Notes of Probability and Stochastics

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Contents

0.1 Notations

$\mathbb{R}$	$(-\infty, \infty)$
$\overline{\mathbb{R}}$	$[-\infty, \infty]$
$\mathbb{R}_+$	$[0, \infty)$
$\overline{A}$	Closure of set A
A°	Interior of set A
$(x_n) \subset A$	A sequence taking value in A
2^A	The power set of A
$\mathcal{A}$	A collection of subsets in A, i.e., $\mathcal{A} \subset 2^A$
$\ker \mathcal{A}$	$\bigcap_{A \in \mathcal{A}} A$
$x_n \nearrow x$	(x_n) is increasing and converges to x.
$\sigma(\mathcal{A})$	σ-algebra generated by $\mathcal{A}$.
$\mathcal{A}_+$	Nonnegative function in $\mathcal{A}$
$\mu \ll \nu$	μ is absolutely continuous w.r.t. ν.
$\mu f = \int f d\mu = \int f(x)\mu(dx)$	integral
$f : X \to Y$	x is a function from X to Y.
$f = x \mapsto 5x$	$f(x) = 5x$
$f : X \hookrightarrow Y$	f is an embedding from X to Y.
s.t.	such that
w.r.t.	with respect to
r.v.	random variable

Chapter 1

Measure and integrations

1.1 Measurable space

1.1.1 σ algebra

Definition 1.1. A nonempty system of subset of Ω is an algebra on Ω if it's

1. Closed under complement: $A^c \in \mathcal{A} \iff A \in \mathcal{A}$
2. Closed under finite union: $\cup_i A_i \in \mathcal{A} \impliedby \forall i, A_i \in \mathcal{A}$

It's an σ algebra on Ω if it's also closed under countable union.

Remark. $\mathcal{A}$ is an algebra auto implies $\varnothing \in \mathcal{A}$ and $\Omega \in \mathcal{A}$. So $\{\varnothing, \Omega\}$ is the minimum algebra on Ω and thus minimum σ algebra while the discrete algebra 2^Ω is maximum.

Let $\left\{\mathcal{A}_\gamma : \gamma \in \Gamma\right\}$ is a collection of σ algebra, then we have $\mathcal{A} = \cap_{\gamma\in\Gamma}\mathcal{A}_\gamma$ is also a σ algebra. Hence

Definition 1.2. The smallest σ algebra as intersection of all σ algebras contains $\mathcal{A}$, that called the σ algebra **generated** by $\mathcal{A}$ and denoted by $\sigma(\mathcal{A})$.

The smallest $\sigma-$algebra generated by the system of all open sets in a topological space (Ω, τ) is called **Borel σ algebra** on Ω and denoted by $\mathcal{B}(\Omega)$, its elements are called **Borel sets**.

1.1.2 π, λ, m systems

Definition 1.3. A collection of subsets $\mathcal{A}$ is called.

- **m-system** if closed under monotone series, that is if $(A_n) \subset \mathcal{A}$ and $A_n \nearrow A$, then $A \in \mathcal{A}$.
- $\pi-$**system** is closed under finite intersection
- $\lambda-$ **system** if
  1. $\Omega \in \mathcal{A}$
  2. closed under proper difference:

$$A - B \in \mathcal{A} \Longleftarrow B \subset A \text{ and } B, A \in \mathcal{A}$$

  3. is an m-system.

Theorem 1.1. *Let $\mathcal{A}$ be a collection of subsets of Ω iff it's both a π system and λ system.*

Proof. For $\Rightarrow$, check:

1. $\Omega \in \mathcal{A}$
2. $A - B = A \cap B^c \in \mathcal{A}$
3. is an m-system

For the converse:

1. $A^c = \Omega - A \in \mathcal{A}$
2. $A \cup B = (A^c \cap B^c)^c \in \mathcal{A}$
3. hence $\mathcal{A}$ is an algebra and $\mathcal{A}$ is a m-system.

Similarly, for m, π, λ -system, they also has a minimum system generated by some collection $\mathcal{C}$.

□

Lemma 1.1. *Let $\mathcal{A}$ be an algebra, then*

1. *$m(\mathcal{A}) = \sigma(\mathcal{A})$*
2. *if $\mathcal{B}$ is an m class and $\mathcal{A} \subset \mathcal{B}$, then $\sigma(\mathcal{A}) = m(\mathcal{A}) \subset \mathcal{B}$*

Similarly, let $\mathcal{A}$ be a π class, then $\lambda(\mathcal{A}) = \sigma(\mathcal{A})$

Then we have **Monotone class theorem**:

Theorem 1.2. *$\forall \mathcal{A} \subset \mathcal{B} \subset \mathcal{P}(\Omega), s.t.$:*

1. *If $\mathcal{A}$ is a π-class, $\mathcal{B}$ is a $\lambda-$class, then $\sigma(\mathcal{A}) \subset \mathcal{B}$*
2. *If $\mathcal{A}$ is an algebra, $\mathcal{B}$ is a $m-$class, then $\sigma(\mathcal{A}) \subset \mathcal{B}$*

1.1.3 Graphical illustration of different classes

$$
\begin{array}{ccccc}
\sigma \text{ algebra} & \Leftrightarrow & \lambda \text{ system} & + & \pi \text{ system} \\
\Downarrow & & \Downarrow & & \\
\text{algebra} & & m \text{ system} & & \\
\Downarrow & & & & \\
\text{semialgebra} & & & & \\
\Downarrow & & & & \\
\pi \text{ system} & & & &
\end{array}
$$

1.1.4 Measurable spaces

Definition 1.4 (Measurable Space)**.** Pair $(\Omega, \mathcal{A})$ where $\mathcal{A}$ is a σ-Algebra on Ω.

Definition 1.5 (Products of measurable spaces)**.** Let $(E, \mathcal{E}), (F, \mathcal{F})$ be two measurable spaces. For $A \subset E, B \subset F$, $A \times B$ is the set of all pairs (x, y) : $x \in A, y \in B$. Note that $\mathcal{E} \times \mathcal{F}$ is also a σ-Algebra with all $A \times B$ where $A \in \mathcal{E}, B \in \mathcal{F}$ which is called *the product σ-Algebra*.

1.2 Measurable function

1.2.1 Mappings

Let $f : \Omega_1 \to \Omega_2$ be a mapping, $\forall B \subset \Omega_2$ and $\mathcal{G} \subset \mathcal{P}(\Omega_2)$, the **inverse image** of

- B is $f^{-1}(B) = \{\omega : \omega \in \Omega_1, f(\omega) \in B\} := \{f \in B\}$
- $\mathcal{G}$ is $f^{-1}(\mathcal{G}) = \{f^{-1}(B) : B \in \mathcal{G}\}$

There is some properties:

1. $f^{-1}(\Omega_2) = \Omega_1, f^{-1}(\varnothing) = \varnothing$
2. $f^{-1}(B^c) = \left[f^{-1}(B)\right]^c$
3. $$\begin{aligned} f^{-1}\left(\cup_{\gamma \in \Gamma} B_\gamma\right) = \cup_{\gamma \in \Gamma} f^{-1}\left(B_\gamma\right) \text{ for } B_\gamma \subset \Omega_2, \gamma \in \Gamma \\ f^{-1}\left(\cap_{\gamma \in \Gamma} B_\gamma\right) = \cap_{\gamma \in \Gamma} f^{-1}\left(B_\gamma\right) \text{ for } B_\gamma \subset \Omega_2, \gamma \in \Gamma \end{aligned}$$

   where Γ may not countable.
4. $f^{-1}(B_1 - B_2) = f^{-1}(B_1) - f^{-1}(B_2) \, \forall B_1, B_2 \subset \Omega_2$
5. $B_1 \subset B_2 \subset \Omega_2 \implies f^{-1}(B_1) \subset f^{-1}(B_2)$

6. If $\mathcal{B}$ is a σ—algebra, $f^{-1}(\mathcal{B})$ is also a σ—algebra. It's easy to check $f^{-1}(\mathcal{B})$ is closed under complement and countable union. (From properties 2 and 3)

7. If $\mathcal{C}$ is nonempty, $f^{-1}(\sigma(\mathcal{C})) = \sigma\left(f^{-1}(\mathcal{C})\right)$

Remarks f^{-1} preserves all the set operations on Ω.

