

# Probability Theory

## Cheat Sheet & Study materials\*

These materials...

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# 1 Set structures

## 1.1 Definitions

Let  $S$  be a set and  $\mathcal{S} \subseteq \mathcal{P}(S)$  a family of subsets. We define a number of terms:  $\mathcal{S}$  is a

(a) **semiring** if

- $A, B \in \mathcal{S} \implies A \cap B \in \mathcal{S}$
- if  $A, B \in \mathcal{S}$  then  $A \setminus B$  is a finite disjoint union of sets in  $\mathcal{S}$

(b) **ring** if

- $A, B \in \mathcal{S} \implies A \cap B \in \mathcal{S}$
- $A, B \in \mathcal{S} \implies A \setminus B \in \mathcal{S}$

(c) **semialgebra** if

- $A, B \in \mathcal{S} \implies A \cap B \in \mathcal{S}$
- $A \in \mathcal{S} \implies A^c$  is a finite disjoint union of sets in  $\mathcal{S}$

(d) **algebra** if it is closed under complements and **finite** unions.

(e) **monotone class** if  $A_j \uparrow A$  and  $A_j \downarrow A$  imply  $A \in \mathcal{S}$

(f)  **$\sigma$ -algebra** if...

(g)  **$\pi$ -system** if  $A, B \in \mathcal{S} \implies A \cap B \in \mathcal{S}$ .

(h)  **$\lambda$ -system** if

- $S \in \mathcal{S}$
- $A \subseteq B, A, B \in \mathcal{S} \implies B \setminus A \in \mathcal{S}$
- $A_j \uparrow A \implies A \in \mathcal{S}$

\* \* \*

Clearly, a  $\sigma$ -algebra is all of the above. Also:

- if  $\mathcal{S}$  is both a monotone class and an algebra, it is a  $\sigma$ -algebra,
- if  $\mathcal{S}$  is an algebra closed with respect to disjoint unions, it is a  $\sigma$ -algebra,
- if  $\mathcal{S}$  is both a  $\pi$ -system and  $\lambda$ -system, it is a  $\sigma$ -algebra.

## 1.2 Equivalent definition of $\lambda$ -system

A  $\lambda$ -system can also be defined by:

- $S \in \mathcal{S}$
- $A \in \mathcal{S} \implies A^c \in \mathcal{S}$
- if  $A_j \in \mathcal{S}$  with  $j \in \mathbb{N}$  are disjoint, then  $\cup_j A_j \in \mathcal{S}$ .

Suppose the first definition and let us prove the other. We simply get complements from  $A^c = S \setminus A$  and  $S \in \mathcal{S}$ . Suppose  $A_1$  and  $A_2$  are disjoint. Then  $A_1 \subseteq A_2^c$  so  $A_2^c \setminus A_1 \in \mathcal{S}$ . This means we have finite disjoint unions because

$$A_2^c \setminus A_1 = A_2^c \cap A_1^c = (A_1 \cup A_2)^c.$$

With finite disjoint unions,

$$\bigcup_{j=1}^{\infty} A_j = \bigcup_{j=1}^{\infty} \left[ \bigcup_{k=1}^j A_k \right] \in \mathcal{S}$$

as this is a monotone union.

Now let us prove the other direction. If  $A \subseteq B$  then  $B \setminus A = B \cap A^c = (B^c \cup A)^c$ . Then suppose  $A_j$  are monotone increasing. We have the disjoint union

$$\bigcup_{j=1}^{\infty} A_j = A_1 \cup \bigcup_{j=2}^{\infty} \left[ A_j \setminus \bigcup_{k=1}^{j-1} A_k \right] \in \mathcal{S}$$

as all the set differences are proper.

