continuous mapping theorem](#).  $\otimes$

It's enough to show  $\|h(T_n)\| = o_p(1)$  since we know that  $\|b_n(T_n - \theta)\| = O_p(1)$  and  $o_p(1)O_p(1) = o_p(1)$  from [Proposition 2.2.6](#). Indeed, as  $T_n \xrightarrow{P} \theta$ ,  $h(T_n) \xrightarrow{P} h(\theta) = 0$  again by [continuous mapping theorem](#) with  $h$  being continuous at  $\theta$ . This further implies  $\|h(T_n)\| \xrightarrow{P} 0$  as we desired.<sup>a</sup> Combining the above, the result follows.  $\blacksquare$

<sup>a</sup>This involves [continuous mapping theorem](#) and [Corollary 2.2.1](#) since  $h(\theta) = 0$ , a constant (so does its norm).

Hence, we see that the answer to our original question is rather simple: as  $b_n(T_n - \theta) \xrightarrow{D} Y$ ,

$$b_n(g(T_n) - g(\theta)) \xrightarrow{D} \nabla g(\theta) \cdot Y$$

for any differentiable  $g$  at  $\theta$ .

## Lecture 7: Skorohod's Representation Theorem

### 2.2.5 Skorohod's Representation Theorem

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So far, we have seen the following.



Now, we show an interesting result that we might not expect.

**Theorem 2.2.7 (Skorohod's representation theorem).** If  $X_n \xrightarrow{D} X$ , there exists  $(\tilde{\Omega}, \tilde{\mathcal{F}}, \tilde{\mathbb{P}})$  on which we can define random vectors  $(Y_n)$  and  $Y$  such that  $Y_n \stackrel{D}{=} X_n$  for all  $n$  and  $Y \stackrel{D}{=} X$ , and  $\tilde{\mathbb{P}}(Y_n \rightarrow Y) = 1$ .

**Intuition.** We have [convergence in distribution](#) “implies” [almost surely convergence](#).

We want to prove [Skorohod's representation theorem](#) for  $d = 1$ . To start, say  $X \sim F$  on  $(\Omega, \mathcal{F}, \mathbb{P})$ . We will consider  $F^{-1}(p)$ , which exists if there exists a unique  $t \in \mathbb{R}$  such that  $F(t) = p$ , then  $F^{-1}(p) = t$ . However, this is not really practical since in the discrete case, the preimage might not exist; and even if in the continuous  $F$ , when  $F$  flats out (at  $p = 1$ ), the preimage is not unique.

**Definition 2.2.6 (Quantile).** A  $p^{\text{th}}$  quantile of  $X$  is defined as any  $t \in \mathbb{R}$  such that

$$\mathbb{P}(X \leq t) \geq p \geq \mathbb{P}(X < t).$$

Now, we can define  $F^{-1}(p)$  as the smallest [quantile](#).

**Definition 2.2.7 (Quantile function).** The *quantile function* of  $X \sim F$  is defined as

$$F^{-1}(p) = \inf\{t \in \mathbb{R} : F(t) \geq p\}.$$

We sometimes also call  $F^{-1}$  as the *generalized inverse* of  $F$ .

**Remark.**  $t \geq F^{-1}(p)$  if and only if  $F(t) \geq p$ ; in other words,  $t < F^{-1}(p)$  if and only if  $F(t) < p$ .

One application of  $F^{-1}$  is that given any CDF  $F$ , we can construct a corresponding random variable.

**Remark (Construction of random variable).** Let  $U \sim \mathcal{U}(0, 1)$  be a uniform random variable on  $(\tilde{\Omega}, \tilde{\mathcal{F}}, \tilde{\mathbb{P}})$ . Then,  $F^{-1}(U) =: Y$  is a random variable with CDF  $F$ .

**Proof.** Since for any  $t \in \mathbb{R}$ ,

$$\tilde{\mathbb{P}}(Y \leq t) = \tilde{\mathbb{P}}(F^{-1}(U) \leq t) = \mathbb{P}(U \leq F(t)) = F(t).$$

⊛

Now we can prove [Skorohod's representation theorem](#).