1.2.2 Measurable functions

Definition 1.6. For two measurable spaces $(\Omega_1, \mathcal{A})$, $(\Omega_1, \mathcal{B})$, $f : \Omega_1 \to \Omega_2$ is a **measurable mapping** if $f^{-1}(\mathcal{B}) \subset \mathcal{A}$, where

$$f^{-1}(\mathcal{B}) = \{f^{-1}(B) : B \in \mathcal{B}\}$$

It is a **measurable function** if $(\Omega_2, \mathcal{B}) = (\mathcal{R}^n, \mathcal{B}(\mathcal{R}^n))$, moreover, a **Borel function** if $(\Omega_1, \mathcal{A}) = (\mathcal{R}^m, \mathcal{B}(\mathcal{R}^m))$

Remark. If $\mathcal{B} = \sigma(\mathcal{C})$, the definition can be reduced to $f^{-1}(\mathcal{C}) \subset \mathcal{A}$ since

$$f^{-1}(\mathcal{B}) = f^{-1}(\sigma(\mathcal{C})) = \sigma\left(f^{-1}(\mathcal{C})\right) \subset \sigma(\mathcal{A}) = \mathcal{A}$$

Lemma 1.2. *Suppose $f : \mathcal{E} \to \mathcal{F}$ and $g : \mathcal{F} \to \mathcal{G}$ are measurable, then so is $f \circ g$.*

Proof. The same as how we proved composition of continuous function is continuous.

□

1.2.3 Random Variable

A r.v. X is a measurable function from $(\Omega_1, \mathcal{A})$ to $(\mathbb{R}, \mathcal{B})$. It denoted by X is $\mathcal{A}$-measurable or $X \in \mathcal{A}$

(Another definition): A r.v. X is a measurable mapping from $(\Omega, \mathcal{A}, P)$ to $(\mathcal{R}, \mathcal{B})$ such that

$$P(|X| = \infty) = P(\{\omega : |X(\omega)| = \infty\}) = 0$$

Lemma 1.3. *X is a r.v. from $(\Omega, \mathcal{A})$ to $(\mathbb{R}, \mathcal{B})$*

$$\begin{aligned} &\iff X \leq x = X^{-1}([-\infty], x) \in \mathcal{A} \quad \forall x \in \mathbb{R} \\ &\iff X \leq x = X^{-1}([-\infty], x) \in \mathcal{A} \quad \forall x \in D \end{aligned}$$

where D is a dense subset of $\mathbb{R}$, e.g. $\mathbb{Q}$. $\{X \leq x\}$ above can be replaced by

$$\{X \leq x\}, \quad \{X \geq x\}, \quad \{X < x\}, \quad \{X > x\}, \quad \{x < X < y\}$$

1.2.4 Construction of random variables

Lemma 1.4. $\mathbf{X} = (X_1, \cdots, X_n)$ *is a random vectors if* X_k *is a r.v.* $\forall k$ *iff* $\mathbf{X}$ *is a measurable function from* $(\Omega, \mathcal{A})$ *to* $(\mathcal{R}^n, \mathcal{B}(\mathcal{R}^n))$.

Proof. Note that

$$\{\mathbf{X} \in \prod I_n\} = \bigcap \{X_n \in I_n\} \in \mathcal{A}$$

where $I_k = (a_k, b_k], -\infty \le a_k \le b_k \le \infty$ and follows from $\sigma(\{\prod I_n\}) = \mathcal{B}(\mathcal{R}^n)$. For the other direction, note

$$\{X_k \le t\} = \{\mathbf{X} \in \prod_{i<k} \mathbb{R} \times \{-\infty, t\} \times \prod_{i>k} \mathbb{R}\} \in \mathcal{A}$$

□

Recall lemma 1.2 we have:

Theorem 1.3. $\forall$ *random* n *vectors* $X = (X_{1:n})$ *and Borel function* f *from* $\mathcal{R}^n \to \mathcal{R}^m$, *then* $f(X)$ *is a random* m *vectors.*

Remark. Note that continuous function are borel measurable since continuity leads to inverse image of an open set is still open. So if $X_{1:n}$ are r.v.'s, so are $\sum X_n$, $\sin(x)$, e^X, $\mathrm{Poly}(X), \cdots$. That implies:

$\forall X, Y \in \mathcal{A}$, so are $aX+bY, X \vee Y = \max\{X, Y\}, X \wedge Y = \min\{X, Y\}, X^2, XY, X/Y, X^+ = \max(x, 0), X^- = -\min(x, 0), |X| = X^+ + X^-$

1.2.5 Limiting opts

Let (X_n) are r.v. on $(\Omega, \mathcal{A})$, then $\sup_{n\to\infty} X_n, \inf_{n\to\infty} X_n, \limsup_{n\to\infty} X_n, \liminf_{n\to\infty} X_n$ are r.v.'s. Moreover, if it exists, $\lim_{n\to\infty} X_n$ is r.v..

Proof. First two follows from, $\forall t \in \mathbb{R}$:

$$\{\sup_{n\to\infty} X_n \le t\} = \bigcap_{n=1}^{\infty} \{X_n \le t\} \in \mathcal{A}$$
$$\{\inf_{n\to\infty} X_n \ge t\} = \bigcap_{n=1}^{\infty} \{X_n \ge t\} \in \mathcal{A}$$

and the last two follows from $\limsup_{n\to\inf} = \inf_{k\to\infty} \sup_{m\ge k} X_m$ and $\liminf_{n\to\inf} = \sup_{k\to\infty} \inf_{m\ge k} X_m$.

□

That implies

Lemma 1.5. *If $S = \sum_1^\infty X_n$ exists everywhere, then S is a r.v.*

Proof. Note $\sum_1^\infty X = \lim_{n\to\infty} \sum_n X_n$ is a r.v.

□

If $X = \lim_{n\to\infty} X_n$ holds **almost** everywhere, i.e., define Ω_0 is the set of all ω, such that $\lim_n X_n(\omega)$ exists, then $P(\Omega_0) = 1$, we say that X_n converges a.s. and write:

$$X_n \to X \quad a.s.$$

For a measurable function f, we may modify it at a null set into f' and it remain measurable since for any open set G, $f'^{-1}(G)$ differ $f^{-1}(G)$ a at most null set, by the completion of Lebesgue measure space, $f'-1(G)$ is measurable and thus f^{-1} measurable. Hence, for $f_n \to f$ a.s., we may ignore a null set and then $f_n \to f$ everywhere and thus f measurable.

1.2.6 Approximations of r.v. by simple r.v.'s

Definition 1.7. If $A \in \mathcal{A}$, the indicator function $\mathbf{1}_A$ is a r.v. If $\Omega = \sum_1^n A_i$, where $A_i \in \mathcal{A}$, then $X = \sum_1^n a_i \mathbf{1}_{A_i}$ is a r.v. and called **simple r.v.**

Any r.v. can be approximated by simple ones:

Theorem 1.4. *$\forall X \in \mathcal{A}$, $\exists 0 \le X_1 \le X_2 \cdots X_n$ s.t. $X_n(\omega) \nearrow X(\omega)$ everywhere.*

Proof. Suppose

$$X_n(\omega) = \sup\{\frac{j}{2^n} : j \in \mathbb{Z}, \frac{j}{2^n} \le \min(X(\omega), 2^n)\}$$

One can check X_n is simple r.v. and $X_n(\omega) \nearrow X(\omega)$ for all $\omega \in \Omega$.

□

1.2.7 σ algebra generated by r.v.

Let $\{X_\lambda, \lambda \in \Lambda\}$ is r.v.s on $(\Omega, \mathcal{A})$. Define

$$\sigma(X_\lambda, \lambda \in \Lambda) := \sigma(X_\lambda \in B, B \in \mathcal{B}, \lambda \in \Lambda) = \sigma(X_\lambda^{-1}(\mathcal{B}), \lambda \in \Lambda) = \sigma(\cup_{\lambda\in\Lambda} X_\lambda^{-1}(\mathcal{B}))$$

which is called σ algebra generated by $\{X_\lambda, \lambda \in \Lambda\}$, where Λ is a index set which can be uncountable.