### 1.3 Dynkin–Sierpinski $\pi$ - $\lambda$ lemma

Let  $S$  be a set,  $\mathcal{C}$  a  $\pi$ -system and  $\mathcal{D}$  a  $\lambda$ -system. Then

$$\mathcal{C} \subseteq \mathcal{D} \implies \sigma(\mathcal{C}) \subseteq \mathcal{D}.$$

The proof is from [3, p. 10]. Clearly we can assume that  $\mathcal{D}$  is the smallest possible  $\lambda$ -system, this being denoted  $\lambda(\mathcal{D})$ . Taking into account that  $\pi$  and  $\lambda$  together make a  $\sigma$ -algebra, the statement becomes:

If  $\mathcal{C}$  is a  $\pi$ -system, then  $\lambda(\mathcal{C})$  is also a  $\pi$ -system.

Therefore, we need to prove  $A \cap B \in \mathcal{D}$  whenever  $A, B \in \mathcal{D}$ . For an arbitrary  $B \in \mathcal{C}$  define

$$\mathcal{S}_B = \{A \in \mathcal{D} : A \cap B \in \mathcal{D}\}.$$

Clearly  $\mathcal{S}_B$  is a  $\lambda$ -system containing  $\mathcal{C}$  (because  $\mathcal{C}$  is itself a  $\pi$ -system). Since  $\mathcal{D} = \lambda(\mathcal{C})$ , it follows that  $\mathcal{D} \subseteq \mathcal{S}_B$ . That is,  $A \cap B \in \mathcal{D}$  whenever  $B \in \mathcal{C}$  and  $A \in \mathcal{D}$ .

Now for any  $A \in \mathcal{D}$  define

$$\mathcal{S}'_A = \{B \in \mathcal{D} : A \cap B \in \mathcal{D}\}.$$

Similarly, and also using the previous result, we get  $\mathcal{D} \subseteq \mathcal{S}'_A$  and we conclude that  $A \cap B \in \mathcal{D}$  whenever  $A, B \in \mathcal{D}$ .

\* \* \*

Suppose  $\mathcal{C} \subseteq \mathcal{D} \subseteq \mathcal{F}$  where  $\mathcal{F}$  is a  $\sigma$ -algebra on a probability space. Let  $\mathcal{D}$  be the set of all events with a certain property, this property naturally making it a  $\lambda$ -system. Suppose also  $\sigma(\mathcal{C}) = \mathcal{F}$ . By the lemma,  $\mathcal{D} = \mathcal{F}$ , that is, all events have the desired property.

## 1.4 Notable exercises

### 1.4.1 Any open set of reals is a countable union of intervals

See [1, ex. 1.1.2]. Define

$$\mathcal{S}_d = \left\{ \prod_{j=1}^d \langle a_j, b_j \rangle : -\infty \leq a < b \leq +\infty \right\} \subseteq \mathbb{R}^d.$$

Note that  $\mathcal{S}_d$  is a semialgebra (automatically, also a  $\pi$ -system). We claim that  $\sigma(\mathcal{S}_d) = \mathcal{B}(\mathbb{R}^d)$ . It suffices to prove that every open set in  $\mathbb{R}^d$  can be written as the countable union of sets in  $\mathcal{S}_d$ .

Take  $d = 1$  with a simple extension afterwards. Let  $A \subseteq \mathbb{R}$  be open, so that for each  $x \in A$  there is  $\varepsilon_x$  such that  $B(x, \varepsilon_x) \subseteq A$ . Also,

$$A = \bigcup_{x \in A} B(x, \varepsilon_x).$$

Note that  $A \cap \mathbb{Q}$  is dense in  $A$ . Namely, each  $x$  is within its ball, and within the ball is a sequence of rationals converging to  $x$ . For each rational  $y$  such that  $|x - y| < \varepsilon_x/2$  we can clearly choose an  $\varepsilon_y$  such that  $x \in B(y, \varepsilon_y) \subseteq A$ . This gives us the countable union<sup>1</sup>

$$A = \bigcup_{y \in A \cap \mathbb{Q}} B(y, \varepsilon_y)$$

\* \* \*

### 1.4.2 Infinite unions of algebras/ $\sigma$ -algebras

See [1, ex. 1.1.4]. Suppose  $\mathcal{F}_1 \subseteq \mathcal{F}_2 \subseteq \dots$  and  $\mathcal{F} = \bigcup_j \mathcal{F}_j$ .

