

Summary: Introduction to Probability

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Chapter 1

Introduction: Part I

1.1 Sets

1.2 The principle of induction

1.3 Order structure of the real numbers

Exercise 1.1 (1.11 TOOL). Let A be a set with n elements. Show that

1. the number of permutations of the elements from A is $n!$;
2. for any $0 \leq k \leq n$, the number of subsets of A having k elements is given by

$$\frac{n!}{(n-k)!k!}.$$

Chapter 2

Introduction: Part II

2.1 Functions

Proposition 2.1. TODO prop 2.12

2.2 Cardinality of Sets

2.3 Euclidean distance

Proposition 2.2. let $f : A \rightarrow B$ be a function. Let $B_* \subset B$. Then,

(a) $f^{-1}(B_*^c) = f^{-1}(B_*)^c$.

Let I and J be some sets and $A_i \subset A, i \in I$, and $B_j \subset B, j \in J$, be a collection of sets from A and B , respectively. Then,

(b) TODO

(c) TODO

(d) TODO

Chapter 3

Introduction: Part III

3.1 Real valued sequences

Chapter 4

Measurable sets: Part I

4.1 Measurable spaces

Definition 4.1. 4.2 TODO

Definition 4.2 (Measurable space). let $\Omega \neq \emptyset$ and \mathcal{F} be a σ -field on Ω . The pair (Ω, \mathcal{F}) is referred to as a measurable space. if $A \in \mathcal{F}$, then A is said to be measurable. if $\mathcal{A} \subset \mathcal{F}$ and \mathcal{A} is a σ -field on Ω , \mathcal{A} is referred to as a sub- σ -field on Ω .

Chapter 5

Measurable sets: Part II

5.1 Measure spaces

5.2 Semirings

Chapter 6

Measurable sets: Part III

6.1 Measure extensions

Proposition 6.1. Let $(a, b]$, $a < b \in \mathbb{R}$, be any left-open interval. Let I be countable and $(a_i, b_i]$, $i \in I$, be s.t., $(a, b] \subset \bigcup_{i \in I} (a_i, b_i]$, then

$$b - a \leq \sum_{i \in I} (b_i - a_i). \quad (10)$$

Proposition 6.2. Let $(a, b]$, $a < b \in \mathbb{R}$, be any left-open interval. let I be countable and $\{(a_i, b_i] : i \in I\}$ be a disjoint collection of left-open intervals s.t. $\bigcup_{i \in I} (a_i, b_i] \subset (a, b]$. Then

$$\sum_{i \in I} (b_i - a_i) \leq b - a.$$

Definition 6.1. Let $\Omega \neq \emptyset$ be a set and \mathcal{A} be a collection of subsets from Ω . Let $A \in \mathcal{P}(\Omega)$ be any subset of Ω . A collection $\{U_i : i \in I\}$ is said to be a covering of A by sets from \mathcal{A} if:

(i) $\{U_i : i \in I\} \subset \mathcal{A}$ (Set membership condition)

NOTE that (i) means $U_i \subset \mathcal{A} \forall i \in I$, not $\bigcup_{i \in I} U_i \subset \mathcal{A}$.

(ii) $A \subset \bigcup_{i \in I} U_i$ (Covering condition)

A covering $\{\bigcup_i : i \in I\}$ of A by sets from \mathcal{A} is referred as countable (resp. finite) if I is countable (resp. finite). We write $C_{\mathcal{A}}(A)$ for the set which contains all the countable covering of A by sets from \mathcal{A} , i.e.,

$$C_{\mathcal{A}}(A) = \{\xi : \xi \text{ is a countable covering of } A \text{ by sets from } \mathcal{A}\}.$$

Why do we say $A \in \mathcal{P}(\Omega)$ instead of $A \in \Omega$? When we use the notation $A \in \mathcal{P}(\Omega)$, it signifies that A is a subset of Ω , not an element of Ω . The power set $\mathcal{P}(\Omega)$ represents all possible subsets of Ω , including Ω itself, any subset of it, or even an empty set. Using $A \in \Omega$ would incorrectly imply that A is an individual element of Ω , which does not align with the context of covering subsets with subsets.

My Example 6.1 (Finite Covering). Let $\Omega = \{1, 2, 3, 4, 5\}$, and let \mathcal{A} be a collection of subsets of Ω , such as $\mathcal{A} = \{\{1\}, \{2, 3\}, \{3, 5\}\}$, if we take $A = \{1, 2, 3\}$, a finite covering of A by sets from \mathcal{A} could be $\{\{1\}, \{2, 3\}\}$. This covering is finite, as I can be $\{1, 2\}$, which is finite. The 2 conditions both hold. Each U_i is a subset of \mathcal{A} , and A is covered by the union of U_i . In this case, the possible countable coverings of A that can be formed using subsets of \mathcal{A} are restricted to the one already provided. Therefore, $C_{\mathcal{A}}(A) = \{\{1\}, \{2, 3\}\}$

Important from Example 6.1 (Script) Let $\Omega = \mathbb{R}$ and $\mathcal{R} = \{A : A = (a, b], a, b \in \mathbb{R}\} \cup \{\emptyset\}$. We define the function $\ell : \mathcal{R} \rightarrow [0, \infty)$ s.t.

$$\ell(U) = \begin{cases} b - a, & \text{if } U = (a, b], \\ 0, & \text{if } U = \emptyset. \end{cases}$$