**Proof of Theorem 2.2.7.** Consider  $\tilde{\Omega} = (0, 1)$ , and  $\tilde{\mathbb{P}}((a, b)) = b - a$  for all  $a < b$ . Then, we can define  $U(p) = p$  for all  $p \in \tilde{\Omega}$ , i.e.,  $U \sim \mathcal{U}(0, 1)$ . Define  $Y_n = F_{X_n}^{-1}(U)$  and  $Y = F_X^{-1}(U)$  from the [quantile functions](#). Denote  $\Phi$  be the CDF of  $\mathcal{N}(0, 1)$ , and let  $Z = \Phi^{-1}(U)$ .

It's clear that  $Y_n \stackrel{D}{=} X_n$  and  $Y \stackrel{D}{=} X$ , so we just need to show  $\tilde{\mathbb{P}}(Y_n \rightarrow Y) = 1$ .

**Claim.** It's equivalent to  $\tilde{\mathbb{P}}(F_{X_n}(Z) < p) \rightarrow \tilde{\mathbb{P}}(F_X(Z) < p)$  for almost all  $p$ 's.

**Proof.** Observe further that  $Y_n(p) = F_{X_n}^{-1}(p)$ ,  $Y(p) = F_X^{-1}(p)$ , and  $Z(p) = \Phi^{-1}(p)$  for all  $p \in (0, 1)$ . Since for almost all  $p$ 's,  $Y_n(p) \rightarrow Y(p)$  if and only if  $\Phi(Y_n(p)) \rightarrow \Phi(Y(p))$  as  $\Phi$  is strictly increasing and continuous, or equivalently,

$$\Phi(Y_n(p)) = \tilde{\mathbb{P}}(Z \leq Y_n(p)) \rightarrow \tilde{\mathbb{P}}(Z \leq Y(p)) = \Phi(Y(p)).$$

As  $Z$  is continuous, this is equivalent to  $\tilde{\mathbb{P}}(Z < Y_n(p)) \rightarrow \tilde{\mathbb{P}}(Z < Y(p))$ , i.e.,

$$\tilde{\mathbb{P}}(Z < F_{X_n}^{-1}(p)) \rightarrow \tilde{\mathbb{P}}(Z < F_X^{-1}(p)),$$

which holds if and only if  $\tilde{\mathbb{P}}(F_{X_n}(Z) < p) \rightarrow \tilde{\mathbb{P}}(F_X(Z) < p)$ .<sup>a</sup> ⊗

<sup>a</sup>Follows from [the remark](#). Explicitly, firstly, it's equivalent to  $\tilde{\mathbb{P}}(Z \geq F_{X_n}^{-1}(p)) \rightarrow \tilde{\mathbb{P}}(Z \geq F_X^{-1}(p))$ , and with  $\tilde{\mathbb{P}}(Z \geq F_X^{-1}(p)) = \tilde{\mathbb{P}}(F_X(Z) \geq p)$  and  $\tilde{\mathbb{P}}(Z \geq F_{X_n}^{-1}(p)) = \tilde{\mathbb{P}}(F_{X_n}(Z) \geq p)$ , the result follows.

Now we show  $\tilde{\mathbb{P}}(F_{X_n}(Z) < p) \rightarrow \tilde{\mathbb{P}}(F_X(Z) < p)$  for almost all  $p$ 's. Since  $X_n \xrightarrow{D} X$  means  $F_{X_n}(t) \rightarrow F_X(t)$ , from [Lemma 2.2.3](#), it further implies  $F_{X_n}(t^-) \rightarrow F_X(t^-)$  for all  $t \in C_{F_X}$ . Note that  $\tilde{\mathbb{P}}(Z \in C_{F_X}) = 1$  since there can be only countably many discontinuities of  $F_X$ . Hence,

$$\tilde{\mathbb{P}}(F_{X_n}(Z) \rightarrow F_X(Z)) = 1,$$

i.e., [converges almost surely](#), which implies  $F_{X_n}(Z) \xrightarrow{D} F_X(Z)$ , i.e., for all  $p \in C_{F_X}(Z)$

$$\tilde{\mathbb{P}}(F_{X_n}(Z) \leq p) \rightarrow \tilde{\mathbb{P}}(F_X(Z) \leq p),$$

and also  $\tilde{\mathbb{P}}(F_{X_n}(Z) < p) \rightarrow \tilde{\mathbb{P}}(F_X(Z) < p)$  from [Lemma 2.2.3](#). Again, as  $F_X$  can have only countably many discontinuities, this holds for almost all  $p$ 's, which is what we want to show. ■

## 2.2.6 Applications

We see one immediate application of [Skorohod's representation theorem](#), which allows us to generalize [Fatou's lemma](#).