For $\Lambda = \mathbb{N}^+$:

1.
$$\sigma(X_i) = \sigma\left(X_i^{-1}(\mathcal{B})\right) = X_i^{-1}(\mathcal{B}) = \{X_i \in \mathcal{B}\}$$
$$\sigma(X_1, \dots, X_n) = \sigma\left(\cup_{i=1}^n X_i^{-1}(\mathcal{B})\right) = \sigma\left(\cup_{i=1}^n \sigma(X_i)\right)$$

2.
$$\sigma(X_1) \subset \sigma(X_1, X_2) \subset \dots \dots \subset \sigma(X_1, \dots, X_n)$$
$$\sigma(X_1, X_2, \dots ..) \supset \sigma(X_2, X_3, \dots ..) \supset \dots \dots \supset \sigma(X_n, X_{n+1}, \dots ..)$$

3. $\bigcap_1^\infty \sigma(X_n, X_{n+1}, \cdots)$ is the tail σ algebra of $X_{1:}$

If $A_{1:n}$ are not mutually exclusive to each other, then we have

$$|\sigma(A_{1:n})| = 2^{2^n}$$

Which follows from for a partition $A_{1:n}$,

$$\sigma(A_1, \cdots, A_n) = \{\bigcup_{i \in J} A_i\}$$

where J is any subset of $\mathbb{N} \leq n$ and $A_0 = \varnothing$. Hence for discrete r.v. Y, $\sigma(Y)$ can be generated from $A_i = \{Y = y_i\}$ forall y_i's. For continuous case, it's generated by all intervals.

1.2.8 Monotone classes of function

Definition 1.8 (monotone class)**.** $\mathcal{M}$ is called a monotone class if:

- $1 \in \mathcal{M}$
- $f, g \in \mathcal{M}_b$ and $a, b \in \mathbb{R} \implies af + bg \in \mathcal{M}$
- $(f_n) \subset M_+, f_n \uparrow f \implies f \in \mathcal{M}$

where $\mathcal{M}_+$ is a subcollection consisting of positive functions in $\mathcal{M}$, and $\mathcal{M}_b$ is the bounded function in $\mathcal{M}$.

Theorem 1.5 (Monotone class theorem for functions)**.** *Let $\mathcal{M}$ be a monotone class of functions on $(\Omega, \mathcal{A})$. Suppose for some π-system $\mathcal{C}$ generating $\mathcal{A}$ and $\mathbf{1}_A \in \mathcal{M}$ for every $A \in \mathcal{C}$. Then $\mathcal{A}_+, \mathcal{A}_b \subset \mathcal{M}$*

Proof. First we need to show that $1_A \in \mathcal{M}$ for every $A \in \mathcal{A}$. Let $\mathcal{D} = \{A \in \mathcal{A} : 1_A \in \mathcal{M}\}$. Now we check that $\mathcal{D}$ is a λ-system:

- $1_\Omega = 1$, so $\Omega \in \mathcal{D}$.
- $B \subset A,\ A, B \in \mathcal{D}$. $1_{A-B} = 1_A - 1_B \in \mathcal{D}$
- $(A_n) \subset \mathcal{D}$ and $A_n \uparrow A$, then $1_{A_n} \uparrow 1_A$, so $1_A \in \mathcal{M}$, then $A \in \mathcal{D}$

By assumption, $\mathcal{C} \subset \mathcal{D}$, and $\sigma(\mathcal{C})$ is the smallest d-system by the theorem above, so $\mathcal{E} \subset \mathcal{D}$, so $1_A \in \mathcal{M}$ for every $A \in \mathcal{E}$.

As $1_A \in \mathcal{M}$ for every $A \in \mathcal{E}$, we can easily prove that all of the positive simple function is generated by the linear combination of 1_A s. And all positive $\mathcal{E}$-measurable functions is generated by a sequence of positive simple functions. Then for general bounded $\mathcal{E}$-measurable function f, using $f = f^+ - f^-$ where $f^+, f^- \in \mathcal{M}$.

□

Definition 1.9. Let $(E, \mathcal{E}), (F, \mathcal{F})$ be two measurable spaces and f is a bijection $E \to F$. Then f is said to be a isomorphism of $(E, \mathcal{E})$ and $(F, \mathcal{F})$ if f is $\mathcal{E}$-measurable and f^{-1} is $\mathcal{F}$-measurable. These two spaces are called isomorphic if there exists an isomorphisms between them.

Definition 1.10. A measurable space $(\Omega, \mathcal{A})$ is said to be *standard* if it there exist an embedding $f : (\Omega, \mathcal{A}) \hookrightarrow (\mathbb{R}, \mathcal{B})$.

Remark. Clearly, $([0,1], \mathcal{B}([0,1]))$, $(\mathbb{N} \leq n, 2^{N \leq n})$ and $(\mathbb{N}, 2^{\mathbb{N}})$ are all standard. In fact, every standard measurable space is isomorphic to one of them.

1.3 Measure

Let Ω be a space and $\mathcal{A}$ a class, then function $\mu : \mathcal{A} \to R = [-\infty, \infty]$ is a **set function**.

It's

- 1. **finite** if $\forall A \in \mathcal{A}, \quad |\mu(A)| < \infty$
  2. **σ-finite** if $\exists A_n \subset \mathcal{A}, \quad s.t. \quad \cup_{i=1}^{\infty} A_i = \Omega \quad \forall n \quad |\mu(A_n)| < \infty$
  3. **s finite** if there exist countable finite (μ_n) s.t. $\mu = \sum_n \mu_n$.
- 1. **additive** $\iff \mu\left(\sum_{i=1}^{n} A_i\right) = \sum_{i=1}^{n} \mu\left(A_i\right)$
  2. $\sigma-$**additive**$\iff \mu\left(\sum_{i=1}^{\infty} A_i\right) = \sum_{i=1}^{\infty} \mu\left(A_i\right)$

Remark. Finite implies σ finite and σ finite implies Σ finite.

μ is a **measure** on $\mathcal{A}$ if

1. $\forall A \in \mathcal{A} : \mu(A) \geq 0$
2. It's σ additive.

the triplet $(\Omega, \mathcal{A}, \mu)$ is a **measure space** when μ is a measure and $(\Omega, \mathcal{A})$ is a measurable space. Whose sets are called **measurable sets** or **$\mathcal{A}$-measurable**.A measure space is a **probability space** if $P(\Omega) = 1$.

Assume that $A_{1:n} \in \mathcal{A}$ and $A \in \mathcal{A}$ and μ is a measure.

1. μ is continues from above, if $A_n \searrow A \implies \mu(A_n) \to \mu(A)$
2. μ is continues from below, if $A_n \nearrow A \implies \mu(A_n) \to \mu(A)$
3. μ is continues at A, if $A_n \to A \implies \mu(A_n) \to \mu(A)$

$\forall$ Measure μ is continues from below and may not continues from above. It will be continues from above if $\exists m < \infty, \mu(A_m) < \infty$.So finite measure μ are always continues.