Given $A \in \mathcal{P}(\mathbb{R})$, we also define the function $v_\ell(\xi) : \mathcal{R} \rightarrow \mathbb{R}^+$, where $\xi \in C_{\mathcal{R}}(A)$ s.t.

$$v_\ell(\xi) = \sum_{U \in \xi} \ell(U).$$

We also show that

$$\inf\{v_\ell(\xi) : \xi \in C_{\mathcal{R}}((a, b])\} = \inf_{\xi \in C_{\mathcal{R}}((a, b])} v_\ell(\xi) = b - a, \quad (11)$$

i.e., $b - a$ is a lower bound for the values of $v_\ell(\xi)$, $\xi \in C_{\mathcal{R}}((a, b])$. We also saw that there exists $\xi \in C_{\mathcal{R}}((a, b])$ s.t. $b - a = v_\ell(\xi)$. Hence, the latter infimum is a minimum (Proposition 6.3).

Proposition 6.3. Given any left open interval $(a, b]$, $\min_{\xi \in C_{\mathcal{R}}((a, b])} v_\ell(\xi) = b - a$

Define ℓ^* We build on the latter result and define the function

$$\ell^* = \inf_{\xi \in C_{\mathcal{R}}(A)} v_\ell(\xi), \quad A \in \mathcal{P}(\mathbb{R}).$$

Note, we know that if $A \in \mathcal{R}$, then $\ell^*(A) = b - a$

Chapter 7

Measurable functions

7.1 The concept of measurable functions

Definition 7.1 (Measurable function). Let (Ω, \mathcal{F}) and $(\Omega^*, \mathcal{F}^*)$ be two measurable spaces (cf. Definition 4.2). A function $f : \Omega \rightarrow \Omega^*$ is said to be measurable $\mathcal{F}/\mathcal{F}^*$ if for any $A^* \in \mathcal{F}^*$, $f^{-1}(A^*) \in \mathcal{F}$.

Proposition 7.1 (Measurable function). Let (Ω, \mathcal{F}) and $(\Omega^*, \mathcal{F}^*)$ be two measurable spaces and $f : \Omega \rightarrow \Omega^*$ be a function. Suppose that $\mathcal{F}^* = \sigma(\mathcal{G})$ and for any $G \in \mathcal{G}$, $f^{-1}(G) \in \mathcal{F}$. Then, f is $\mathcal{F}/\mathcal{F}^*$ measurable.

Definition 7.2 (Borel function). A function $f : \mathbb{R}^m \rightarrow \mathbb{R}^k$ is called Borel function if it is measurable $\mathfrak{B}(\mathbb{R}^m)/\mathfrak{B}(\mathbb{R}^k)$.

Proposition 7.2 (Continuous functions and Borel functions). Any continuous function $f : \mathbb{R}^m \rightarrow \mathbb{R}^k$ is a Borel function.

Proposition 7.3 ($\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable). Let (Ω, \mathcal{F}) be a measurable space and $f : \Omega \rightarrow \mathbb{R}$ be a real-valued function. Suppose that $\{\omega \in \Omega : f(\omega) \leq x\} \in \mathcal{F}$ for any $x \in \mathbb{R}$, then f is $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable. In other words: f is a measurable function if the pre-image of any interval $(-\infty, x]$ under f is a measurable set in \mathcal{F} , or $f^{-1}((-\infty, x]) \in \mathcal{F}$. since $\mathfrak{B}(\mathbb{R}) = \sigma(\{(-\infty, x] : x \in \mathbb{R}\})$, we also clearly see the proof (cf. Proposition 7.1).

Thinking about $f^{-1}((-\infty, x])$ If $B \in \mathfrak{B}(\mathbb{R})$, then, $f^{-1}(B) = \{\omega \in \Omega : f(\omega) \in B\}$ Is the same as saying, $f^{-1}((-\infty, x]) = \{\omega \in \Omega : f(\omega) \leq x\}$. $f^{-1}(B)$ will return ALL of the values $\omega \in \Omega$ for which $f(\omega) \in B$. See My Example 7.1 for further intuition.

Define $\mathbb{1}_A(\omega)$ TODO

Example 7.1 (Simple measurable function). Let $\Omega = \{h, t\}$ and $\mathcal{F} = \mathcal{P}(\{h, t\}) = \{\emptyset, \{h\}, \{t\}, \{h, t\}\}$. Then, $\{h\} \in \mathcal{P}(\{h, t\})$. Thus

$$f(\omega) = \begin{cases} 1, & \text{if } \omega = h, \\ 0, & \text{if } \omega = t, \end{cases}$$

is $\mathcal{P}(\{h, t\})/\mathfrak{B}(\mathbb{R})$ measurable. In order for f to be $\mathcal{P}(\{h, t\})/\mathfrak{B}(\mathbb{R})$ measurable, the pre-image of every Borel set in \mathbb{R} under f must be an element of \mathcal{F} . For any $x \in \mathbb{R}$, $f^{-1}((-\infty, x])$ will either be \emptyset , $\{h\}$, or $\{t\} \in \mathcal{F}$.

Proposition 7.4 ($\mathcal{F}/\mathfrak{B}(\mathbb{R}^k)$ measurable). Let (Ω, \mathcal{F}) be a measurable space and $f : \Omega \rightarrow \mathbb{R}^k$, i.e.,

$$f(\omega) = (f_1(\omega), \dots, f_k(\omega)).$$

Then, f is $\mathcal{F}/\mathfrak{B}(\mathbb{R}^k)$ measurable if and only if for any $i = 1, \dots, k$, $f_i : \Omega \rightarrow \mathbb{R}$ is $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable.