If  $\mathcal{F}_j$  are algebras, then  $\mathcal{F}$  is also an algebra because

$$\bigcup_{j \in N} A_j \in \mathcal{F}_{\max N}, \quad A_j \in \mathcal{F}_j.$$

where  $N \subseteq \mathbb{N}$  is finite.

The analogous claim is not true if  $\mathcal{F}_j$  are  $\sigma$ -algebras. Let  $S = \mathbb{R}$  and

$$\mathcal{F}_j = \sigma \left( \left[ \frac{n}{2^j}, \frac{n+1}{2^j} \right) : n \in \mathbb{N} \right), \quad j \in \mathbb{N}.$$

If  $\mathcal{F}$  is a  $\sigma$ -algebra,

$$\{0\} = \bigcap_{j \in \mathbb{N}} \left[ 0, \frac{1}{2^j} \right) \in \mathcal{F},$$

but there is no  $j$  such that  $\{0\} \in \mathcal{F}_j$ , giving us a contradiction.

---

<sup>1</sup>while different  $x$  can give different  $\varepsilon_y$ , these clearly have a finite supremum

## 2 Measure and integration

### 2.1 Products of $\sigma$ -algebras

#### 2.1.1 Definitions of product $\sigma$ -algebra

If  $(S_\alpha)_{\alpha \in A}$  are measurable spaces with  $\sigma$ -algebras  $\mathcal{F}_\alpha$  and  $S = \prod_\alpha S_\alpha$ , then  $S$  has the **product  $\sigma$ -algebra**  $\mathcal{F} = \prod_\alpha \mathcal{F}_\alpha = \bigotimes_\alpha \mathcal{F}_\alpha$  defined as

$$\mathcal{F} = \sigma(\pi_\alpha^{-1}(E_\alpha) : \alpha \in A, E_\alpha \in \mathcal{F}_\alpha),$$

i.e. **generated by one-dimensional measurable cylinders**.

\* \* \*

If  $A$  is countable, then  $\mathcal{F}$  is **generated by cuboids**  $\prod_\alpha E_\alpha$ ,  $\alpha \in A$  (see [2, p. 23]). To prove it, define

$$\mathcal{F}_1 = \sigma(\pi_\alpha^{-1}(E_\alpha) : \alpha \in A, E_\alpha \in \mathcal{F}_\alpha), \quad \mathcal{F}_2 = \sigma\left(\prod_{\alpha \in A} E_\alpha : E_\alpha \in \mathcal{F}_\alpha\right).$$

Firstly,  $\pi_\alpha^{-1}(E_\alpha) = \prod_\alpha E_\alpha$  where  $E_\beta = S_\beta$  for  $\beta \neq \alpha$ , so  $\mathcal{F}_1 \subseteq \mathcal{F}_2$ .

Secondly,

$$\prod_{\alpha \in A} E_\alpha = \bigcap_{\alpha \in A} \pi_\alpha^{-1}(E_\alpha) \in \mathcal{F}_1,$$

so that  $\mathcal{F}_2 \subseteq \mathcal{F}_1$ .

\* \* \*

Instead of taking  $E_\alpha$ 's from the  $\sigma$ -algebras, we can restrict ourselves to **sets of generators**. Suppose  $\sigma(\mathcal{E}_\alpha) = \mathcal{F}_\alpha$ , then (the second part again if  $A$  is countable, and proven the same way)

$$\bigotimes_{\alpha \in A} \mathcal{F}_\alpha = \sigma(\pi_\alpha^{-1}(E_\alpha) : \alpha \in A, E_\alpha \in \mathcal{E}_\alpha) = \sigma\left(\prod_{\alpha \in A} E_\alpha : E_\alpha \in \mathcal{E}_\alpha\right).$$

To prove the first part, consider the sets

$$\mathcal{D} = \{\pi_\alpha^{-1}(E_\alpha) : \alpha \in A, E_\alpha \in \mathcal{E}_\alpha\}, \quad \mathcal{C}_\alpha = \{E \in F_\alpha : \pi_\alpha^{-1}(E) \in \sigma(\mathcal{D})\}.$$

Then  $C_\alpha$  is a  $\sigma$ -algebra containing  $\mathcal{E}_\alpha$ , which means that  $C_\alpha = \mathcal{F}_\alpha$  and  $\sigma(\mathcal{D}) = \bigotimes_\alpha \mathcal{F}_\alpha$ .