1.3.1 Properties of measure

1.3.1.1 Semialgebras

Let μ be a nonnegative additive set function on a semialgebra $\mathcal{A}$. $\forall A, B \in \mathcal{A}$ and $\{A_n, B_n, n \geq 1\} \in \mathcal{A}$

1. (**Monotonicity**): $A \subset B \implies \mu(A) \leq \mu(B)$
2. (**σ-subadditivity**):
    1. $\sum_1^\infty A_n \subset A, \quad \implies \quad \sum_1^\infty \mu(A_n) \leq \mu(A)$
    2. Moreover, if μ is a measure, then

$$B \subset \sum_{n=1}^{\infty} B_n \implies \mu(B) \leq \sum_{n=1}^{\infty} \mu(B_n)$$

We can assert a nonnegative set function μ is a measure by:

1. μ is additive
2. μ is σ subadditive on $\mathcal{S}$

1.3.1.2 Algebras

Algebras enjoy all the properties of semialgebra, also, we have

Theorem 1.6 (σ subadditivity)**.** *Let μ be a measure on an algebra $\mathcal{A}$*

$$A \subset \cup_1^\infty A_n \implies \mu(A) \leq \sum_1^\infty \mu(A_n)$$

Proof. Note $A = A \cap (\cup A_n) = \cup(A \cap A_n)$, hence we can write A as union in $\mathcal{A}$ by take $B_n = A \cap A_n \in \mathcal{A}$.

$$A = \cup_1^\infty B_n$$

and then we can take $C_n = B_n - \cup_1^{n-1} B_i \in \mathcal{A}$ to write A as disjoint union:

$$A = \sum C_n$$

Then

$$\mu(\mathcal{A}) = \mu(\sum C_n) = \sum \mu(C_n) \leq \sum \mu(B_n) \leq \sum \mu(A_n)$$

as $C_n \subset B_n \subset A_n$.

$\square$

1.3.1.3 σ algebras

Let μ be a measure on an σ algebra $\mathcal{A}$

1. Monotonicity
2. Boole's inequality(Countable Sub-Additivity)

$$\mu\left(\cup_{i=1}^{\infty} A_i\right) \leq \sum_{i=1}^{\infty} \mu\left(A_i\right)$$

3. Continuity from below
4. Continuity from above if μ is finite in A_i.

The sense of **4** follows from suppose $A_i \searrow A$, then $A_1 - A_i \nearrow A_1 - A$, then

$$\mu(A_1) - \mu(A) = \mu(A_1 - A) = \lim \mu(A_1 - A_i) = \mu(A_1) - \lim(A_i)$$

where $\mu(A_1)$ cannot be cancelled if $\mu(A_i) = \infty$.

Definition 1.11. Let $(\Omega, \mathcal{A}, \mu)$ be a measure space, and $N \subset \Omega$

1. N is a μ **null set** iff $\exists B \in \mathcal{A} \quad s.t. \quad \mu(B) = 0, \quad N \subset B$
2. This measure space is a **complete measure** space if $\forall$ μ null space N, $N \in \mathcal{A}$

Theorem 1.7. *Given any measure space* $(\Omega, \mathcal{A}, \mu)$ *, there exist a complete measure space* $(\Omega, \bar{\mathcal{A}}, \bar{\mu})$*, such that* $\mathcal{A} \subset \bar{\mathcal{A}}$ *and* $\bar{\mu}$ *is an extension of* μ*. This space is called completion of* $(\Omega, \mathcal{A}, \mu)$*.*

Proof. Take

$$\bar{\mathcal{A}} = \{A \cup N : A \in \mathcal{A}\}$$
$$\bar{\mathcal{B}} = \{A \Delta N : A \in \mathcal{A}\}$$

$\bar{\mathcal{A}} = \bar{\mathcal{B}}$ since $A \cup N = (A - B)\Delta(B \cap (A \cup N))$ and $A \Delta N = (A - B) \cup (B \cap (A \Delta N))$. Then we can show that $\bar{\mathcal{A}}$ is a σ algebra. Let $\Omega_i = A_i \cup N_i \in \bar{\mathcal{A}}$, then

$$\bigcup_1^\infty \Omega_i = \bigcup_1^\infty A_i \cup \bigcup_1^\infty N_i$$

and note $\bigcup_1^\infty A_i \in \mathcal{A}$ and $\mu(\bigcup_1^\infty N_i) \leq \mu(\cup_1^\infty B_i) \leq \cup_1^\infty \mu(B_i) = 0$. Thus $\bar{\mathcal{A}}$ is closed by countable union. As for complements, note $\Omega^c = A^c \cap N^c = (A^c \cap N^c \cap B^c) \cup (A^c \cap N^c \cap B) = (A^c \cap B^c) \cup (A^c \cap N^c \cap B) \in \bar{\mathcal{A}}$.

Finally we define a measure $\bar{\mu}$ on $\bar{\mathcal{A}}$ by

$$\bar{\mu}(A \cup N) = \mu(A)$$

We should prove it's well defined. Suppose $A_1 \cup N_1 = A_2 \cup N_2 \in \bar{\mathcal{A}}$, note $A \Delta B \Delta C = A \Delta (B \Delta C)$ and $A \Delta B = B \Delta A$.

$$\begin{aligned}(A_1 \Delta A_2)\Delta(N_1 \Delta N_2) &= (A_1 \Delta A_2 \Delta N_1)\Delta N_2 \\ &= (A_1 \Delta N_1)\Delta(A_2 \Delta N_2) \\ &= \varnothing\end{aligned}$$

Hence $A_1 \Delta A_2 = N_1 \Delta N_2$, note $N_1 \Delta N_2 \subset N_1 \cup N_2 \subset B_1 \cup B_2$, hence $\mu(A_1 \Delta A_2) = 0$ and thus $\mu(A_1 - A_2) = \mu(A_2 - A_1) = 0$. Therefore

$$\mu(A_1) = \mu(A_1 - A_2) + \mu(A_1 \cap A_2) = \mu(A_1 \cap A_2)$$
$$\mu(A_2) = \mu(A_2 - A_1) + \mu(A_1 \cap A_2) = \mu(A_1 \cap A_2)$$

$\bar{\mu}$ is do well defined. μ^* is auto σ additive since so is μ and is easy to check that all μ^* null set is μ null set.

□

1.3.2 Specification of measures

Theorem 1.8. *Let $(\Omega, \mathcal{A})$ be a measurable space and μ, ν be finite measures. If μ, ν agree on a π system generating $\mathcal{A}$, then μ, ν are identical.*

If μ, ν are just σ finite, then the π system must include the partition $(A_n) \subset \mathcal{A}$.

Proof. Let $\mathcal{C}$ be the π system generating $\mathcal{A}$ and $\mu(A) = \nu(A)$ for every $A \in \mathcal{C}$. Consider $\mathcal{D} = \{A \in \mathcal{A} : \mu(A) = \nu(A)\}$ which satisfies $\mathcal{C} \subset \mathcal{D} \subset \Omega$. Then we need to prove that $\mathcal{D}$ is a λ system:

- $\Omega \in \mathcal{D}$ by the assumption.
- Let $A, B \in \mathcal{D}$ and $B \subset A$. Then $\mu(A-B) = \mu(A)-\mu(B) = \nu(A)-\nu(B) = \nu(A-B)$, so $A - B \in \mathcal{D}$
- Let $(A_n) \uparrow A$ and $(A_n) \subset \mathcal{D}$, then $\mu(A_n) \uparrow \mu(A)$, $\nu(A_n) \uparrow \nu(A)$, since $\mu(A_n) = \nu(A_n)$ for every n, so $\mu(A) = \nu(A)$.

So $\mathcal{D}$ is a d-system. It follows that $\sigma(\mathcal{C}) = \mathcal{A} \subset \mathcal{D}$.

□

As consequence, we have

Corollary 1.1. *Suppose μ and ν are probability measures on space on $(\overline{\mathbb{R}}, \mathcal{B})$ then $\mu = \nu$ iff $\mu[-\infty, r] = \nu[-\infty, r], \forall r \in \mathbb{R}$.*

Proof. Note $\{[-\infty, r] : r \in \mathbb{R}\}$ is a π system and generates $\mathcal{B}$.

□

1.3.3 Atomic and diffuse measure

Definition 1.12. Let $(\Omega, \mathcal{A}, \mu)$ be a measure space where $\mathcal{A}$ contains all the singletons: $\{x\} \in \mathcal{A}$ for every $x \in \Omega$ (it's true for all the standard measure).

A point x is said to be an **atom** if $\mu(\{x\}) > 0$, the measure is said to be **diffuse** if it has no atoms. It is said to be **purely atomic** if the set D of its atoms is countable and $\mu(\Omega - D) = 0$.

Lemma 1.6. *A s-finite measure has at most countable many atoms.*

Proof. It suffices to show that when μ is finite. Suppose $A_n = \{x : \mu\{x\} > \frac{1}{n}\}$ and A consists all atoms, then the claim follows from $A_n \nearrow A$ and $|A_n| \leq n\mu(\Omega)$ as $A = \bigcup_n A_n$.

