

# STATS310A - Lecture 18

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11/30/21

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## 1 Announcements

- Thursday's lecture will also be on Zoom.
- Wednesday's office hours will be on Zoom.

Here goes.

## 2 Helly's selection theorem

**Theorem 1** (Helly's selection theorem). *If  $\{F_n\}_{n=1}^\infty$  are any cumulative distribution functions on  $\mathbb{R}$ , then there exists a subsequence  $n_k$  and a monotone, right continuous function  $F$  such that  $F_{n_k}(x) \rightarrow F(x)$  for all  $x$  such that  $F$  is continuous at  $x$ .*

Before we prove the above theorem it is important to note that  $F$  might not be a cumulative distribution function.

*Proof.* Let  $\{r_i\}_{i=1}^\infty$  be an enumeration of  $\mathbb{Q}$ . We can form the array

$$\begin{array}{cccc} F_1(r_1) & F_2(r_1) & F_3(r_1) & \dots \\ F_1(r_2) & F_2(r_2) & F_3(r_2) & \dots \\ F_1(r_3) & F_2(r_3) & F_3(r_3) & \dots \\ \vdots & \vdots & \vdots & \ddots \end{array}$$

Each row is bounded since  $F_n(x) \in [0, 1]$  for all  $n$  and  $x \in \mathbb{R}$ . Thus Cantor's diagonal argument implies that there exists a subsequence  $n_k$  and a function  $G : \mathbb{Q} \rightarrow \mathbb{R}$  such that  $F_{n_k}(r) \rightarrow G(r)$  for all  $r \in \mathbb{Q}$ .

Note that if  $r < s$ , then  $F_{n_k}(r) \leq F_{n_k}(s)$  for all  $k$  and so  $G(r) \leq G(s)$ . Now define

$$F(x) = \inf\{G(r) : r > x, r \in \mathbb{Q}\}.$$

Since  $G$  is non-decreasing,  $F$  is also non-decreasing. We will now show that  $F$  is right continuous. Given  $x$  and  $\varepsilon > 0$ , find  $r > x$  such that  $G(r) < F(x) + \varepsilon$ . If  $x < y < r$ , then

$$F(x) \leq F(y) \leq G(r) < F(x) + \varepsilon.$$

Thus,  $F$  is right continuous. Now we just need to prove that if  $x$  is a continuity point of  $F$ , then  $F_{n_k}(x) \rightarrow F(x)$ .

This is elementary but (slightly) tedious. Given  $x$  a continuity point and  $\varepsilon > 0$ , choose  $y < x$  such that  $F(x) - \varepsilon < F(y)$ . Next choose rational numbers  $r$  and  $s$  so that  $y < r < x < s$  and

$$G(s) < F(x) + \varepsilon.$$

It follows that

$$F(x) - \varepsilon < F(y) \leq G(r) \leq G(s) < F(x) + \varepsilon.$$

We also have  $F_{n_k}(r) \leq F_{n_k}(x) \leq F_{n_k}(s)$  for all  $k$  and so

$$\begin{aligned} F(x) - \varepsilon &\leq G(r) \\ &= \lim_k F_{n_k}(r) \\ &\leq \lim_k F_{n_k}(x) \\ &\leq \overline{\lim}_k F_{n_k}(x) \\ &\leq \lim_k F_{n_k}(s) \\ &= G(s) \\ &\leq F(x) + \varepsilon. \end{aligned}$$

Thus  $\lim_k F_{n_k}(x)$  and  $\overline{\lim}_k F_{n_k}(x)$  are both within  $\varepsilon$  of  $F(x)$ . Since  $\varepsilon$  was arbitrary we can conclude that  $\lim_k F_{n_k}(x) = F(x)$ .  $\square$

**Example 1.** As mentioned before, the limiting function  $F$  need not be a cumulative distribution function. For example,

- If  $F_n$  is the cumulative distribution function of a point mass at  $n$ , then  $F_n(x) \rightarrow 0$  for all  $x$ .
- If  $F_n$  is the cumulative distribution function of a point mass at  $-n$ , then  $F_n(x) \rightarrow 1$  for all  $x$ .

Neither of these limits are cumulative distribution functions.

The kind of convergence in the statement of the Helly's selection theorem is called *vague convergence*.

### 3 Tightness

How can we be sure that the limit function  $F$  in Helly's selection theorem is a distribution? It turns out that the key property is tightness.

**Definition 1.** A family of probability distributions  $\{\mu_n\}$  on  $\mathbb{R}$  is *tight* if for all  $\varepsilon > 0$ , there exists  $a < b$  such that  $\mu_n([a, b]) > 1 - \varepsilon$  for all  $n$ .