Proposition 7.5 (Composite measurable function). Let (Ω, \mathcal{F}) be a measurable space and $f_i : \Omega \rightarrow \mathbb{R}, i = 1, \dots, k$, be $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable. Suppose that $g : \mathbb{R}^k \rightarrow \mathbb{R}$ is $\mathfrak{B}(\mathbb{R}^k)/\mathfrak{B}(\mathbb{R})$ measurable. Then,

$$w \mapsto g((f_1(\omega), \dots, f_k(\omega))) = g(f_1(\omega), \dots, f_k(\omega)).$$

is $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable. (Composite function usually written without double brackets)

Proposition 7.6 (Continuity preserves measurability in function composition). Let (Ω, \mathcal{F}) be a measurable space and $f_i : \Omega \rightarrow \mathbb{R}, i = 1, \dots, k$, be $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable. Then, if $g : \mathbb{R}^k \rightarrow \mathbb{R}$ is continuous,

$$w \mapsto g(f_1(\omega), \dots, f_k(\omega)).$$

is $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable.

Example 7.2 (Continuity preserves measurability). Let (Ω, \mathcal{F}) be a measurable space and $f_i : \Omega \rightarrow \mathbb{R}, i = 1, \dots, k$, be $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable. Then, $\sum_{i=1}^k f_i$ is $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable (cf. Proposition 2.1).

Example 7.3 (Continuity preserves measurability). Let (Ω, \mathcal{F}) be a measurable space and $f_i : \Omega \rightarrow \mathbb{R}, i = 1, \dots, k$, be $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable. Then, $\prod_{i=1}^k f_i$ is $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable (cf. Proposition 2.1).

Definition 7.3 (Simple functions). A function $f : \Omega \rightarrow \mathbb{R}$ is called simple if there exists $n \in \mathbb{N}, \alpha_1, \dots, \alpha_n \in \mathbb{R}$ and sets $A_1, \dots, A_n \subset \Omega$ s.t.

$$f(\omega) = \sum_{i=1}^n \alpha_i \mathbb{1}_{A_i}(\omega) \quad \omega \in \Omega.$$

That is, a simple function is a finite linear combination of indicator functions.

Example 7.4 (Simple function). Let (Ω, \mathcal{F}) be a measurable space and f be a simple function on Ω , i.e., $f(\omega) = \sum_{i=1}^n \alpha_i \mathbb{1}_{A_i}(\omega)$. Then, if $A_i \in \mathcal{F}$ for any $i = 1, \dots, n$, f is $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable.

My Example 7.1 (Simple function). Let (Ω, \mathcal{F}) be a measurable space and $f : \Omega \rightarrow \mathbb{R}$ be the function defined in 7.3. For this simplified setting, suppose $\Omega = \{1, 2, 3, 4\}$ and $\mathcal{F} = \{\emptyset, \{1, 2\}, \{3, 4\}, \Omega\}$. Moreover, we define our function with $n = 2$, where $\alpha_1 = 3, \alpha_2 = 5, A_1 = \{1, 2\}$ and $A_2 = \{3, 4\}$. Then,

$$f(\omega) = 3 \cdot \mathbb{1}_{\{1,2\}}(\omega) + 5 \cdot \mathbb{1}_{\{3,4\}}(\omega).$$

Now, let's consider two preimages of this function, $f^{-1}(\{3\})$ and $f^{-1}(\{12\})$. Note that both of these sets are Borel sets in \mathbb{R} . Also note that, if $B \in \mathfrak{B}(\mathbb{R})$, then,

$$f^{-1}(B) = \{\omega \in \Omega : f(\omega) \in B\}.$$

As seen in Thinking about 7.1. Since f takes the value 3 for $\omega \in \{1, 2\}$, $f^{-1}(\{3\}) = \{1, 2\} \in \mathcal{F}$. And, as f doesn't take any value for values $\notin \{\{1, 2\}, \{3, 4\}\}$, $f^{-1}(\{12\}) = \emptyset \in \mathcal{F}$. So indeed, f is $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable.

Definition 7.4 (Simple functions in standard form). Let (Ω, \mathcal{F}) be a measurable space and $f : \Omega \rightarrow \mathbb{R}$ be a simple function, as defined in Definition 7.3. f is called standard if $\cup_{i=1}^n A_i = \Omega$ and $\{A_1, \dots, A_n\} \subset \mathcal{F}$ is disjoint. if f is standard, we say that it is a simple function in standard form.

Proposition 7.7 (7.7). TODO

Proposition 7.8 (7.8). TODO

7.2 Functions taking values in the extended real numbers

Definition 7.5 (Measurable functions in $\overline{\mathbb{R}}$). Let (Ω, \mathcal{F}) be a measurable space and $f : \Omega \rightarrow \overline{\mathbb{R}}$. We say that f is \mathcal{F} measurable if for any $A \in \mathfrak{B}(\mathbb{R})$, $\{\omega \in \Omega : f(\omega) \in A\} \in \mathcal{F}$ and $\{\omega \in \Omega : f(\omega) = -\infty\} \in \mathcal{F}$ and $\{\omega \in \Omega : f(\omega) = \infty\} \in \mathcal{F}$. Or, in other words, $f^{-1}(A), f^{-1}(-\infty), f^{-1}(\infty) \in \mathcal{F}$.