□

Theorem 1.9. *Let μ be a s-finite measure on $(\Omega, \mathcal{A})$. Then $\mu = \nu + \lambda$ where λ is a diffuse measure and ν is purely atomic.*

Proof. Let D be set of all atoms and define

$$\lambda(A) = \mu(A - D)$$
$$\nu(A) = \mu(A \cap D)$$

for all $A \in \mathcal{A}$. Clearly, $\lambda + \nu = \mu$. Then

- λ is diffuse as $\lambda\{x\} = 0$ for all $x \in D$ and if $\lambda\{x\} > 0$, it must be $x \in D$.
- ν is purely atomic as $D_\nu = D$ clearly and $\nu(\Omega - D) = \mu(\varnothing) = 0$.

□

sdf

1.4 Integration

let f be Borel measurable on $(\Omega, \mathcal{A}, \mu)$. The **integral** of f w.r.t μ is denoted by

$$\int f(\omega)\mu(d\omega) = \int f d\mu = \int f$$

1. If $f = \sum_1^n a_i \mathbf{1}_{A_i}$ with $a_i \geq 0$,

$$\int f d\mu = \sum_1^n a_i \mu\left(A_i\right)$$

2. If $f \geq 0$,define

$$\int f d\mu = \lim_n \int f_n d\mu$$

   where f_n are simple functions and $f_n \nearrow f$.

3. For any f, we have $f = f^+ - f^-$, define

$$\int f d\mu := \int f^+ d\mu - \int f^- d\mu$$

4. f is said to be integrable w.r.t. μ if $\int |f| d\mu < \infty$. We denote all integrable functions by L^1.

Proposition 1.1. ***(Integral over sets)***

$$\int_A f d\mu = \int f \mathbf{1}_A d\mu = \int f(\omega)\mathbf{1}_A(\omega)\mu(d\omega)$$

*(**Absolute integrability**). $\int f$ is finite iff $\int |f|$ is finite.*

(Linearity) *If $f, g, a, b \geq 0$ or $f, g \in L^1$*

$$\int (af + bg) = a \int f + b \int g$$

(σ additivity over sets) If $A = \sum_{i=1}^{\infty} A_i$, then

$$\int_A f = \sum_{i=1}^{\infty} \int_{A_i} f$$

(Positivity) *If $f \geq 0$ a.s., then $\int f \geq 0$*

(Monotonicity) *If $f_1 \leq f \leq f_2$ a.s., then $\int f_1 \leq \int f \leq \int f_2$*

(Mean value theorem) *If $a \leq f \leq b$ a.s., then*

$$a\mu(A) \leq \int_A f \leq b\mu(A)$$

(Modulus inequality)*: $|\int f| \leq \int |f|$*

1.4.1 Monotone Convergence Theorem

Theorem 1.10 (Monotone Convergence Theorem)**.** *Suppose nonnegative $f_n \nearrow f$ a.e., then $\int f_n d\mu \nearrow \int f d\mu$.*

Theorem 1.11. *We may ignore a null set then $f_n \nearrow f$ and their integration still equal. Note $\int f_n d\mu \leq \int f d\mu$, $\int f_n d\mu$ must converges to some $L \leq \int f$. Then we show $L \geq \int f$.*

Let $s = \sum a_i \chi_{E_i}$ be simple function and $s \leq f$. Let $A_n = \{x : f_n(x) \geq cs(x)\}$ where $c \in (0,1)$, then $A_n \nearrow X$. For each n

$$\begin{aligned} \int f_n \geq \int_{A_n} f_n \geq c \int_{A_n} s \\ = c \int_{A_n} \sum a_i \chi_{E_i} \\ = c \sum a_i \mu(E_i \cap A_n) \\ \nearrow c \int s \end{aligned}$$

hence $L \geq c \int s \implies L \geq \int s \implies L = \lim L \geq \lim \int s_n = \int f$.

Lemma 1.7 (Fatou's Lemma)**.** *If $f_n \geq 0$ a.e. then*

$$\int \left(\liminf_n f_n \right) \leq \liminf_n \int f_n$$

Proof. Suppose $g_n = \inf_{i\geq n} f_i$ and recall that $\lim g_n = \liminf f_n$. Clearly $g_n \leq f_i \forall i \geq n$ hence

$$\int g_n \leq \inf_{i\geq n} \int f_i$$

Take limit both side and note g_n is increasing:

$$\lim \int g_n = \int \lim g_n = \int \liminf f_n \leq \liminf \int f_n$$

□

Theorem 1.12 (Dominated Convergence Theorem)**.** *Suppose $f_n(x) \to f(x) \forall x$, and there exists a nonnegative integrable g s.t. $|f_n(x)| \leq g(x)$(then we get $f_n \in L^1$ immediately), then*

$$\lim \int f_n d\mu = \int f d\mu$$

Proof. Since $f_n + g \geq 0$

$$\int f + \int g = \int f + g \leq \liminf \int f_n + g = \liminf \int f_n + \int g$$

thus $\int f \leq \liminf_{n\to\infty} \int f_n$. Similarly, we can get $\int f \leq \liminf_{n\to\infty} \int f_n$ from $g - f_n \geq 0$.

□

Theorem 1.13 (Tonelli's Throrem)**.** *If $\sum_1^\infty \int |f_n| < \infty$, then*

$$\int \left(\sum_{i=1}^{\infty} f_n \right) = \sum_{i=1}^{\infty} \int f_n$$

Proof. Let $g_k = \sum_1^k |f_n|, g = \sum_1^\infty |f_n|, h_k = \sum_1^k f_n, h = \sum_1^\infty f_n$. Then $g_k \nearrow g$, by MCT, we have

$$\int g = \lim \int g_k = \lim \sum_1^k \int |f_n| = \sum_1^\infty \int |f_n| < \infty$$

Hence we may let g dominate h_k and get

$$\int h = \lim \int h_k = \sum_1^\infty \int f_n$$

□

1.4.2 Criteria for zero a.e.

Lemma 1.8 (Markov inequality)**.** *Let* $A = \{x \in \Omega : f(x) \geq M\}$, *then*

$$\mu(A) \leq \frac{\int f}{M}$$

Proof.

$$\mu(A) = \int \chi_A = \int_A \chi_A \leq \int_A \frac{f}{M} \leq \int_X \frac{f}{M} = \frac{\int f}{M}$$

□

Suppose f is measurable and non-negative and $\int f d\mu = 0$. Then $f = 0$ a.e.

Proof. By lemma 1.8 and define $A_M = \{x \in \Omega : f(x) \geq M\}$. Consequently, $\mu(A_M) = 0$ for all $M > 0$, note $A_{\frac{1}{n}} \nearrow A_0$:

$$A_0 = \bigcup_1^\infty A_{\frac{1}{n}} \implies \mu(A_0) = \sum 0 = 0$$

Hence $f = 0$ a.e.

□

Lemma 1.9. *Suppose f is integrable and $\int_A f = 0$ for all measurable A. Then $f = 0$ a.e.*

Proof. Suppose $A_n = \{x \in \Omega : f(x) \geq \frac{1}{n}\}$, then

$$0 = \int_{A_n} f \geq \frac{\mu(A_n)}{n} \Rightarrow \mu(A_n) = 0$$

thus $\mu\{x \in \Omega : f(x) > 0\} = 0$. Similarly, $\mu\{x \in \Omega : f(x) < 0\} = 0$ and the claim follows.

□

Theorem 1.14. *Suppose $f : \mathbb{R} \to \mathbb{R}$ is integrable and $\int_a^x f = 0$ for all x, then $f = 0$ a.e.*

Proof. For any interval $I = [c, d]$,

$$\int_i f = \int_a^d f - \int_a^c f = 0$$

Then the integral is 0 for finite disjoint union of intervals from additivity. Note open sets G can be written as countable union of disjoint open intervals $G = \sum_1^\infty I_i = \lim \sum I_n \implies$

$$\int_G f = \int f\chi_G = \int f \sum_1^\infty \chi_{I_i} = \int \lim f \sum \chi_{I_i} = \lim \int f \sum \chi_{I_i} = 0$$

If $G_n \searrow H$, then

$$\int_H f = \int f\chi_H = \int \lim f\chi_{G_n} = \lim \int f\chi_{G_n} = \lim \int_{G_n} f = 0$$

where we apply DMT twice and take dominated function $g = |f|$.