We will sometimes say  $\{\mu_n\}$  are “almost compactly supported” to mean  $\{\mu_n\}$  is tight.

**Theorem 2.** Let  $\{\mu_n\}$  be a family of probability distributions on  $\mathbb{R}$ . Then  $\{\mu_n\}$  is tight if and only if for every subsequence  $n_k$ , there exists a further subsequence  $n_{k_i}$  and a probability distribution  $\mu$  such that  $\mu_{n_{k_i}} \Rightarrow \mu$  as  $i \rightarrow \infty$ .

In the remaining lectures, we will only use that if  $\{\mu_n\}$  is tight, then for every subsequence  $n_k$ , there exists a further subsequence  $n_{k_i}$  and a probability distribution  $\mu$  such that  $\mu_{n_{k_i}} \Rightarrow \mu$  as  $i \rightarrow \infty$ . Thus we will only prove this direction of the above theorem.

*Proof.* Let  $\{\mu_n\}$  be a tight family of probability distributions with corresponding cumulative distribution functions  $F_n$ . Let  $n_k$  be a subsequence. By Helly's selection theorem, there exists a further subsequence  $n_{k_i}$  and a monotone right-continuous function  $F$  such that  $F_{n_{k_i}}(x) \rightarrow F(x)$  for all  $x$  such that  $F$  is continuous at  $x$ .

We wish to show that  $F$  is a cumulative distribution function for some probability measure  $\mu$  as this will imply that  $\mu_n \Rightarrow \mu$ . To show that  $F$  is a cumulative distribution function, it suffices to show that  $\lim_{x \rightarrow \infty} F(x) = 1$  and  $\lim_{x \rightarrow -\infty} F(x) = 0$ . We know that  $F(x) \in [0, 1]$  for all  $x$  since each  $F_{n_{k_i}}$  is a cumulative distribution function. Furthermore since  $\{\mu_n\}$  is tight, for every  $\varepsilon > 0$  there exist  $a < b$  such that  $F$  is continuous at  $a$  and  $b$  and for all  $i$

$$F_{n_{k_i}}(b) - F_{n_{k_i}}(a) > 1 - \varepsilon.$$

By taking a limit we have  $F(b) - F(a) \geq 1 - \varepsilon$  which is sufficient to conclude that  $F$  has the correct limits.  $\square$

**Remark 1.** If  $\int_{\mathbb{R}} |x| \mu_n(dx)$  is uniformly bounded in  $n$ , then the family  $\{\mu_n\}$  is tight.

Likewise, if  $\int_{\mathbb{R}} f(|x|) \mu_n(dx)$  is uniformly bounded in  $n$  for some unbounded monotone function  $f : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ , then  $\{\mu_n\}$  is tight. Both of these claims follow by Markov's inequality for monotonically increasing functions.

**Remark 2.** All of what we have done works for a complete separable metric space  $\mathcal{X}$ . We have to work with  $\mathcal{B}(\mathcal{X})$  the Borel  $\sigma$ -algebra on  $\mathcal{X}$  which is the  $\sigma$ -algebra generated by the open subsets of  $\mathcal{X}$ . A sequence of probabilities  $\mu_n$  on  $(\mathcal{X}, \mathcal{B}(\mathcal{X}))$  converges weak\* to  $\mu$  if for all bounded and continuous functions  $f$  on  $\mathcal{X}$ , we have

$$\int_{\mathcal{X}} f(x) \mu_n(dx) \rightarrow \int_{\mathcal{X}} f(x) \mu(dx).$$

In this setting, we say that  $\{\mu_n\}$  is tight if for all  $\varepsilon > 0$ , there exists a compact set  $K \subseteq \mathcal{X}$  so that

$$\mu_n(K) > 1 - \varepsilon,$$

for all  $n$ . Some references for this topic are:

- Billingsley "Convergence of probability measures."
- Kallenberg "Probability Theory" (3<sup>rd</sup> edition).
- Dudley "Real Analysis and Probability."

All three are great books.

## 4 The continuity theorem

The below theorem states that pointwise convergence of characteristic functions is exactly convergence in distribution. This was a missing link in Laplace's argument for the central limit theorem.

**Theorem 3.** Let  $\{F_n\}, F$  be cumulative distribution functions with characteristic functions  $\phi_n, \phi$ , then  $F_n \Rightarrow F$  if and only if for all  $t \in \mathbb{R}$ ,  $\phi_n(t) \rightarrow \phi(t)$ .