Remark 7.2 As seen in the script, as, if $f : \Omega \rightarrow \mathbb{R}$, $f^{-1}(-\infty), f^{-1}(\infty) = \emptyset$, any results on \mathcal{F} measurable functions $f : \Omega \rightarrow \overline{\mathbb{R}}$ also apply to $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable functions $f : \Omega \rightarrow \mathbb{R}$.

Remark 7.3 TODO, but important for notation, read it from the script.

Proposition 7.9 (7.9). TODO

Proposition 7.10 (7.10). TODO

Definition 7.6 (Positive and negative parts of a function). TODO

Proposition 7.11. This proposition states that any \mathcal{F} -measurable function f can be approximated by a sequence of \mathcal{F} -measurable simple functions $(f_n)_{n \in \mathbb{N}}$ such that $f_n(\omega) \rightarrow f(\omega)$ for all $\omega \in \Omega$.

My Example 7.2. Consider $\Omega = [0, 1]$ and \mathcal{F} be the Borel σ -field on $[0, 1]$. Let $f(x) = x$. Define the sequence of simple functions $f_n(x) = \frac{\lfloor nx \rfloor}{n}$. Each f_n is \mathcal{F} -measurable and $f_n(x) \rightarrow x$ as $n \rightarrow \infty$.

Proposition 7.12. This proposition extends 7.11 by specifying that if f is non-negative, the convergence of the simple functions can be made monotone, i.e., $f_n(\omega)$ increases with n and converges to $f(\omega)$.

My Example 7.3. Using the same function $f(x) = x$ on $\Omega = [0, 1]$, define $f_n(x) = \frac{\lfloor nx \rfloor}{n}$. Note that $f_n(x) \leq f_{n+1}(x)$ for all $x \in [0, 1]$ and $n \in \mathbb{N}$, ensuring that $f_n(x) \uparrow f(x)$ as $n \rightarrow \infty$.

7.3 Sequence of measurable functions

Chapter 8

Integration: Part I

8.1 The integral for non-negative functions

If $f : \Omega \rightarrow \overline{\mathbb{R}}$ is s.t. $f(\omega) \geq 0$ for any $\omega \in \Omega$, f is said to be nonnegative.

Definition 8.1 (Finite partitions). Let Ω be a set. A partition of Ω is a disjoint collection $\{A : A \in P\}$, $P \subset \mathcal{P}(\Omega)$, s.t. $\cup_{A \in P} A = \Omega$. That is, a partition of Ω is a disjoint collection of subsets of Ω whose union is Ω . If ξ is a partition of Ω , a set $A \in \xi$ is referred to as an atom of ξ . A partition ξ of Ω is said to be finite, if it contains a finite number of atoms.

Example 8.1 (Finite partition). Let $\Omega = \{0, 1, \dots, N\}$, $N \in \mathbb{N}$. Then, $\xi = \{\{\omega\} : \omega \in \Omega\}$ is a finite partition of Ω . (Partition contains $N + 1$ elements).

Definition 8.2 ($Z_0^{\mathcal{F}}$). Let (Ω, \mathcal{F}) be a measurable space. We use the notation $Z_0^{\mathcal{F}}(\Omega) = Z_0^{\mathcal{F}}$ for the set which contains all the finite partitions of Ω with atoms from \mathcal{F} . That is,

$$Z_0^{\mathcal{F}} = \{\xi : \xi \text{ is finite partition of } \Omega \text{ s.t. for any } A \in \xi, A \in \mathcal{F}\}.$$

Definition 8.3 (Integral for a nonnegative standard simple function). Let $(\Omega, \mathcal{F}, \mu)$ be a measure space and $f : \Omega \rightarrow \overline{\mathbb{R}}$ be nonnegative and \mathcal{F} measurable. Then, we define

$$S_{\mu}^f(\xi) = \sum_{A \in \xi} \left(\inf_{\omega \in A} f(\omega) \right) \mu(A), \quad \xi \in Z_0^{\mathcal{F}},$$

Essentially, $S_{\mu}^f(\xi)$ approximates the integral of f by considering the smallest value f takes on each piece of the partition and multiplying this by the measure of the piece. And

$$\int_{\Omega} f(\omega) \mu(d\omega) = \sup_{\xi \in Z_0^{\mathcal{F}}} S_{\mu}^f(\xi).$$

The integral of f over Ω with respect to μ , is the supremum of $S_{\mu}^f(\xi)$ over all possible partitions ξ of Ω in $Z_0^{\mathcal{F}}$. This definition captures the idea of the integral as the limit of finer and finer approximations of f by simple functions. Upon the latter definition, we deduce the integral for a (nonnegative) standard simple function (cf. Definition 7.4).