**Proposition 2.2.7 (Fatou's lemma).** Let  $X_n \xrightarrow{D} X$ <sup>a</sup> and  $g: \mathbb{R}^d \rightarrow [0, \infty)$  continuous. Then

$$\mathbb{E}[g(X)] \leq \liminf_{n \rightarrow \infty} \mathbb{E}[g(X_n)].$$

<sup>a</sup>Can be on different probability spaces.

**Proof.** Let  $(\tilde{\Omega}, \tilde{\mathcal{F}}, \tilde{\mathbb{P}})$ , from [Skorohod's representation theorem](#), we can construct  $Y_n \stackrel{D}{=} X_n$ ,  $Y \stackrel{D}{=} X$ , and  $Y_n \xrightarrow{\text{a.s.}} Y$ , which implies  $g(Y_n) \xrightarrow{\text{a.s.}} g(Y)$ . From [Fatou's lemma](#) in  $d = 1$ ,  $\tilde{\mathbb{E}}[g(Y)] \leq \liminf_{n \rightarrow \infty} \tilde{\mathbb{E}}[g(Y_n)]$ . The result then follows directly from

$$\mathbb{E}[g(X)] = \tilde{\mathbb{E}}[g(Y)] \leq \liminf_{n \rightarrow \infty} \tilde{\mathbb{E}}[g(Y_n)] = \liminf_{n \rightarrow \infty} \mathbb{E}[g(X_n)].$$

The following is well-known from real analysis (dominant convergence theorem).

**Theorem 2.2.8.**  $X_n \xrightarrow{\text{a.s.}} X$  and  $g: \mathbb{R}^d \rightarrow \mathbb{R}$  is continuous and  $(g(X_n))$  is uniformly integrable<sup>a</sup> if and only if  $\mathbb{E}[g(X_n)] \rightarrow \mathbb{E}[g(X)]$ .

<sup>a</sup>I.e.,  $\lim_{t \rightarrow \infty} \sup_{n \geq 1} \mathbb{E}[|g(X_n)| \mathbb{1}_{g(X_n) \geq t}] = 0$ .

in  $L_1$ ?

If  $X_n \xrightarrow{w} X$ , then from the definition, we will have  $\mathbb{E}[g(X_n)] \rightarrow \mathbb{E}[g(X)]$  if  $g$  is continuous and bounded. We can indeed relax both continuity and boundedness as follows.

**Proposition 2.2.8.** If  $X_n \xrightarrow{w} X$  and  $\mathbb{P}(X \in C_g) = 1$  where  $g: \mathbb{R}^d \rightarrow \mathbb{R}$  such that  $(g(X_n))$  is uniformly integrable, then  $\mathbb{E}[g(X_n)] \rightarrow \mathbb{E}[g(X)]$ .

**Proof.** From  $\mathbb{P}(X \in C_g) = 1$  and  $X_n \xrightarrow{w} X$ , from [continuous mapping theorem](#),  $g(X_n) \xrightarrow{w} g(X)$ , hence  $\mathbb{E}[g(X_n)] \rightarrow \mathbb{E}[g(X)]$ . ■

Seems no need of  $(g(X_n))$  being u.i.

**Remark.** Proposition 2.2.8 can be proved with [Skorohod's representation theorem](#) also.

the in  $L_1$  version?

## 2.3 Characteristic Function

We often want to prove  $X_n \xrightarrow{D} X$ , which is not efficient if we start from definition. To get some intuition for potential proof strategies, consider a deterministic sequence  $(x_n)$  in a metric space  $(S, \rho)$ .

**Theorem 2.3.1.**  $(x_n)$  converges to  $x$  if and only if every subsequence of  $(x_n)$  has a subsequence that converges to the same limit  $x$ .

**Proof.** The forward direction is clear. For the backward direction, if not, there exists  $(x_{n_k})$  and  $\epsilon > 0$  such that  $\rho(x_{n_k}, x) \geq \epsilon$  for every  $k \geq 1$ . But if there exists a subsubsequence  $(x_{n_{k_\ell}})$  that converges to  $x$ , this is clearly a contradiction. ■

In the same vein, with the same argument, we have the following.