#### 2.1.2 Borel $\sigma$ -algebra on product metric space

Suppose  $S_j$  are separable metric spaces ( $j \in \mathbb{N}$ ) with Borel  $\sigma$ -algebras  $\mathcal{B}_j$ . Then (see [3, p. 11])

$$\mathcal{B}(S_1 \times S_2 \times \dots) = \mathcal{B}_1 \otimes \mathcal{B}_2 \otimes \dots \tag{2.1}$$

Consider the sets

$$\mathcal{C}_1 = \left\{A : A \text{ open in } \bigtimes_j S_j\right\}, \quad \mathcal{C}_2 = \{S_1 \times \dots \times B_j \times S_{j+1} \times \dots : B_j \in \mathcal{B}_j\},$$

and  $\mathcal{C}$  defined similar to  $\mathcal{C}_2$  but where  $B_j$  has to be open instead. The claim is then  $\sigma(\mathcal{C}_1) = \sigma(\mathcal{C}_2)$ .

Clearly  $\mathcal{C} \subseteq \mathcal{C}_1, \mathcal{C}_2$ . But it is also clear that  $\sigma(\mathcal{C}) \supseteq \sigma(\mathcal{C}_2)$ , so  $\sigma(\mathcal{C}) = \sigma(\mathcal{C}_2)$ . This proves that the  $\supseteq$  part in (2.1) holds without separability.

If  $S_j$  are separable,  $\mathcal{C}$  is a topological basis of  $\times_j S_j$ , so that  $\sigma(\mathcal{C}) \supseteq \sigma(\mathcal{C}_1)$ . Then  $\sigma(\mathcal{C}) = \sigma(\mathcal{C}_1)$  as well.

### 2.1.3 Measurability in coordinate functions

See [3, p. 15]. Suppose that  $(\Omega, \mathcal{A})$  and  $(S_j, \mathcal{S}_j)$  are measurable spaces for  $j \in \mathbb{N}$ , denoting  $S = \times_j S_j$ . Let  $f: \Omega \rightarrow S$  be a function and define  $f_j$  as its **coordinate functions**  $f_j = \pi_j \circ f$ . Then

$f$  is measurable if and only if all  $f_j$  are measurable.

The “only if” part is trivial, because each  $f_j$  is a composition of measurable  $f$  and  $\pi_j$ . For the “if” part, note that  $f$  satisfies the definition of measurability on a generating subset, those being measurable cuboids:

$$f^{-1}(B) = \bigcap_j f_j^{-1}(B_j), \quad B = B_1 \times B_2 \times \dots, \quad (2.2)$$

where  $B$  and all  $B_j$  are measurable sets.

**Note** that (2.2) indeed holds specifically for cuboid sets  $B$  and not generally. Instead of these cuboids, we could have also chosen the simpler generating set of one-dimensional cylinders  $\pi_j^{-1}(B_j)$ .

## 2.2 Convergence theorems

We consider whether  $\int f_n \rightarrow \int f$  if  $f \rightarrow f_n$  pointwise, where the functions are defined on a  $\sigma$ -finite measure space  $X$ . Following [1, §1.4], we present the convergence theorem in order: bounded, Fatou’s lemma, monotone, dominated. Note that in all cases pointwise convergence can be replaced with a.e. convergence, which is weaker but without affecting integration.

### 2.2.1 Bounded convergence theorem

Suppose the  $f_n$  have

- **bounded domain:**  $f_n$  vanishes on  $E^c$  for some  $E$  with  $\mu(E) < \infty$ ,
- **bounded range:**  $|f_n| \leq M$  uniformly,
- $f_n \rightarrow f$  in measure.

Then  $\int f_n \rightarrow \int f$ .