*Proof.* Let  $\mu_n$  and  $\mu$  be the probability distributions corresponding to  $F_n$  and  $F$ . The functions  $x \mapsto \cos(tx)$  and  $x \mapsto \sin(tx)$  are both bounded and continuous. Thus if  $F_n \Rightarrow F$ , then

$$\phi_n(t) = \int_{\mathbb{R}} (\cos(tx) + i \sin(tx)) \mu_n(dx) \rightarrow \int_{\mathbb{R}} (\cos(tx) + i \sin(tx)) \mu(dx) = \phi(t).$$

Now suppose that  $\phi_n(t) \rightarrow \phi(t)$  for all  $t$ . We will show later that this implies that  $\{\mu_n\}$  is tight. Now suppose that  $F_n \not\Rightarrow F$ . Then there exists some  $x \in \mathbb{R}$  such that  $F$  is continuous at  $x$  but  $F_n(x) \not\rightarrow F(x)$ . Thus there exists a subsequence  $n_k$  and  $\varepsilon > 0$  such that  $|F_{n_k}(x) - F(x)| > \varepsilon$  for all  $k$ . Since we will show that  $\phi_n$  is tight, this implies that there exists a cumulative distribution function  $G$  and a further subsequence  $n_{k_i}$  such that  $F_{n_{k_i}} \Rightarrow G$ . Note that we cannot have  $G = F$  as this will imply that  $G$  is continuous at  $x$  and hence  $F_{n_{k_i}}(x) \rightarrow G(x) = F(x)$ .

Let  $\phi_G$  be the characteristic function of  $G$ . Since  $F_{n_{k_i}} \Rightarrow G$ , we have  $\phi_{n_{k_i}}(t) \rightarrow \phi_G(t)$  and thus  $\phi_G(t) = \phi(t)$ . By the uniqueness theorem (which we state below and will prove next lecture) this implies that  $G = F$ , a contradiction.

It thus remains to show that  $\{\mu_n\}$  is tight. For  $u > 0$ , consider the quantity

$$\frac{1}{u} \int_{-u}^u (1 - \phi(t)) dt.$$

By Fubini's theorem we have

$$\begin{aligned} \frac{1}{u} \int_{-u}^u 1 - \phi(t) dt &= \int_{-\infty}^{\infty} \frac{1}{u} \int_{-u}^u 1 - e^{itx} dt \mu(dx) \\ &= 2 \int_{-\infty}^{\infty} \left[ 1 - \frac{\sin(ux)}{ux} \right] \mu(dx) \\ &\geq 2 \int_{\{x: |x| > 2/u\}} 1 - \frac{\sin(ux)}{ux} \mu(dx) \\ &\geq 2 \int_{\{x: |x| > 2/u\}} 1 - \frac{1}{ux} \mu(dx) \\ &\geq 2 \int_{\{x: |x| > 2/u\}} \frac{1}{2} \mu(dx) \\ &= \mu \left( \left\{ x : |x| > \frac{2}{u} \right\} \right) \end{aligned}$$

Now  $\phi(t)$  is continuous and  $\phi(0) = 1$ . Thus for all  $t > 0$ , there exists  $u > 0$  sufficiently small such that  $|1 - \phi(t)| < \frac{\varepsilon}{2}$ , given  $|t| < u$ . This implies that

$$\left| \frac{1}{u} \int_{-u}^u 1 - \phi(t) dt \right| < \varepsilon.$$

We know that  $\phi_n(t) \rightarrow \phi(t)$  for all  $t \in \mathbb{R}$ . Thus by the bounded convergence theorem, there exists  $n_0$  such that if  $n \geq n_0$ , then

$$\mu_n \left( \left\{ x : |x| > \frac{2}{u} \right\} \right) \leq \frac{1}{u} \int_{-u}^u 1 - \phi_n(t) dt \leq 2\varepsilon.$$

By taking  $u$  smaller we can ensure that  $u > 0$  and

$$\mu_n \left( \left\{ x : |x| > \frac{2}{u} \right\} \right) \leq 2\varepsilon,$$

for  $n = 1, 2, \dots, n_0 - 1$ . Thus we have shown that  $\{\mu_n\}$  is tight.  $\square$

If you'd like to learn more about Laplace and his proof of the central limit theorem, search for "Steve Stigler, Laplace."

**Remark 3.** Two comments.

- The continuity theorem is a substantial theorem that uses topology and Helly's selection theorem.
- Our proof relies on the uniqueness theorem which we have not yet proved.