**Theorem 2.3.2.**  $X_n \xrightarrow{w} X$  if and only if every subsequence of  $(X_n)$  has a subsequence that [converges weakly](#), and all [weakly convergent](#) subsequences have the same limit  $X$ .

## Lecture 8: Characteristic Functions

We see other similar theorems apart from [Theorem 2.3.2](#).

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**Theorem 2.3.3.** If  $X_n \xrightarrow{w} X$  and  $X_n \xrightarrow{w} Y$ , then  $X \stackrel{D}{=} Y$ . More generally, if  $X_n \xrightarrow{w} X$  and  $Y_n \xrightarrow{w} Y$ , with  $X_n \stackrel{D}{=} Y_n$  for all  $n \geq 1$ ,  $X \stackrel{D}{=} Y$ .

**Proof.** We have for every  $n \geq 1$ ,  $\mathbb{E}[g(X_n)] = \mathbb{E}[g(Y_n)]$  for all  $g: \mathbb{R}^d \rightarrow \mathbb{R}$ . If  $g$  is bounded and continuous,  $\mathbb{E}[g(X_n)] \rightarrow \mathbb{E}[g(X)]$  and  $\mathbb{E}[g(Y_n)] \rightarrow \mathbb{E}[g(Y)]$ . To show that  $X \stackrel{D}{=} Y$ , we want to show  $F_X = F_Y$ , or  $\mathbb{P}(X \in B) = \mathbb{P}(Y \in B)$  for all  $B \in \mathcal{F} = \mathcal{B}(\mathbb{R}^d)$ . In fact, it's enough to show this for closed  $B$ . With [Lemma 2.2.1](#), there exists  $(g_k) \searrow \mathbb{1}_B$  for closed  $B$  and bounded, Lipschitz  $g_k$ , i.e.,

$$\begin{aligned} \mathbb{E}[\mathbb{1}_B(X)] &= \lim_{k \rightarrow \infty} \mathbb{E}[g_k(X)] = \lim_{k \rightarrow \infty} \lim_{n \rightarrow \infty} \mathbb{E}[g_k(X_n)] \\ &= \lim_{k \rightarrow \infty} \lim_{n \rightarrow \infty} \mathbb{E}[g_k(Y_n)] = \lim_{k \rightarrow \infty} \mathbb{E}[g_k(Y)] = \mathbb{E}[\mathbb{1}_B(Y)], \end{aligned}$$

where the third equality follows from the fact that  $X_n \stackrel{D}{=} Y_n$ . ■

One question is that, if we don't have things like [weak convergent](#) but just some moment information (i.e., when  $g(x) = x^k$  when computing  $\mathbb{E}[g(X)]$ ), can we conclude the same thing?

**Problem.** If  $\mathbb{E}[X^k] = \mathbb{E}[Y^k] < \infty$  for all  $k \geq 1$ , does  $X \stackrel{D}{=} Y$ ?

**Answer.** Not in general. ⊛

On the other hand, it actually suffices to show only for  $g(x) = \cos(t \cdot x)$  or  $\sin(t \cdot x)$  for  $t, x \in \mathbb{R}^d$ . This leads to the so-called [characteristic functions](#).

**Definition 2.3.1 (Characteristic function).** The *characteristic function* of  $X$  is defined as  $\phi_X: \mathbb{R}^d \rightarrow \mathbb{C}$  where  $t \in \mathbb{R}^d$  such that

$$\phi_X(t) = \mathbb{E}[\cos(t \cdot X)] + i\mathbb{E}[\sin(t \cdot X)] = \mathbb{E}[e^{i(t \cdot X)}].$$

**Notation.** We will now drop the inner product, i.e., write  $t \cdot X =: tX$ .

If we write out explicitly, we have

$$\phi_X(t) = \mathbb{E}[e^{itX}] = \int e^{itx} f_X(x) dx = \int e^{itx} F_X(dx).$$

**Remark.** Characteristic functions are bounded.

**Proof.** Since

$$|\phi_X(t)| = \sqrt{(\mathbb{E}[\cos(tX)])^2 + (\mathbb{E}[\sin(tX)])^2} \leq \sqrt{\mathbb{E}[\cos^2(tX)] + \mathbb{E}[\sin^2(tX)]} = 1.$$

⊛

**Remark.** If  $X$  and  $Y$  are independent,  $\phi_{X+Y}(t) = \phi_X(t) \cdot \phi_Y(t)$ .

We make one more remark for future reference.