Proposition 8.1. TODO

My Example 8.1 (Integral of a nonnegative standard simple function). Let $(\Omega, \mathcal{F}, \mu)$ be a measure space with $\Omega = \{a, b, c, d\}$, $\mathcal{F} = \mathcal{P}(\Omega)$, and μ is the counting measure, i.e., $\mu(A)$ is the number of elements in A . Let $f : \Omega \rightarrow \overline{\mathbb{R}}$,

$$f(\omega) = \begin{cases} 1 & \text{if } \omega = a, \\ 2 & \text{if } \omega = b, \\ 3 & \text{if } \omega = c, \\ 0 & \text{if } \omega = d \end{cases}$$

Consider the partition $\xi = \{\{a\}, \{b\}, \{c\}, \{d\}\}$. $\inf_{\omega \in \{a\}} f(\omega) = 1$, $\inf_{\omega \in \{b\}} f(\omega) = 2$, $\inf_{\omega \in \{c\}} f(\omega) = 3$, $\inf_{\omega \in \{d\}} f(\omega) = 4$. Since each singleton set in ξ as measure of 1 under μ ,

$$S_\mu^f(\xi) = (1 \times 1) + (2 \times 1) + (3 \times 1) + (4 \times 1) = 6$$

if $\sup_{\xi \in \mathcal{Z}_0^f} S_\mu^f = 6$, which I think it should be, then $\int_\Omega f(\omega) \mu(d\omega) = 6$.

Example 8.2. Example 8.2 interesting and clear, TODO.

Proposition 8.2 (Monotone convergence theorem). Let $(\Omega, \mathcal{F}, \mu)$ be a measure space and $f_n : \Omega \rightarrow \overline{\mathbb{R}}$, $n \in \mathbb{N}$, be a sequence of nonnegative \mathcal{F} measurable functions s.t. for any $\omega \in \Omega$, $f_n(\omega) \uparrow f(\omega)$ for some $f : \Omega \rightarrow \overline{\mathbb{R}}$. Then,

$$\int_\Omega f_n(\omega) \mu(d\omega) \uparrow \int_\Omega f(\omega) \mu(d\omega).$$

Proposition 8.3 (The integral of nonnegative functions is linear). Let $(\Omega, \mathcal{F}, \mu)$ be a measurable space, $f, g : \Omega \rightarrow \overline{\mathbb{R}}$ be two nonnegative and \mathcal{F} measurable functions. Given $\alpha, \beta \in [0, \infty)$ we have that

$$\int_\Omega (\alpha f + \beta g)(\omega) \mu(d\omega) = \alpha \int_\Omega f(\omega) \mu(d\omega) + \beta \int_\Omega g(\omega) \mu(d\omega).$$

As a consequence of the latter two proposition we have the following result:

Proposition 8.4. Let $(\Omega, \mathcal{F}, \mu)$ be a measure space and $f_i : \Omega \rightarrow \overline{\mathbb{R}}$, $i \in \mathbb{N}$, be a sequence of nonnegative \mathcal{F} measurable functions, then

$$\int_\Omega \left(\sum_{i \in \mathbb{N}} f_i \right) (\omega) \mu(d\omega) = \sum_{i \in \mathbb{N}} \left(\int_\Omega f_i(\omega) \mu(d\omega) \right).$$

Definition 8.4 (True almost everywhere (*a.e.*)). Let $(\Omega, \mathcal{F}, \mu)$ be a measure space. Suppose that for any $\omega \in \Omega$, $S(\omega)$ is a statment on Ω . We say S is true μ almost everywhere (*a.e.*) if $\mu(\{\omega : S(\omega) \text{ is false}\}) = 0$.

Example 8.3 ($\mu(a.e.)$). Interesting and clear. TODO.

Proposition 8.5. Let $(\Omega, \mathcal{F}, \mu)$ be a measure space. Assume that $f, g : \Omega \rightarrow \overline{\mathbb{R}}$ be two nonnegatibe and \mathcal{F} measurable functions.

- (i) If $\mu(\{\omega : f(\omega) > 0\}) > 0$, then $\int_\Omega f(\omega) \mu(d\omega) > 0$;
- (ii) If $\int_\Omega f(\omega) \mu(d\omega) < \infty$, then $f < \infty$ μ *a.e.*;
- (iii) If $f \leq g$ μ *a.e.*, then $\int_\Omega f(\omega) \mu(d\omega) \leq \int_\Omega g(\omega) \mu(d\omega)$;
- (iv) If $f = g$ μ *a.e.*, then $\int_\Omega f(\omega) \mu(d\omega) = \int_\Omega g(\omega) \mu(d\omega)$.

8.2 Integrable functions

We recall the definiton of the positive (f^+) and negative (f^-) parts of a function (cf. Definition 7.6). Pay attention, f^- is basically the negative part of the function, but reflected by the x-axis. The result is positive. Also see 7.2

Definition 8.5 (Integral of an integrable function). Let $(\Omega, \mathcal{F}, \mu)$ be a measure space and $f : \Omega \rightarrow \overline{\mathbb{R}}$ be a \mathcal{F} measurable function. The integral of f is defined by:

$$\int_\Omega f(\omega) \mu(d\omega) = \int_\Omega f^+(\omega) \mu(d\omega) - \int_\Omega f^-(\omega) \mu(d\omega),$$

unless $\int_\Omega f^+(\omega) \mu(d\omega) = \int_\Omega f^-(\omega) \mu(d\omega) = \infty$, in which case $\int_\Omega f(\omega) \mu(d\omega)$ is not defined. If both $\int_\Omega f^+(\omega) \mu(d\omega) < \infty$ and $\int_\Omega f^-(\omega) \mu(d\omega) < \infty$, f is said to be integrable.

(NOTE) This assumption is defined upon the measure μ , i.e., if one wants to further refer to the measure of integration one specifies that f is integrable with respect to μ .