To **prove** it, we have:

$$\begin{aligned} \left| \int f - f_n \right| &\leq \int |f - f_n| \\ &= \int_{\{|f-f_n| \geq \varepsilon\}} |f - f_n| + \int_{\{|f-f_n| < \varepsilon\}} |f - f_n| \\ &\leq 2M\mu(|f - f_n| \geq \varepsilon) + \varepsilon\mu(E) \rightarrow 0, \quad n \rightarrow \infty, \quad \varepsilon \downarrow 0. \end{aligned}$$

We implicitly used that  $|f| \leq M$  as well. We obtain this because  $|f| \geq M + \varepsilon$  implies  $|f - f_n| \geq \varepsilon$ , giving us  $\mu(|f| > M) = 0$  after some simple work.

### 2.2.2 Fatou's lemma

Suppose  $f_n \geq 0$ , then

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

**Recall** that

$$\liminf_{n \rightarrow \infty} f_n = \sup_m \inf_{n \geq m} f_n,$$

thus we define  $g_n = \inf_{m \geq n} f_m$  so that  $g_n \uparrow g := \liminf_n f_n$ .

It then suffices to show (note  $f_n \geq g_n$ )

$$\liminf_{n \rightarrow \infty} \int g_n \geq \int g.$$

Let  $E_m \uparrow X$  be measurable sets with  $\mu(E_m) < \infty$ . For fixed  $m$ :

$$(g_n \wedge m) \cdot 1_{E_m} \rightarrow (g \wedge m) \cdot 1_{E_m}.$$

Finally,

$$\liminf_{n \rightarrow \infty} \int g_n \geq \int_{E_m} g_n \wedge m \rightarrow \int_{E_m} g \wedge m \rightarrow \int g.$$

The inequality holds on a subsequence, the first convergence ( $n \rightarrow \infty$ ) is the bounded convergence theorem, and the second ( $m \rightarrow \infty$ ) is the below lemma.

\* \* \*

In the proof we used the following **lemma** (see [1, p. 22]): let  $E_n \uparrow X$  be measurable sets with  $\mu(E_n) < \infty$ . Then

$$\int_{E_n} f \wedge n \rightarrow \int f.$$

Clearly the left side is increasing and below  $\int f$ . By definition of the Lebesgue integral, it suffices to show that for every simple nonnegative  $\varphi$ , there exists  $n$  with

$$\int \varphi \leq \int_{E_n} f \wedge n \leq \int f.$$

Let  $N$  be such that  $\mu(\varphi > N) = 0$  and choose  $n \geq N$ . Then

$$\begin{aligned} \int_{E_n} f \wedge n &\geq \int_{E_n} \varphi = \int \varphi - \int_{E_n^c} \varphi \\ &\geq \int \varphi - N\mu(E_n^c), \end{aligned}$$

so that

$$\liminf_{n \rightarrow \infty} \int_{E_n} f \wedge n \geq \int \varphi,$$

since  $\mu(E_n^c) \rightarrow 0$ .

### 2.2.3 Monotone convergence theorem

Suppose  $f_n \geq 0$  and  $f_n \uparrow f$ , then

$$\int f_n \rightarrow \int f.$$

Since  $f_n \leq f$  we have  $\limsup_n \int f_n \leq \int f$ , and by Fatou's lemma we have  $\liminf_n \int f_n \geq \int f$ .

### 2.2.4 Dominated convergence theorem

Let  $f_n$  be such that  $|f_n| \leq g$  uniformly, for some integrable  $g$ . If  $f_n \rightarrow f$ , then

$$\int f_n \rightarrow \int f.$$

The condition  $|f_n| \leq g$  can be written as  $g \pm f_n \geq 0$ . With  $g \pm f_n \rightarrow f$ , we apply Fatou's lemma twice. The + and - parts respectively give  $\int f \geq \limsup_n \int f_n$  and  $\int f \leq \liminf_n \int f_n$ .

## 2.3 Measure extension

Carathéodory's theorem (multiple variations) extends measure from family of subsets to whole  $\sigma$ -algebra (unique?); Kolmogorov's theorem extends measures on finite-dimensional subspaces to a single measure on an infinite-dimensional metric probability space.