Finally, for any borel measurable set E, there is $G_\delta \supset E$ and $m(G_\delta - E) = 0$, then

$$\int_E f = \int f\chi_E = \int f\chi_{G_\delta} = \int_{G_\delta} f = 0$$

□

1.4.3 Characterization of the integral

Theorem 1.15. *Let $(\Omega, \mathcal{A})$ be a measurable space and $L : \mathcal{A} \to \overline{\mathbb{R}}_+$, then there is a unique measure μ on $(\Omega, \mathcal{A})$ s.t. $L(f) = \int f$ for every $f \in \mathcal{A}_+$ iff:*

- $f = 0 \implies L(f) = 0$
- $f, g \in \mathcal{A}_+$ *and* $a, b \in \mathbb{R}_+ \implies L(af + bg) = aL(f) + bL(g)$
- $(f_n) \subset \mathcal{A}_+$ *and* $f_n \nearrow f \implies L(f_n) \nearrow L(f)$

Proof. $\Rightarrow$ follows from the definition and properties of integral. For $\Leftarrow$, let there is a function L satisfies above conditions and give a μ and let $\mu(A) = L(1_A)$, then use those conditions we can prove that μ is a measure a $(\Omega, \mathcal{A})$.

□

1.5 Transforms and Indefinite integral

Definition 1.13 (Image measure)**.** Let $(F, \mathcal{F})$ and $(E, \mathcal{E})$ be measurable spaces. Let ν be a measure on $(F, \mathcal{F})$ and let $h : F \to E$ be measurable relative to $\mathcal{F}$ and $\mathcal{E}$, then define a mapping $\nu \circ h^{-1}(B) = \nu(h^{-1}B),\ B \in \mathcal{E}$. Then $\nu \circ h^{-1}$ is a measure on $(E, \mathcal{E})$, which is called the **image** of ν under h.

Remark. Image inherit finite and s-finite, but not σ-finite.

Theorem 1.16. *For every $f \in \mathcal{E}$, we have $(\nu \circ h^{-1})f = \nu(f \circ h)$.*

Proof. We only need to show that $\mathcal{E}_+$ case and then the general case follows easily.

Let $L : \mathcal{E}_+ \to \overline{\mathbb{R}}_+$ by letting $L(f) = \nu(f \circ h)$. Then as the property of $\nu(f \circ h)$, f satisfies the properties of integral characterization theorem. Then, $L(f) = \mu f$ for some unique measure μ on $(E, \mathcal{E})$. And note $\mu = \nu \circ h$

$$\mu(B) = L(\mathbf{1}_B) = \nu(\mathbf{1}_B \circ h) = \nu(h^{-1}B)$$

□

1.5.1 Images of the Lebesgue measure

By theorem 1.16, we have a convenient tool for creating new measure from old and, we may integral a measure using Lebesgue measure:

Theorem 1.17. *Let $(\Omega, \mathcal{A}, \mu)$ be a standard measure space where μ is s-finite and $b = \mu(\Omega)$. Then there exists a measurable mapping $h : ([0, b), \mathcal{B}_{[0,b]}) \to (\Omega, \mathcal{A})$ s.t. $\mu = \lambda \circ h^{-1}$, where λ is the Lebesgue measure on $[0, b)$.*

Proof. See 5.15 and 5.16 on page 34 in *Probability and Stochastic.*

□

1.5.2 Indefinite integrals

Definition 1.14. Let $(\Omega, \mathcal{A}, \mu)$ be a measure space and $p \in \mathcal{A}_+$. Define:

$$\nu(A) = \mu(p\mathbf{1}_A) = \int_A p d\mu$$

then ν is a measure on $(\Omega, \mathcal{A})$ and called **indefinite integral** of p w.r.t. μ.

Remark. ν is a measure follows from MCT.

Theorem 1.18. *For any $f \in \mathcal{A}_+$, $\nu f = \mu(pf)$.*

Proof. Let $L(f) = \mu(pf)$. Check L :

- $f = 0 \implies L(f) = 0$
- Give $f, g \in \mathcal{E}_+$ and $a, b \in \mathbb{R}_+ \implies L(af+bg) = \mu(p(af+bg))$ and based on the arithmetic rules on $\mathbb{R}$ and the linearity of μ, $L(af+bg) = aL(f)+bL(g)$
- Give $(f_n) \subset \mathcal{E}_+$ and $f_n \nearrow f$, $L(f_n) = \mu(pf_n)$ and as $f_n \nearrow f$, $pf_n \nearrow pf$ so $\lim L(f_n) = \lim \mu(pf_n)$. According to the monotone converging theorem, $\lim \mu(pf_n) = \mu(pf) = L(f)$

So there exists $\hat{\mu}$ s.t. $\mu(pf) = \hat{\mu}f$ and that force $\hat{\mu} = \nu$ as

$$\hat{\mu}(A) = L(\mathbf{1}_A) = \mu(p\mathbf{1}_A) = \nu(A)$$

□

Remark. Writing above result in an explicit notation:

$$\int_E f d\nu = \int_E pf d\mu$$

that is:

$$d\nu = pd\mu$$

and it's precisely Fundamental theorem of calculus. Thus we can say:

- ν is the indefinite integral of p w.r.t. μ or
- p is the density of ν w.r.t. μ.

1.5.3 Radon-Nikodym theorem

Definition 1.15 (absolutely continuous)**.** Let ν and μ be measures on a measurable space $(\Omega, \mathcal{A})$. Then ν is said to be **absolutely continuous** w.r.t. μ if for any set $A \in \mathcal{E}$, $\mu(A) = 0 \implies \nu(A) = 0$ and denoted by $\nu \ll \mu$.

Clearly, if ν is the indefinite integral of some $p \in \mathcal{A}_+$ w.r.t. μ, then it's absolutely continuous w.r.t. μ. And the follows shows that the converse is true.

Theorem 1.19 (Radon-Nikodym Theorem)**.** *Suppose that μ is σ-finite and ν is absolutely continuous w.r.t. μ. Then there exists unique(up to a.e.) $p \in \mathcal{A}_+$ s.t. for every $f \in \mathcal{A}_+$:*

$$\int_\Omega f d\nu = \int_\Omega fp d\mu$$

1.6 Kernels and Product spaces

Definition 1.16 (transition kernel)**.** Let $(E, \mathcal{E})$ and $(F, \mathcal{F})$ be measurable spaces. Let $K : E \times \mathcal{F} \to \overline{\mathbb{R}}_+$. Then, K is called a transition kernel from $(E, \mathcal{E})$ into $(F, \mathcal{F})$ if:

- the mapping $x \mapsto K(x, B)$ is $\mathcal{E}$-measurable for every set $B \in \mathcal{F}$
- the mapping $B \mapsto K(x, B)$ is a measure on $(F, \mathcal{F})$ for every $x \in E$

Example 1.1. If ν is a finite measure on $(F, \mathcal{F})$, and k is a positive function on $E \times F$ that is $\mathcal{E} \times \mathcal{F}$-measurable, then

$$K(x, B) = \int_B k(x, y) d\nu$$

when fix $x \in E$, $K(x, B) = \nu(k(x, y)\mathbf{1}_B) = \mu(B)$ for some μ which is the measure on $(F, \mathcal{F})$;
when fix $B \in \mathcal{F}$, $f(x) = K(x, B)$ is measurable follows from theorem 1.4.