Proposition 8.6 (Generalisation of the condition for f to be integrable). Let $(\Omega, \mathcal{F}, \mu)$ be a measure space and $f : \Omega \rightarrow \overline{\mathbb{R}}$ be \mathcal{F} measurable. Then, f is integrable if and only if $\int_{\Omega} |f(\omega)| \mu(d\omega) < \infty$.

Proposition 8.7 (Extension (cf. (iii) Proposition 8.5)). Let $(\Omega, \mathcal{F}, \mu)$ be a measure space and $f, g : \Omega \rightarrow \overline{\mathbb{R}}$ be \mathcal{F} measurable. If f and g are integrable and $f \leq g$ a.e., then, $\int_{\Omega} f(\omega) \mu(d\omega) \leq \int_{\Omega} g(\omega) \mu(d\omega)$.

Proposition 8.8 (Extension (c.f. Proposition 8.3)). Let $(\Omega, \mathcal{F}, \mu)$ be a measurable space, $f, g : \Omega \rightarrow \overline{\mathbb{R}}$ be two integrable and \mathcal{F} measurable functions. Then, for any $\alpha, \beta \in \mathbb{R}$ we have that $\alpha f + \beta g$ is integrable and

$$\int_{\Omega} (\alpha f + \beta g)(\omega) \mu(d\omega) = \alpha \int_{\Omega} f(\omega) \mu(d\omega) + \beta \int_{\Omega} g(\omega) \mu(d\omega).$$

8.3 Fatou's lemma and Lebesgue's dominated convergence theorem

Proposition 8.9 (Fatou's lemma). Let $(\Omega, \mathcal{F}, \mu)$ be a measure space and $f_n : \Omega \rightarrow \overline{\mathbb{R}}, n \in \mathbb{N}$, be a sequence of nonnegative and \mathcal{F} measurable function. Then,

$$\int_{\Omega} \liminf_{n \rightarrow \infty} f_n(\omega) \mu(d\omega) \leq \liminf_{n \rightarrow \infty} \int_{\Omega} f_n(\omega) \mu(d\omega).$$

Chapter 9

Integration: Part II

9.1 Pushforward measure

Definition 9.1 (Pushforward function). Let (Ω, \mathcal{F}) and $(\Omega^*, \mathcal{F}^*)$ be two measurable spaces and $g : \Omega \rightarrow \Omega^*$ be $\mathcal{F}/\mathcal{F}^*$ measurable. Let μ be a measure on \mathcal{F} . Define the function

$$\mu g^{-1}(A^*) = \mu(g^{-1}(A^*)) = \mu(\{\omega \in \Omega : g(\omega) \in A^*\}), \quad A^* \in \mathcal{F}^*.$$

The measure μg^{-1} is referred to as the pushforward measure of μ . This means that μg^{-1} measures, in terms of μ , the pre-image of each set A^* under g . Hence, μ is a valid measure on $(\Omega^*, \mathcal{F}^*)$!! It provides a way to "transfer" the measure from (Ω, \mathcal{F}) to $(\Omega^*, \mathcal{F}^*)$ via the function g .

Proposition 9.1. TODO

9.2 Densities

Proposition 9.2 (ν is a measure on \mathcal{F}). Let $(\Omega, \mathcal{F}, \mu)$ be a measure space and $\phi : \Omega \rightarrow \overline{\mathbb{R}}$ be a nonnegative and \mathcal{F} measurable function. Then, ν defined by

$$\nu(A) = \int_A \phi(\omega) \mu(d\omega), \quad A \in \mathcal{F},$$

is a measure on \mathcal{F}

Definition 9.2 (ϕ , density of ν in respect to μ). Let $(\Omega, \mathcal{F}, \mu)$ be a measure space and ν be a measure on \mathcal{F} . A nonnegative and \mathcal{F} measurable function $\phi : \Omega \rightarrow \overline{\mathbb{R}}$ is said to be a density of ν with respect to μ if for any $A \in \mathcal{F}$, $\nu(A) = \int_A \phi(\omega) \mu(d\omega)$.

Proposition 9.3. Let $(\Omega, \mathcal{F}, \mu)$ be a measure space. Suppose that ν is a measure on \mathcal{F} with density ϕ with respect to μ . Then

(i) for any nonnegative and \mathcal{F} measurable function f ,

$$\int_A f(\omega) \nu(d\omega) = \int_A f(\omega) \phi(\omega) \mu(d\omega), \quad A \in \mathcal{F};$$

(ii) f is integrable with respect to ν if and only if $f\phi$ (the product of the two functions) is integrable with respect to μ . This is clear in (i).

(iii) if $f\phi$ is integrable with respect to μ , then (i) holds.

9.3 Integration with respect to the Lebesgue measure on the real line

Definition 9.3. Consider the measure space $(\mathbb{R}, \mathfrak{B}(\mathbb{R}), \lambda)$, where λ is the Lebesgue measure on the Borel σ -field $\mathfrak{B}(\mathbb{R})$. In accordance with Definition 8.5, a $\mathfrak{B}(\mathbb{R})$ measurable function $f : \mathbb{R} \rightarrow \overline{\mathbb{R}}$ is Lebesgue integrable if $\int_{\mathbb{R}} |f(x)| \lambda(dx) < \infty$. The integral of f with respect to λ is denoted with $\int_{\mathbb{R}} f(x) dx$, i.e., $\int_{\mathbb{R}} f(x) dx = \int_{\mathbb{R}} f(x) \lambda(dx)$. If $E \subset \mathbb{R}$ and $\lambda|_E$ is the restriction of λ to $\mathfrak{B}(E)$ (cf. Definition 4.1), then a $\mathfrak{B}(E)$ measurable function $f : E \rightarrow \overline{\mathbb{R}}$ is referred to as Lebesgue integrable if $\int_E |f(x)| \lambda|_E(dx) < \infty$. Also in this case we write $\int_E |f(x)| \lambda|_E(dx) = \int_E f(x) dx$.