## 2.4 Product measure

Suppose  $(S, \mathcal{S}, \mu)$  and  $(T, \mathcal{T}, \nu)$  are  $\sigma$ -finite measure spaces. We wish to introduce a measure on the product measurable space  $(S \times T, \mathcal{S} \otimes \mathcal{T})$ .

### 2.4.1 Sections

For any **measurable set**  $E \in \mathcal{S} \otimes \mathcal{T}$ ,  $s \in S$  and  $t \in T$  we define the sections

$$E_s = \{t \in T : (s, t) \in E\}, \quad E^t = \{s \in S : (s, t) \in E\}.$$

For any measurable **function**  $f: S \times T \rightarrow U$  and any  $s \in S$  and  $t \in T$  we define the sections  $f_s: T \rightarrow U$  and  $f^t: S \rightarrow U$  with

$$f_s(t) = f(s, t), \quad f^t(s) = f(s, t).$$

We claim that the sections are **always measurable** (sets or functions). Consider first the set  $E_s$ . Define

$$\mathcal{D} = \{E \in \mathcal{S} \otimes \mathcal{T} : E_s \in \mathcal{T} \text{ for all } s \in S\}.$$

Clearly,  $\mathcal{D}$  is a  $\lambda$ -system and contains the generating  $\pi$ -system of rectangles  $A \times B$  since  $(A \times B)_s = B$  if  $s \in A$  and  $\emptyset$  otherwise. By Dynkin's lemma,  $\mathcal{D} = \mathcal{S} \otimes \mathcal{T}$ .

To prove the measurability of functions  $f_s$ , it is simple to show that  $f_s^{-1}(B) = (f^{-1}(B))_s \in \mathcal{T}$ , for any measurable  $B$ .

\* \* \*

Let  $f: S \times T \rightarrow \mathbb{R}_{\geq 0}$  be a measurable function. We claim that the **maps**

$$s \mapsto \int_T f(s, t) \nu(dt), \quad t \mapsto \int_S f(s, t) \mu(ds)$$

are measurable.

We use a type of Lebesgue's induction. Assume first that  $\mu$  and  $\nu$  are finite and that  $f = 1_E$  where  $E = A \times B$ . Then

$$\int_T 1_E(s, t) \nu(dt) = \nu(E_s) = \nu(B) \cdot 1_A(s).$$

Clearly,  $s \mapsto \nu(B) \cdot 1_A(s)$  is measurable. We wish to extend this to **arbitrary indicator function** so we define

$$\mathcal{D} = \{E \in \mathcal{S} \otimes \mathcal{T} : s \mapsto \nu(E_s) \text{ is measurable}\}$$

Again,  $\mathcal{D}$  is a  $\lambda$ -system containing the generating  $\pi$ -system of measurable rectangles, so  $\mathcal{D} = \mathcal{S} \otimes \mathcal{T}$ .

This is then extended to simple functions (linearity of integration) and to general nonnegative measurable functions. For the latter, note that monotone convergence of integrals  $\int_T f_n(s, t) \nu(dt)$  means the pointwise convergence of the maps  $s \mapsto \int_T f_n(s, t) \nu(dt)$ , and the class of measurable functions is closed under pointwise limits (see [1, ex. 1.2.7])

**Note.** The requirement  $f \geq 0$  serves to insure that the integrals exist. An alternative requirement is  $\int |f| d\xi < \infty$  (with  $\xi$  product measure).

**Note.** The assumption of finite measures (important for  $\mathcal{D}$  being a  $\lambda$ -system) does not lose on generality because of the following: take  $F_n \uparrow T$  with  $\nu(F_n) < \infty$ . Then the maps  $s \mapsto \nu(E_s \cap F_n)$  converge pointwise to  $s \mapsto \nu(E_s)$  with pointwise convergence preserving measurability. The family

$$\mathcal{D}' = \{E \in \mathcal{S} \otimes \mathcal{T} : s \mapsto \nu(E_s \cap F_n) \text{ is measurable for all } n\}$$

is certainly a  $\lambda$ -system, ensuring the measurability of all  $s \mapsto \nu(E_s \cap F_n)$ .