## 5 Uniqueness theorem

**Theorem 4** (Inversion theorem). *Let  $\mu$  be a probability on  $\mathbb{R}$  with characteristic function  $\phi$ . If  $a < b$ , then,*

$$\mu((a, b)) + \frac{1}{2}\mu(\{a, b\}) = \lim_{T \rightarrow \infty} \frac{1}{2\pi} \int_{-T}^T \frac{e^{-ita} - e^{-itb}}{it} \phi(t) dt.$$

The uniqueness theorem is a corollary.

**Corollary 1.** *If  $\mu$  and  $\nu$  are probability measures and  $\phi_\mu = \phi_\nu$ , then  $\mu = \nu$ .*

*Proof.* The family of sets

$$\mathcal{P} = \{(a, b) : \mu(\{a\}) = \mu(\{b\}) = \nu(\{a\}) = \nu(\{b\}) = 0\},$$

is a  $\pi$ -system that generates the Borel  $\sigma$ -algebra. Since  $\phi_\mu = \phi_\nu$ , the inversion theorem implies that  $\mu$  and  $\nu$  agree on  $\mathcal{P}$ . By the trusty old  $\pi - \lambda$  theorem, this implies that  $\mu = \nu$ .  $\square$

The inversion theorem does not give a formula for  $\mu$  in terms of  $\phi$  since it involves a limit. If we put additional assumptions on  $\phi$ , then we do get a formula for  $\mu$ .

**Theorem 5.** *If  $\int_{-\infty}^{\infty} |\phi(t)| dt < \infty$ , then  $\mu$  has a bounded density  $f$  and*

$$f(y) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-ity} \phi(t) dt.$$

We will prove these theorems on Thursday.

## 6 Generalizations

There are versions of characteristic functions for measures on lots of spaces other than  $\mathbb{R}$ . For example one can work with measures on groups and do Fourier analysis on non-commutative groups. See "Group Representations in Probability and Statistics" by Persi. We won't talk about characteristic functions on non-commutative groups here but we will talk about characteristic functions on  $\mathbb{R}^d$ .

**Definition 2.** Let  $\mu$  be a probability distribution on  $\mathbb{R}^d$ . The *characteristic function* of  $\mu$  is the function  $\phi_\mu : \mathbb{R}^d \rightarrow \mathbb{C}$  given by

$$\phi_\mu(t) = \mathbb{E}_\mu[e^{it \cdot x}],$$

where  $t \cdot x$  denotes the dot product between  $t$  and  $x$ .

All of the theorems we studied on  $\mathbb{R}$ , hold for characteristic functions on  $\mathbb{R}^d$ . We also have the following result.

**Proposition 1** (Cramer-Wold device). *If  $X \in \mathbb{R}^d$  is a random vector and we know the distribution of  $\sum_{j=1}^d a_j X_j$  for all  $a \in \mathbb{R}^d$ , then we know the distribution of  $X$ .*

*Proof.* If we know the distribution of  $t \cdot X$  for all  $t \in \mathbb{R}^d$ , then we know  $\phi(t) = \mathbb{E}[e^{it \cdot X}]$  for all  $t$ . Thus we know the characteristic function of  $X$  and hence the distribution of  $X$ .  $\square$

**Example 2.** The Cramer-Wold device can be used to prove multivariate central limit theorems for  $(X_1^{(n)}, \dots, X_d^{(n)})$  from univariate central limit theorems for  $t \cdot X^{(n)}$ . For example, if  $X_1, X_2, \dots$  are i.i.d. in  $\mathbb{R}^d$  with mean  $\mu$  and covariance matrix  $\Sigma$ . If  $S_n = \frac{1}{n} \sum_{j=1}^n (X_j - \mu)$ , then

$$\sqrt{n}S_n \Rightarrow \mathcal{N}_d(0, \Sigma),$$

by the univariate central limit theorem and the Cramer-Wold device. There are also multivariate central limit theorems for triangular arrays.

**Remark 4.** Some final comments:

- Please look in the book to see how similar the proof of the central limit theorem is to the one that we proved in class. They both use a swapping argument.
- Persi would have liked to have talked about infinitely divisible laws but there wasn't time this quarter.
- There are all kinds of tricks, maneuvers and proofs that are achievable with characteristic functions and the full power of complex analysis. The best source for this is W. Feller - "An introduction to probability and its applications" Vol II (2nd edition) chapter 15. For example, these tools can prove the following:

**Theorem 6.** Suppose  $X, Y$  are independent and there exist non-zero  $a, b, c, d \in \mathbb{R}$ , such that  $(aX + bY, cX + dY)$  has the same distribution as  $(X, Y)$ , then  $X$  and  $Y$  are normal.