1.6.1 Measure-kernel-function

Theorem 1.20. *Let K be a transition kernel from $(E, \mathcal{E})$ into $(F, \mathcal{F})$. Then*

$$Kf(x) = \int_F K(x, dy) f(y)$$

defines a function $Kf \in \mathcal{E}_+$ for every $f \in \mathcal{F}_+$;

$$\mu K(B) = \int_E \mu(dx) K(x, B)$$

defines a measure μK on $(F, \mathcal{F})$ for each measure μ on $(E, \mathcal{E})$; and

$$(\mu K) f = \mu(Kf) = \int_E \mu(dx) \int_F K(x, dy) f(y)$$

for every measure μ on $(E, \mathcal{E})$ and function f in $\mathcal{F}_+$.

Proof. Kf is well-defined and measurable follows form theorem 1.4.

Define $L : \mathcal{F}_+ \to \overline{\mathbb{R}}_+ = f \mapsto \mu(Kf)$. Check

- $f(0) \Rightarrow L(f) = 0$

- If $f, g \in \mathcal{F}_+$ and $a, b \in \overline{\mathbb{R}}_+$, then:

$$\begin{aligned} L(af+bg) &= \mu(K(af+bg)) \\ &\xlongequal{Linearity} \mu(aKf+bKg) \\ &\xlongequal{linearity} a\mu(Kf)+b\mu(Kg) \\ &= aL(f)+bL(g) \end{aligned}$$

- Suppose $(f_n) \subset \mathcal{F}_+$ and $f_n \nearrow f$, then

$$L(f_n) = \mu(Kf_n) \nearrow \mu(Kf) = L(f)$$

  as MCT.

Hence, there exists a measure ν s.t. $L(f) = \mu(Kf) = \nu f$ as theorem 1.15. Then it suffices to show $\nu = \mu K$. Taking $f = \mathbf{1}_B$, we have $\nu(B) = \nu(\mathbf{1}_B) = \mu(K\mathbf{1}_B)$, it follows that

$$\mu(K\mathbf{1}_B) = \int_E \mu(dx) \int_F K(x,dy)\mathbf{1}_B(y) = \int_E \mu(dx)K(x,B) = \mu K(B)$$

□

Corollary 1.2. *A mapping $f \mapsto Kf : \mathcal{F}_+ \to \mathcal{E}_+$ specifies a transition kernel K iff*

- $K0 = 0$
- $K(af+bg) = aKf + bKg$ *for* $f, g \in \mathcal{F}_+$ *and* $a, b \in \overline{\mathbb{R}}_+$
- $Kf_n \nearrow Kf$ *for every* $(f_n) \nearrow f \subset \mathcal{F}_+$.

1.6.2 Products of kernels

Definition 1.17. Let K be a transition kernel from $(E, \mathcal{E})$ into $(F, \mathcal{F})$ and let L be a transition kernel from $(F, \mathcal{F})$ into $(G, \mathcal{G})$. Then their **product** is the transition kernel KL from $(E, \mathcal{E})$ into $(G, \mathcal{G})$ defined by

$$(KL)f = K(Lf)$$

Remark. We can check KL is a transition kernel indeed by corollary 1.2. Obviously

$$KL(x,B) = \int_F K(x,dy)L(y,B)$$

1.6.3 Markov kernel

Definition 1.18. Let K be a transition kernel from $(\Omega, \mathcal{A})$ into $(\Omega', \mathcal{A}')$, it's called simply a transition kernel on $(\Omega, \mathcal{A})$ if $\mathcal{A}' = \mathcal{A}$, moreover, it's called a **Markov kernel** if $K(x, \Omega) = 1, \forall x \in \Omega$ and a **sub-Markov kernel** if $K(x, \Omega) \leq 1, \forall x \in \Omega$.

If K is a transition kernel on $(\Omega, \mathcal{A})$, similarly with product kernel, we can define its **power** by $K^n = KK^{n-1}$ and $K^0 = I$ where I is the identity kernel on $(\Omega, \mathcal{A})$: $I(x, A) = \mathbf{1}_A(x)$. To see why it's called "identity", check

$$\begin{aligned} If(x) &= \int_\Omega I(x, dx)f(x) = \int_{\{x\}} f(x) = f(x) \\ \mu I(A) &= \int_\Omega \mu(dx)I(x, A) = \int_A \mu(dx) = \mu(A) \end{aligned}$$

and thus $IK = KI = K$. It follows that if K is Markov, so is K^n:

$$\begin{aligned} KK(x, \Omega) &= \int_\Omega K(x, dy)K(y, \Omega) \\ &= \int_\Omega K(x, dy) \\ &= K(x, \Omega) = 1 \end{aligned}$$

1.6.4 finite and bounded kernels

Definition 1.19. Let K be a transition kernel from $(E, \mathcal{E})$ into $(F, \mathcal{F})$. In analogy with measures, it's called σ finite and finite if $B \mapsto K(x, B)$ is so for each $x \in E$

It's called bounded if $x \mapsto K(x, F)$ is bounded and σ bounded if there exists a partition $(F_n) \subset \mathcal{F}$ s.t. $x \mapsto K(x, F_n)$ is bounded for each n.

It's said to be s-finite if there exists countable finite (K_n) s.t. $K = \sum K_i$ and s-bounded if those (K_n) can be bounded.

If $K(x, \mathcal{F}) = 1$ for all x, the kernel is said to be a **transition probability kernel**.

Remark.

$$\begin{array}{ccccc} \text{bounded} & \Longrightarrow & \sigma\text{-bounded} & \Longrightarrow & s\text{-bounded} \\ \Downarrow & & \Downarrow & & \Downarrow \\ \text{finite} & \Longrightarrow & \sigma\text{-finite} & \Longrightarrow & s\text{-finite} \end{array}$$

1.6.5 Functions on product spaces

Sections of a measurable function are measurable:

Proposition 1.2. *Let $f \in \mathcal{X} \times \mathcal{Y}$, then it's selection, $x \mapsto f(x, y)$ and $y \mapsto f(x, y)$ are measurable for each x and y.*

Then we can generalize theorem 1.20 to functions on product spaces:

Lemma 1.10. *Let K be a s-finite kernel from $(X, \mathcal{X})$ into $(X, \mathcal{Y})$, then, $\forall f \in (\mathcal{X} \times \mathcal{Y})_+$, define*

$$Tf(x) = \int_F f(x, y) K(x, dy) \in \mathcal{X}_+$$

moreover, $T : (\mathcal{X} \times \mathcal{Y}) \to \mathcal{X}_+$ is linear and continuous from below:

- *$T(af + bg) = aTf + bTg$ for $f, g \in (\mathcal{X} \times \mathcal{Y})_+$ and $a, b \in \mathbb{R}_+$*
- *If $(f_n) \subset \mathcal{X} \times \mathcal{Y} \nearrow f$, then $Tf_n \nearrow Tf$.*

Proof. By proposition 1.2, $f_x : y \mapsto f(x, y)$ is measurable in $\mathcal{F}_+$ and thus $Tf(x) = Kf_x(x)$, hence

- Linearity:

$$\begin{aligned} T(af + bg)(x) &= K(af_x + bg_x)(x) \\ &= aKf_x(x) + bKg_x(x) \\ &= aTf(x) + bTg(x) \\ &= (aTf + bTg)(x) \end{aligned}$$

- Continuity from below

$$f_n \nearrow f \implies Kf_{n_x}(x) \nearrow Kf_x(x) \implies Tf_n(x) \nearrow Tf(x)$$

Then it's remain to show $Tf \in \mathcal{X}_+$, assume K is bounded, suppose

$$\mathcal{M} = \{f \in (\mathcal{X} \times \mathcal{Y})_+ \cup (\mathcal{X} \times \mathcal{Y})_b : Tf \in \mathcal{X}\}$$

it's easy to check it's a monotone class and include all indicator of measurable rectangle $A \times B$. By theorem 1.5, we have $\mathcal{M} = (\mathcal{X} \times \mathcal{Y})_+ \cup (\mathcal{X} \times \mathcal{Y})_b$.