**Remark.** If  $X, Y$  are discrete,  $f_{X+Y}(x) = \sum_y f_Y(x-y)f_X(y)$ . More generally, if  $X, Y$  have PDFs,

$$f_{X+Y}(x) = \int f_Y(x-y)f_X(y) dy = \int f_Y(x-y)F_X(dy).$$

Furthermore, even if  $X$  doesn't have PDF, as long as  $Y$  does, the above still holds.

Now we can prove the following.

**Theorem 2.3.4 (Uniqueness).** If  $\phi_X(t) = \phi_Y(t)$  for all  $t \in \mathbb{R}^d$ , then  $X \stackrel{D}{=} Y$ . The converse is trivial.

**Proof.** Consider  $d = 1$ . Observe that if we can write  $F_X$  in terms of only  $\phi_X$ , then  $\phi_X = \phi_Y$  implies  $F_X = F_Y$ . To do this, consider the following.

**Claim.** For  $Z, Z' \sim \mathcal{N}(0, 1)$  (independent of  $X$  and  $Y$ ), if one can write  $F_{X+\sigma Z}$  for all  $\sigma > 0$  in terms of only  $\phi_X$ ,  $\phi_X = \phi_Y$  implies  $X \stackrel{D}{=} Y$ .

**Proof.** Fix some  $\sigma > 0$ . In this case, if we can write  $F_{X+\sigma Z}$  in terms of only  $\phi_X$ ,  $\phi_X = \phi_Y$  implies  $F_{X+\sigma Z} = F_{Y+\sigma Z}$ . This implies  $X + \sigma Z \stackrel{D}{=} Y + \sigma Z$ . Now, for  $\sigma = 1/k$ ,  $k \in \mathbb{N}$ ,

$$X + \frac{1}{k}Z \stackrel{D}{=} Y + \frac{1}{k}Z'.$$

With [Corollary 2.2.2](#), since  $Z/k \xrightarrow{P} 0$  (and also  $Z'/k \xrightarrow{P} 0$ ), we have  $X + Z/k \xrightarrow{D} X$  and  $Y + Z'/k \xrightarrow{D} Y$ , which implies  $X \stackrel{D}{=} Y$  from [Theorem 2.3.3](#). ⊛

Hence, our goal now is to write  $F_{X+\sigma Z}$  in terms of  $\phi_X$ . Firstly, for all  $t \in \mathbb{R}$ ,

$$\phi_Z(t) = \int e^{itz} F_Z(dz) = \int e^{itz} f_Z(z) dz = \int e^{itz} \frac{1}{\sqrt{2\pi}} e^{-z^2/2} dz = e^{-t^2/2}. \quad (2.1)$$



Now, we compute  $F_{X+\sigma Z}(t)$ : for any bounded  $g: \mathbb{R} \rightarrow \mathbb{R}_+$ ,

$$\begin{aligned}\mathbb{E}[g(X + \alpha Z)] &= \int g(x) F_{X+\sigma Z}(\mathrm{d}x) \\ &= \int g(x) f_{X+\sigma Z}(x) \mathrm{d}x \\ &= \int g(x) \int \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-y)^2/2\sigma^2} F_X(\mathrm{d}y) \mathrm{d}x,\end{aligned}$$

where we use the fact that  $F_{X+\sigma Z}$  indeed has a PDF from the [remark](#). By replacing  $e^{-(x-y)^2/2\sigma^2}$  from [Equation 2.1](#) with  $t = (x-y)/\sigma$ ,

$$\begin{aligned}&= \int g(x) \int \frac{1}{\sigma\sqrt{2\pi}} \int e^{i\frac{y-x}{\sigma}z} \frac{1}{\sqrt{2\pi}} e^{-z^2/2} \mathrm{d}z F_X(\mathrm{d}y) \mathrm{d}x. \\ &= \frac{1}{2\pi} \int g(x) \int e^{i(y-x)u} e^{-\sigma^2 u^2/2} \mathrm{d}u F_X(\mathrm{d}y) \mathrm{d}x, \quad z/\sigma =: u\end{aligned}$$

interchanging the order of integrals with [Fubini's theorem](#) (integrands are absolute integrable),

$$= \frac{1}{2\pi} \int g(x) \int e^{-ixu - \sigma^2 u^2/2} \underbrace{\int e^{iyu} F_X(\mathrm{d}y)}_{\phi_X(u)} \mathrm{d}u \mathrm{d}x.$$