In accordance with the fact that the Lebesgue measure of a single point is zero, we adapt the following definition.

Definition 9.4. TODO. Interesting but easy and well known.

We review the definition of a Riemann integrable function:

Definition 9.5 (title).

9.4 Lecture

Partial integration and substitution TODO.

Exercise 9.1 (9.6). ν is a measure with density ϕ with respect to μ . f nonnegative and \mathcal{F} measurable. Prove:

$$(i) \int_A f(\omega) \nu(d\omega) = \int_A f(\omega) \phi(\omega) \mu(d\omega)$$

NOTE $\nu(d\omega) = \phi(\omega) \mu(d\omega)$ short notation for ν has density ϕ :

1. Definition of ν having a density ϕ with respect to μ : When we say that ν has a density ϕ with respect to μ , it means that for any measurable set $A \in \mathcal{F}$, the measure ν of A can be computed as:

$$\nu(A) = \int_A \phi(\omega) \mu(d\omega).$$

This is the integral of the function ϕ over the set A , with respect to the measure μ .

2. Notation $\nu(d\omega) = \phi(\omega) \mu(d\omega)$: This notation is shorthand and is used to express how ν acts on infinitesimal elements in a manner analogous to how μ acts, but scaled by the function ϕ . It is essentially saying that for a small element $d\omega$, the measure $\nu(d\omega)$ is given by $\phi(\omega) \mu(d\omega)$.

3. Clarification on $\int_{d\omega} \phi(\omega) \mu(d\omega)$: The correct notation or expression should not involve integrating over an "infinitesimal element" $d\omega$. The differential notation $\nu(d\omega) = \phi(\omega) \mu(d\omega)$ is symbolic and used to express the relationship between ν and μ at a small scale, rather than an actual operation.

In summary, $\nu(d\omega) = \phi(\omega) \mu(d\omega)$ is a concise way to denote that ν is derived by weighting μ by the density ϕ , and this relationship is used to transform integrals with respect to ν into integrals with respect to μ weighted by ϕ .

(ii) f integrable w.r.t. $\nu \iff f\phi, (f(\omega)\phi(\omega))$, integrable w.r.t. μ .

(iii) if either of the two statements in (ii) holds, then (i) holds.

Proof:

(i). Let f be a standard simple function, $f = \sum_{n=1}^N \alpha_i \mathbb{1}_{A_i}$, then

$$\begin{aligned} \int_A f(\omega) \nu(d\omega) &= \int_A \left(\sum_{n=1}^N \alpha_i \mathbb{1}_{A_i}(\omega) \right) \nu(d\omega) = \sum_{n=1}^N \alpha_i \int_A \mathbb{1}_{A_i}(\omega) \nu(d\omega) = \sum_{n=1}^N \alpha_i \int_{\Omega} \mathbb{1}_A(\omega) \mathbb{1}_{A_i}(\omega) \nu(d\omega) \\ &= \sum_{n=1}^N \alpha_i \int_{\Omega} \mathbb{1}_{A \cap A_i}(\omega) \nu(d\omega) = \sum_{n=1}^N \alpha_i \nu(A \cap A_i) = \sum_{n=1}^N \alpha_i \int_{A \cap A_i} \phi(\omega) \mu(d\omega) = \sum_{n=1}^N \alpha_i \int_A \mathbb{1}_{A_i}(\omega) \phi(\omega) \mu(d\omega) \\ &= \int_A \sum_{n=1}^N \alpha_i \mathbb{1}_{A_i}(\omega) \phi(\omega) \mu(d\omega) = \int_A f(\omega) \phi(\omega) \mu(d\omega). \end{aligned}$$

Hence we have verified (i) if f is standard and simple.

In order to verify it for nonnegative functions:

(IMPORTANT; TOOL, TO ADD) Recall (chapter 7): Any f nonnegative and \mathcal{F} measurable can be approximated by a standard simple function, i.e., $\exists (f_n)_{n \in \mathbb{N}}$ s.t. $f_n(\omega) \uparrow f(\omega)$. By the monotone convergence theorem,

$$\int_{\Omega} f(\omega) \nu(d\omega) = \lim_{n \rightarrow \infty} \int_{\Omega} f_n(\omega) \nu(d\omega) = \lim_{n \rightarrow \infty} \int_{\Omega} f_n(\omega) \phi(\omega) \mu(d\omega)$$

f_n converges to f

$$\stackrel{\text{(again monotone convergence)}}{=} \int_{\Omega} f(\omega) \phi(\omega) \mu(d\omega).$$

This proves (i).

(ii). $\int_A |f(\omega)|\nu(d\omega) < \infty$ (definition of integrability), $= \int_A |f(\omega)\phi(\omega)|\mu(d\omega)$, and we know that the equality holds by (i). This shows (ii).