□

1.6.6 Measures on the product space

Theorem 1.21. *Let μ be a measure on $(X, \mathcal{X})$ and K be a s-finite kernel from $(X, \mathcal{X})$ to $(Y, \mathcal{Y})$, then for any $f \in (\mathcal{X} \times \mathcal{Y})_+$*

$$\pi f = \int_X \int_Y f(x,y) K(x, dy) d\mu$$

define a measure π on the product space. Moreover, if μ if σ-finite and K is σ bounded, then π is σ finite and unique that satisfying:

$$\pi(A \times B) = \int_A K(x, B) d\mu$$

Proof. To see πf define a measure, check theorem 1.15, which follows from $\pi f = \mu(Tf)$ and similar properties enjoyed by T from lemma 1.10.

And the unique follows from theorem 1.8 by noting that all measurable rectangles is a π-system.

□

1.6.7 Product measures and Fubini

Definition 1.20. If $K(x, B) = \nu(B)$, i.e., independent to x, for some s-finite measure ν on $(Y, \mathcal{Y})$, then such π is called **product** of μ and ν.

Theorem 1.22 (Fubini's theorem)**.** *Let μ and ν be s-finite measures on $(X, \mathcal{X})$ and $(F, \mathcal{F})$, respectively.*

- *There exists a unique s-finite measure π on $(X \times Y, \mathcal{X} \times \mathcal{Y})$ s.t. $\forall f \in (X \times Y)_+$:*

$$\pi f = \int_X \int_Y f(x,y) d\nu d\mu = \int_Y \int_X f(x,y) d\mu d\nu$$

- *If $f \in \mathcal{X} \times \mathcal{Y}$ and $\pi f < \infty$, then $y \mapsto f(x,y)$ is ν integrable μ a.e. for every y, $x \mapsto f(x,y)$ is μ integrable ν a.e. for every x.*

Remark. For $A \in \mathcal{X}$ and $B \in \mathcal{Y}$, we have

$$\begin{aligned}
\pi(A \times B) &= \pi \mathbf{1}_{A \times B} \\
&= \int_X \int_Y \mathbf{1}_{A \times B}(x,y) d\nu d\mu \\
&= \int_X \int_Y \mathbf{1}_A(x) \mathbf{1}_B(y) d\nu d\mu \\
&= \mu(A)\nu(B)
\end{aligned}$$

and this is the reason we call π the product and write $\pi = \mu \times \nu$.

Remark. By theorem 1.21, only if both μ and ν are σ-finite the π is the unique product

1.6.8 Finite products

Now we can extend previous results to finitely many spaces' product. Similarly to product topology, $\prod_{i\in I}\mathcal{A}_i$ is generated by all measurable rectangles $\prod_{i\in I}A_i$ where I is finite.

Let (μ_n) be s-finite measures, their product measure is defined by analogy with theorem 1.22, $\forall f\in\prod_{i\in I}\mathcal{A}_i$,

$$\pi f=\int\dots\int f d\mu_n\dots d\mu_1$$

1.6.9 Infinite products

Similar again with product topology, $\prod_{i\in I}\mathcal{A}_i$ is generated by all measurable rectangles $\prod_{i\in I}A_i$ where $A_i=\Omega_i$ with finite exception. In analogy with topology product, we have:

Proposition 1.3. *Suppose there is $f_i:(X,\mathcal{F})\to(\Omega_i,\mathcal{A}_i)$ for $i\in I$ and define $f(x)=(f_i(x))_{i\in I}$, then f is measurable iff each f_i is measurable.*

Chapter 2

Probability Spaces

2.1 Probability Spaces and Random Variables

Definition 2.1. Let $(\Omega, \mathcal{F}, \mathbb{P})$ be a probability space. The set Ω is called the **sample space** and whose elements are called **outcomes**. $\mathcal{F}$ is called **history** and whose elements are called **events**.

Note here $\mathbb{P}$ is finite measure, so it's continuous. We collect it's properties below :

Proposition 2.1. *For probability measure, which has following properties:*

1. $\forall A \in \mathcal{A}, \quad 0 \leq \mathbb{P}(A) \leq 1$
2. $\mathbb{P}(\Omega) = 1$
3. $\mathbb{P}\left(\sum_1^\infty A_n\right) = \sum_1^\infty \mathbb{P}\left(A_n\right)$
4. $\mathbb{P}(A) \leq \mathbb{P}(B) \impliedby A \subset B$
5. $\mathbb{P}$ *is continuous, as well as continuous from above and below.*
6. ***Boole's inequality***

$$\mathbb{P}\left(\bigcup_{i=1}^{\infty} A_i\right) \leq \sum_{i=1}^{\infty} \mathbb{P}\left(A_i\right)$$

2.1.1 Measure-theoretic and probabilistic languages

Measure	Probability
Integral	Expectation
Measurable set	Event
Measurable function	Random Variable
a.e.	a.s.

2.1.2 Distribution of a r.v.

Let X be a r.v. taking values in some measurable space $(Y, \mathscr{Y})$, then let μ be the image of $\mathbb{P}$ under X, i.e.:

$$\mu(A) = \mathbb{P}(X^{-1}A) = \mathbb{P}\{X \in A\}$$

then μ is a probability measure on $(Y, \mathscr{Y})$, it's called the **distribution** of X. In view of theorem 1.8, it suffices to specify $\mu(A)$ forall A belongs to a π-system which generates $\mathscr{Y}$. In particular, if $(Y, \mathscr{Y}) = (\overline{\mathbb{R}}, \mathcal{B})$, it's enough to specify

$$c(x) = \mu[-\infty, x] = \mathbb{P}\{X \leq x\}$$

and such $c : \mathbb{R} \to [0, 1]$ is called **distribution function(d.f.)**

Remark. Distribution function is nondecreasing and right continuous.

2.1.3 Joint distributions

Let X and Y taking values in $(E, \mathcal{E})$ and $(F, \mathcal{F})$ respectively then pair $Z = (X, Y)$ is measurable from $\mathcal{F}$ to $\mathcal{E} \times \mathcal{F}$.

Recall the product spaces, to specifies distribution π of Z is suffices to:

$$\pi(A \times B) = \mathbb{P}\{X \in A, Y \in B\}$$

thus we have

$$\mu(A) = \mathbb{P}\{x \in A\} = \pi(A \times F)$$

μ and ν are called **marginal distributions**

2.1.4 Independence

Let X and Y taking values in $(E, \mathcal{E})$ and $(F, \mathcal{F})$ with marginal μ and ν, then they are said **independent** if their joint distribution is the product formed by their marginals:

$$\mathbb{P}\{X \in A, Y \in B\} = \mathbb{P}\{X \in A\}\mathbb{P}\{Y \in B\}$$

A finite collection $\{X_i\}_i^n$ is said to be **independency** if their product distribution has form $\prod_{i=1}^n \mu_i$. An arbitrary collection of r.v. is an independency if every finite subcollection is so.

2.1.5 Stochastic process and probability laws

Definition 2.2. Suppose $\{X_t : t \in T\}$ is a collection of r.v. taking values in $(E, \mathcal{E})$. If T can be seen as time, then $(X_t)_{t \in T}$ is called a **stochastic process** with **state space** $(E, \mathcal{E})$ and **parameter set** T.

Now we can treat $X(\omega)$ as function $T \to E : t \mapsto X_t(\omega)$, thus $X : \mathcal{F} \to E^T$ is measurable as proposition 1.3 and it's a r.v. live in the same spaces as X_i and taking values in $(E^T, \mathcal{E}^T)$. It's distribution, $P \circ X^{-1}$ is called **probability law** of stochastic process $\{X_t : t \in T\}$.

Recall the product σ algebra construction, the probability law is determined by:

$$\mathbb{P}\{\bigcap_{i \in I} X_i \in A_i\}$$

where $I \subset T$ is finite.

2.2 Expectation

Suppose X taking values in $\overline{\mathbb{R}}$, then we can talk about it's expectation:

$$\mathbb{E}X = \int_{\Omega} X d\mathbb{P} = \mathbb{P}X$$

the integral of X over an event $H \in \mathcal{F}$ is $\mathbb{E}X\mathbf{1}_H$

Bonferroni's inequality

$$\mathbb{P}\left(\bigcap_{i=1}^{n} A_i\right) \geq \sum_{i=1}^{n} \mathbb{P}\left(A_i\right) - (n-1)$$