Lecture Notes
MATH205A: Real Analysis I (Autumn 2020)
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October 28, 2020

1 Measures

1.1 Motivation

Motivation of this course is to define a notion of *length* on subsets of $\mathbb{R}$ such that

1. $length([a,b]) = b - a$.
2. (countable additivity) $length(\bigcup^\infty A_i) = \sum^\infty length(A_i)$ where A_i's are disjoint.
3. (translation invariance) for all $a \in \mathbb{R}$, $length(A + a) = length(A)$.

Fact 1.1. it is impossible to construct such length for all subsets of $\mathbb{R}$.

Proof. This proof shows it is impossible to construct a notion of length on $[0,1]$ with desired properties.

For $x, y \in [0,1]$, define an equivalence relation as $x \sim y \iff x - y \in \mathbb{Q}$. By the axiom of choice, we may construct a set A containing exactly one element from each equivalence class of $x \in [0,1]$. Obviously, $A \subseteq [0,1]$.

For each $r \in [-1,1] \cap \mathbb{Q}$, let $A_r := A + r$, and $A_r \subseteq [-1,2]$. By translation invariance, $length(A_r) = length(A)$. Note that for any $y \in [0,1]$, there exists some $x \in A$ such that $x \sim y$, therefore, $y \in A_{y-x} \subseteq \bigcup_r A_r$. Hence, $[0,1] \subseteq \bigcup_r A_r$.

If the notion of length satisfies countable additivity, $length(\bigcup_r A_r)$ is either zero or infinity, which leads to a contradiction. ■

Lebesgue's Resolution: we only defines length for a subset of $\mathcal{P}(\mathbb{R})$, which contains *everything that may ever arrive in practice*, i.e., σ-algebras.

1.2 Algebras and σ-algebra

Definition 1.1. Let X be a set, a collection $\mathcal{A}$ of subsets of X is called an **algebra** if

1. $X \in \mathcal{A}$,

2. $A \in \mathcal{A} \implies A^c \in \mathcal{A}$,

3. $A, B \in \mathcal{A} \implies A \cup B \in \mathcal{A}$.

Consequently: (1) $A, B \in \mathcal{A} \implies A \cap B \in \mathcal{A}$; (2) $A_1, \ldots, A_n \in \mathcal{A} \implies \bigcup_i A_i, \bigcap_i A_i \in \mathcal{A}$ (easily shown by induction); (3) $\varnothing \in \mathcal{A}$.

Definition 1.2. Let X be a set, a collection $\mathcal{A}$ of subsets of X is called a σ-**algebra** if

1. $X \in \mathcal{A}$,

2. $A \in \mathcal{A} \implies A^c \in \mathcal{A}$,

3. $A_1, A_2 \ldots, \in \mathcal{A}, \implies \bigcup_i^\infty A_i \in \mathcal{A}$.

Example 1.1 (trivial examples)**.** The power set of X is a σ-algebra on X; $\{\varnothing, X\}$ is a σ-algebra on X.

Example 1.2 (finite/co-finite algebra)**.** Let X be an infinite set and $\mathcal{A}$ be the collection of subsets A such that either A is finite or A^c is finite. $\mathcal{A}$ is an algebra.

Proof. $X \in \mathcal{A}$ since $X^c = \varnothing$ is finite. For a $X \in \mathcal{A}$, if X is finite, then $X^c \in \mathcal{A}$. If X is infinite, X^c is finite and $X^c \in \mathcal{A}$. Let $A, B \in \mathcal{A}$, if both A and B are finite, $A \cup B$ is finite and in $\mathcal{A}$. If A is finite and B is co-finite, then $(A \cup B)^c = A^c \cap B^c \subseteq B^c$ is finite. If both A and B are co-finite, $(A \cup B)^c$ is finite so that $A \cup B \in \mathcal{A}$. ■

Note the $\mathcal{A}$ is not a σ-algebra if X is infinite: take distinct points $x_1, x_2, \dots \in \mathcal{A}$, then the union of them is neither finite or co-finite, and therefore not in $\mathcal{A}$.

Example 1.3 (countable/co-countable σ-algebra)**.** The collection of subsets $A \subseteq X$, such that either A is countable or A^c is countable, forms a σ-algebra.

Example 1.4. Let $X = \mathbb{R}$ and $\mathcal{A}$ be the collection of all finite disjoint unions of half-open intervals (i.e., sets like $(a, b], (-\infty, b], (a, \infty)$), $\mathcal{A}$ is an algebra. (Not working for open intervals).

Example 1.5 (counter example)**.** Let X be an infinite set, $\mathcal{A}$ be the collection of finite subsets of X. Then, $\mathcal{A}$ is not an algebra.

Proposition 1.1. Let X be a set and $\{\mathcal{A}_i\}_{i \in \mathcal{I}}$ be an arbitrary (not necessarily countable) collection of σ-algebras, then $\bigcap_{i \in \mathcal{I}} \mathcal{A}_i$ is a σ-algebra.

Proof. Since $X \in \mathcal{A}_i$ for all $i \in \mathcal{I}$ ■

Corollary 1.1. Let X be a set, and $\mathcal{P}$ is an arbitrary collection of subsets of X, then $\exists!$ smallest σ-algebra $\mathcal{A}$ containing $\mathcal{P}$. That is, for any σ-algebra $\mathcal{B} \supseteq \mathcal{P}$, $\mathcal{A} \subseteq \mathcal{B}$. $\mathcal{A}$ is defined as the σ-algebra **generated by** $\mathcal{P}$, denoted as $\sigma(\mathcal{P})$.