## 2.4.2 Definitions

We can define a measure  $\xi$  on measurable rectangles with

$$\xi(A \times B) = \mu(A)\nu(B), \quad A \in \mathcal{S}, B \in \mathcal{T}.$$

The function  $\xi$  is then extended to a unique measure on  $\mathcal{S} \otimes \mathcal{T}$  by Carathéodory-type theorems.

\* \* \*

**Alternatively**, we can define

$$\xi'(E) = \int_T \mu(E^t) \nu(dt) = \int_S \nu(E_s) \mu(ds), \quad E \in \mathcal{S} \otimes \mathcal{T}. \quad (2.3)$$

\* \* \*

Let us **prove** these definitions are equivalent. Formally using Fubini's theorem:

$$\begin{aligned} \xi(E) &= \int_{S \times T} 1_E(u) \xi(du) \\ &= \int_S \mu(ds) \int_T 1_E(s, t) \nu(dt) \\ &= \int_S \nu(E_s) \mu(ds) = \xi'(E). \end{aligned} \quad (2.4)$$

Conversely, for  $E = A \times B$ ,

$$\xi'(E) = \int_S \nu(E_s) \mu(ds) = \int_T \nu(B) 1_A(s) \mu(ds) = \mu(A)\nu(B) = \xi(E). \quad (2.5)$$

\* \* \*

We should also **justify** the second equality in (2.3). Define  $\xi'(E) = \int_T \mu(E^t)\nu(ds)$  and  $\xi''(E) = \int_S \nu(E_s)\mu(dt)$ . By (2.5)  $\xi'$  and  $\xi''$  agree on the generating  $\pi$ -system of measurable rectangles. By a well known lemma,  $\xi' = \xi''$ . This argument also suffices to prove  $\xi = \xi'$  (Fubini's theorem is not necessary, (2.4) serves a heuristic purpose).

### 2.4.3 Fubini's theorem

Let  $f: S \times T \rightarrow \mathbb{R}$  be a measurable function such that  $\int_{S \times T} |f| d\xi < \infty$ . Then

$$\int_{S \times T} f d\xi = \int_S \mu(ds) \int_T f(s, t) \nu(dt) = \int_T \nu(dt) \int_S f(s, t) \nu(ds). \quad (2.6)$$

Consider first a measurable function  $f \geq 0$ . By previous discussion, the integrals are well-defined and  $\xi$  satisfies:

$$\xi(E) = \int_S \mu(ds) \int_T 1_E(s, t) \nu(dt), \quad E \in \mathcal{S} \otimes \mathcal{T},$$

where we also know the order of integration can be reversed. Thus (2.6) holds for indicator functions, and is extended to arbitrary nonnegative functions by linearity and monotone convergence. For general integrable  $f$ , apply the previous case to  $f^+$  and  $f^-$  and subtract. Integrability ensures that the integrands are measurable and the difference is well-defined.

## 2.5 Notable exercises

### 2.5.1 Equality of measures agreeing on a generating $\pi$ -system

Let  $\mu$  and  $\nu$  be finite measures on measurable space  $(S, \mathcal{S})$ . If

$$\mu(C) = \nu(C), \quad C \in \mathcal{C},$$

where  $\mathcal{C}$  is a generating  $\pi$ -system, then  $\mu = \nu$ . This can be extended to  $\sigma$ -finite measures.

To **prove** this, note that

$$\mathcal{D} = \{E \in \mathcal{S}: \mu(E) = \nu(E)\}$$

is a  $\lambda$ -system containing  $\mathcal{C}$ .