We see that  $F_{X+\sigma Z}(\mathrm{d}x)$  indeed can be written in terms of  $\phi_X$  (in the distribution sense) with no other dependencies, hence we're done.  $\blacksquare$

**Note.** Now showing  $X \stackrel{D}{=} Y$  reduces to calculus.

One immediate consequence of the [uniqueness theorem](#) is that it's enough to have the [characteristic functions](#) converging to some function (not necessarily a [characteristic functions](#) of some  $X$ ) for us to conclude that the subsequences of  $(X_n)$  have the same weak limit. To do this, we need to prove [Prokhorov's theorem](#).

**Theorem 2.3.5** (Prokhorov's theorem). If  $(X_n) = O_p(1)$ , then there exists a [weakly convergent](#) subsequence of  $(X_n)$ .

**Proof.** Based on [Helly's selection theorem](#),  $F_{X_n}(t) \rightarrow F(t)$  for all  $t \in C_F$ , there exists an increasing  $F$ , right continuous,  $F(+\infty) \leq 1$  and  $F(-\infty) \geq 0$  (called the *defective CDF*). Consider  $d = 1$ , we show that this  $F$  is indeed a CDF when  $X_n = O_p(1)$ .

Fix  $\epsilon > 0$ , then there exists  $M_\epsilon > 0$  in  $C_F$  such that

$$F_{X_n}(M_\epsilon) = \mathbb{P}(X_n \leq M_\epsilon) \geq \mathbb{P}(|X_n| \leq M_\epsilon) \geq 1 - \epsilon$$

for all  $n \geq 1$ . Since  $M_\epsilon \in C_F$ ,  $F_{X_n}(M_\epsilon) \rightarrow F(M_\epsilon)$ . We then see that for all  $\epsilon > 0$ , there exists  $M_\epsilon > 0$  such that  $F(+\infty) \geq F(M_\epsilon) \geq 1 - \epsilon$ . As  $\epsilon \rightarrow 0$ ,  $F(+\infty) = 1$ . Similarly,  $F(-\infty) = 0$ .  $\blacksquare$

We now state the theorem.

**Theorem 2.3.6.** If  $\phi_{X_n}(t) \rightarrow \phi_X(t)$  for all  $t \in \mathbb{R}^d$ , then  $X_n \stackrel{D}{\rightarrow} X$ .

In fact, one can prove a generalized version of this as follows.

**Theorem 2.3.7.** If  $\phi_{X_n}(t) \rightarrow \phi(t)$  for all  $t \in \mathbb{R}^d$ , then all [weakly convergent](#) subsequences of  $(X_n)$  have the same weak limit. Furthermore, if also  $\phi$  is continuous at 0, then there exists  $X$  such that  $\phi = \phi_X$  and  $X_n \stackrel{D}{\rightarrow} X$ .

**Proof.** Let's start with the first claim. Suppose  $Y_n \xrightarrow{w} Y$  and  $Z_n \xrightarrow{w} Z$  are two subsequences of  $X_n$  such that  $Y \neq Z$ . But since  $\phi_{Y_n}(t) \rightarrow \phi_Y(t)$  and  $\phi_{Z_n}(t) \rightarrow \phi_Z(t)$ , with the fact that  $(\phi_{Y_n}(t))$  and  $(\phi_{Z_n}(t))$  are subsequences of  $(\phi_{X_n}(t))$  for every  $t$ , as  $\phi_{X_n}(t) \rightarrow \phi(t)$ , both subsequences need to

---

converge to the same limit, i.e.,

$$\phi_Y(t) = \phi(t) = \phi_Z(t)$$

for all  $t \in \mathbb{R}^d$ . From the [uniqueness theorem](#),  $Y \stackrel{D}{=} Z$ .

For the second part, we just need to prove the following.

**Claim.** It's enough to show that if  $\phi$  is continuous at 0,  $(X_n) = O_p(1)$ .

**Proof.** Since if we can show  $(X_n) = O_p(1)$  from our assumption, [Prokhorov's theorem](#) implies there exists a [weakly convergent](#) subsequence of  $(X_n)$ . With the first claim, we can find the weak limit  $X$ . ⊕

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

## Lecture 9

We now finish the proof of [Theorem 2.3.7](#).

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**Proof of Theorem 2.3.7 (cont.)** ■

# Appendix

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