(iii). Recall $f^+ = \max(f, 0)$, $f^- = \max(-f, 0)$. Positive and negative parts of f . Cuts out all negative points. We know,

$$f(\omega) = f^+ - f^-(\omega).$$

f integrable w.r.t. ν implies that,

$$\int_{\Omega} f(\omega)\nu(d\omega) = \int_{\Omega} f^+\nu(d\omega) - \int_{\Omega} f^-(\omega)\nu(d\omega).$$

By (i) applied to f^+ and f^- ,

$$= \int_{\Omega} f^{(+)}(\omega)\phi(\omega)\mu(d\omega) - \int_{\Omega} f^-(\omega)\phi(\omega)\mu(d\omega) = \int_{\Omega} f(\omega)\phi(\omega)\mu(d\omega).$$

Exercise 9.2 (9.7). b) TODO

$\frac{1}{2\pi} \int_{\mathbb{R}^2} e^{-(\frac{x^2+y^2}{2})} d(x, y)$, continuous as composition of continuous functions, and nonnegative. Fobini - Tonelli Theorem:

$$\begin{aligned} &= \frac{1}{2\pi} \int_{\mathbb{R}} e^{-\frac{x^2}{2}} \left(\int_{\mathbb{R}} e^{-\frac{y^2}{2}} dy \right) dx. \\ &= \frac{1}{2\pi} \left(\int_{\mathbb{R}} e^{-\frac{x^2}{2}} dx \right)^2. \end{aligned}$$

$u = \frac{x}{\sqrt{2}}$ substitute

$$\begin{aligned} &= \frac{1}{2\pi} \left(\int_{\mathbb{R}} e^{-u^2} \sqrt{2} du \right)^2. \\ &= \frac{1}{\pi} \left(\int_{\mathbb{R}} e^{-u^2} du \right)^2 = \frac{\pi}{\pi}. \end{aligned}$$

Remember Gaussian integral:

$$\int_{\mathbb{R}} e^{-x^2} dx = \sqrt{\pi}.$$

Chapter 10

General notions in Probability

10.1 Probability spaces

Definition 10.1. Let (Ω, \mathcal{F}) be a measurable space. A probability \mathbb{P} on \mathcal{F} is a measure on \mathcal{F} s.t. $\mathbb{P}(\Omega) = 1$. The triple $(\Omega, \mathcal{F}, \mathbb{P})$ is referred to as a probability space.

Example 10.1. Let Ω be a finite and nonempty set. Define

$$\mathbb{P}(A) = \frac{\#A}{\#\Omega}, \quad A \in \mathcal{P}(\Omega),$$

Where $\mathcal{P}(\Omega)$ is the power set on Ω . Then, \mathbb{P} is a probability on $\mathcal{P}(\Omega)$.

Example 10.2. Let C be a set s.t. $\#C = 52$. Suppose that

$$C = S_1 \cup S_2 \cup S_3 \cup S_4,$$

with $\{S_1, S_2, S_3, S_4\}$ disjoint and s.t. $\#S_i = 13$ for all $i = 1, 2, 3, 4$. We remain in the setting of the previous example with

$$\Omega = \{A \subset C : \#A = 5\},$$

and \mathbb{P} on $\mathcal{P}(\Omega)$ defined as in exercise 10.1. Upon exercise 1.1, we already know that $\#\Omega = \binom{52}{5}$. Let

$$A_i = \{A \subset S_i : \#A = 5\}, \quad i = 1, 2, 3, 4,$$

TODO

10.2 Random variables and random vectors

Definition 10.2 (Random variable). Let (Ω, \mathcal{F}) be a measurable space. A map $X : \Omega \rightarrow \mathbb{R}$ is referred to as a random variable on (Ω, \mathcal{F}) if it is $\mathcal{F}/\mathfrak{B}(\mathbb{R})$ measurable.

Definition 10.3 (Random vector). Let (Ω, \mathcal{F}) be a measurable space. A map $X : \Omega \rightarrow \mathbb{R}^k$ is referred to as a random vector on (Ω, \mathcal{F}) if it is $\mathcal{F}/\mathfrak{B}(\mathbb{R}^k)$ measurable.

Proposition 10.1. Let $(\Omega, \mathcal{F}, \mathbb{P})$ be a probability space and X be a random vector on (Ω, \mathcal{F}) . A random variable Y on (Ω, \mathcal{F}) is $\sigma(X)$ measurable if and only if there exists a function $f : \mathbb{R}^k \rightarrow \mathbb{R}$ which is $\mathfrak{B}(\mathbb{R}^k)$ measurable s.t. $Y = f(X)$.

Definition 10.4. Let $(\Omega, \mathcal{F}, \mathbb{P})$ be a probability space. The distribution or law of a random vector on (Ω, \mathcal{F}) is the pushforward measure $P_X = \mathbb{P}X^{-1}$ on $\mathfrak{B}(\mathbb{R}^k)$ (cf. Definition 9.1).

Chapter 11

Collection of random vectors

11.1 Independence

Definition 11.1 (Independent sub- σ -fields). Let $(\Omega, \mathcal{F}, \mathbb{P})$ be a probability space and $\mathcal{A}_1, \dots, \mathcal{A}_n$ be n sub- σ -fields on Ω . $\mathcal{A}_1, \dots, \mathcal{A}_n$ are said to be independent if for any $A_1 \in \mathcal{A}_1, \dots, A_n \in \mathcal{A}_n$,

$$\mathbb{P}(A_1 \cap \dots \cap A_n) = \mathbb{P}(A_1) \times \dots \times \mathbb{P}(A_n).$$