For  **$\sigma$ -finite** measures, note that the previous implies that  $\mu = \nu$  when restricted to finite measure spaces  $(S \cap E_n, \mathcal{S} \cap E_n)$ , where  $E_n \uparrow S$  and  $\mu(E_n) < \infty$ . Then for any  $E \in \mathcal{S}$

$$\mu(E) = \lim_{n \rightarrow \infty} \mu(E \cap E_n) = \lim_{n \rightarrow \infty} \nu(E \cap E_n) = \nu(E).$$

### 2.5.2 Pointwise convergence preserves measurability

See [1, ex. 1.3.7]. Suppose  $f_n \rightarrow f$  pointwise with  $f_n$  measurable. Then  $f$  is measurable because

$$\{f \leq a\} = \bigcup_{r \in \mathbb{N}} \bigcup_{k=1}^{\infty} \bigcap_{n \geq k} \left\{ f_n \leq a + \frac{1}{r} \right\}.$$

### 2.5.3 Tail-formula for $p$ -th moment

If  $f$  is a measurable function, then

$$\|f\|_p = \left( p \int_{\mathbb{R}} y^{p-1} \mu(|f(x)| \geq y) dy \right)^{1/p}.$$

It can be derived, using Fubini for nonnegative functions:

$$\begin{aligned} \|f\|_p^p &= \int_{\mathbb{R}} |f(x)|^p dx \\ &= \int_{\mathbb{R}} \int_0^{|f(x)|} py^{p-1} dy dx \\ &= \int_{\mathbb{R}} py^{p-1} \int_{\mathbb{R}} 1_{[0,|f(x)|]}(y) dx dy \\ &= p \int_{\mathbb{R}} y^{p-1} \mu(|f(x)| \geq y) dy. \end{aligned}$$

\* \* \*

This holds for all  $0 < p < \infty$ . In probability, this is written

$$\mathbb{E}(X^p) = p \int_{\mathbb{R}} x^{p-1} \mathbb{P}(X \geq x) dx, \quad X \geq 0.$$

### 2.5.4 $\infty$ -norm as limit of $p$ -norms

We claim that

$$\|f\|_{\infty} = \lim_{p \rightarrow \infty} \|f\|_p.$$

where  $f$  is a measurable function on a probability space.

Let  $\varphi = \sum_{j=1}^n a_j 1_{A_j}$  be a **simple** function on an **arbitrary** measure space, so that  $\|\varphi\|_p^p = \sum_j |a_j|^p \mu(A_j)$ . Define also  $M = \max \{|a_j| : 1 \leq j \leq n\} = \|\varphi\|_{\infty}$  and let  $m$  be the corresponding index. Clearly  $\|\varphi\|_p \leq \|\varphi\|_{\infty}$ , but also

$$\|\varphi\|_p \geq M (\mu(A_m))^{1/p} \rightarrow M, \quad p \rightarrow \infty,$$

proving the claim for simple functions on arbitrary measure spaces.

Similar ideas are used for general  $f$  on a **probability** space. Again  $\|f\|_p \leq \|f\|_{\infty}$ . Take arbitrary  $\varepsilon > 0$  and set  $A_{\varepsilon} = \{|f| > M - \varepsilon\}$ . By definition of  $M$ ,  $0 < \mu(A_{\varepsilon}) < \infty$ . Then,

$$\|f\|_p^p \geq \int_{A_{\varepsilon}} |f|^p d\mu \geq (M - \varepsilon)^p \mu(A_{\varepsilon}).$$

Again  $\liminf_p \|f\|_p \geq M - \varepsilon$ , and the claim follows by  $\varepsilon \downarrow 0$ .

### 3 Basics of probability

## References

- [1] R. Durrett. **Probability: Theory and Examples**. 5th ed. Cambridge University Press, Apr. 2019. ISBN: 9781108591034 9781108473682. DOI: [10.1017/9781108591034](https://doi.org/10.1017/9781108591034). URL: <https://www.cambridge.org/core/product/identifier/9781108591034/type/book> (visited on 10/16/2025).
- [2] G. B. Folland. **Real analysis: modern techniques and their applications**. eng. 2. ed. A Wiley-Interscience publication. New York Weinheim: Wiley, 1999. ISBN: 9780471317166.
- [3] O. Kallenberg. **Foundations of Modern Probability**. en. Vol. 99. Probability Theory and Stochastic Modelling. Cham: Springer International Publishing, 2021. ISBN: 9783030618704 9783030618711. DOI: [10.1007/978-3-030-61871-1](https://doi.org/10.1007/978-3-030-61871-1). URL: <https://link.springer.com/10.1007/978-3-030-61871-1> (visited on 10/16/2025).