Proof. For any $\mathcal{P}$, the power set of X is obviously a σ-algebra containing $\mathcal{P}$. Then we can take $\mathcal{A}$ as the intersection of all σ-algebras containing $\mathcal{P}$. ■

1.3 Borel σ-algebra

Definition 1.3. The **Borel σ-algebra** of $\mathbb{R}$, denoted as $\mathcal{B}(\mathbb{R})$, is the σ-algebra generated by the set of open intervals in $\mathbb{R}$.

Fact 1.2. $\mathcal{B}(\mathbb{R})$ is generated by the collection of all closed intervals as well.

Proof. Let $\mathcal{F}$ denote the σ-algebra generated by all closed intervals. Any open interval can be written as a countable union of closed sets: $(a, b) = \bigcup_{n=1}^{\infty}[a + 1/n, b - 1/n]$, therefore $(a, b) \in \mathcal{F}$ and $\mathcal{B}(\mathbb{R}) \subseteq \mathcal{F}$.

Similarly, $[a, b] = \bigcap_{n=1}^{\infty}(a - 1/n, b + 1/n)$, hence $\mathcal{B}(\mathbb{R})$ is a σ-algebra contains all closed sets. Therefore, $\mathcal{F} \subseteq \mathcal{B}(\mathbb{R})$. ■

Fact 1.3. $\mathcal{B}(\mathbb{R})$ is generated by

1. all open sets,
2. all closed sets,
3. all half-open intervals.

Example 1.6 (counter example)**.** $\mathcal{B}(\mathbb{R})$ is not generated by the collection of singletons.

Proof. ■

Definition 1.4. The Borel algebra of $\mathbb{R}^d$, $\mathcal{B}(\mathbb{R}^d)$, is the σ-algebra generated by

1. all open sets in $\mathbb{R}^d$,
2. all closed sets in $\mathbb{R}^d$,
3. all closed cubes (regions) in $\mathbb{R}^d$: $\prod_{i=1}^{d}[a_i, b_i]$.

1.4 Measures

Definition 1.5. For a set X and a σ-algebra $\mathcal{A}$ of X, the pair $(X, \mathcal{A})$ is called a **measurable space**.

Definition 1.6. A **measure** μ on a measurable space $(X, \mathcal{A})$ is a map $\mu : \mathcal{A} \to [0, \infty]$ such that

1. $\mu(\varnothing) = 0$,
2. $\mu(\cup_i^{\infty} A_i) = \sum_i^{\infty} \mu(A_i)$ for disjoint sequence (A_i)

For now, we don't require the translation invariance property.

The triple $(X, \mathcal{A}, \mu)$ is called a **measure space**.

Example 1.7 (counting measure)**.**

Example 1.8 (point-mass measure)**.**

Proposition 1.2. A measure μ possesses the following basic properties:

1. (Monotonicity) $A \subseteq B \implies \mu(A) \leq \mu(B)$.
2. (Sub-additivity) $\mu(\bigcup_{i=1}^{\infty} A_i) \leq \sum_{i=1}^{\infty} \mu(A_i)$.
3. Let $A_1 \subseteq A_2 \subseteq \dots$ be an increasing set, let $\cup_{i=1}^{\infty} A_i$ denoted $A_i \nearrow A$, $\mu(A) = \lim_{n\to\infty} \mu(A_n)$.
4. If $A_1 \searrow A \equiv \cap_{i=1}^{\infty} A_i$, and there exists $\mu(A_i) < \infty$, then $\mu(A) = \lim_{n\to\infty} \mu(A_n)$.

Proof. ■

Example 1.9 (counter example)**.** Let $X = \mathbb{Z}$, $\mathcal{A} = 2^{\mathbb{Z}}$ and μ be the counting measure. Define $A_i = \{i, i+1, \dots\}$, then $A_i \searrow A = \varnothing$, but $\lim_{n\to\infty} \mu(A_n) = \infty \neq \mu(\varnothing)$.

1.5 Outer Measure

Definition 1.7. Let X be a set, $\mu^* : 2^X \to [0, \infty]$ is an **outer measure** if

1. $\mu^*(\varnothing) = 0$.
2. $\mu^*(A) \leq \mu^*(B)$ whenever $A \subseteq B$.
3. (countable sub-additivity) $\mu^*(\cup_{i=1}^{\infty} A_i) \leq \sum_{i=1}^{\infty} \mu^*(A_i)$.

Key difference between outer measure and measure:

1. Outer measure does not require countable additivity,
2. outer measure is defined on 2^X instead of a σ-algebra .

Example 1.10.

1.6 Lebesgue Measure on $\mathbb{R}$

Definition 1.8. Let $A \subseteq \mathbb{R}$, define the **Lebesgue outer measure**:

$$\lambda^*(A) = \inf \left\{ \sum_{i\in\mathbb{N}} b_i - a_i : A \subseteq \bigcup_{i\in\mathbb{N}} (a_i, b_i) \right\} \tag{1}$$

The Lebesgue outer measure of a set A is simply in the infimum of total lengths (the conventional notion of length) of open intervals cover A.

Proposition 1.3. The Lebesgue measure satisfies the following properties:

1. λ^* is an outer measure on $\mathbb{R}$,
2. $\lambda^*([a, b]) = b - a$ for all $a < b$.

Proof. (1.1) $\lambda^*(\varnothing) = 0$ since $(-\varepsilon, \varepsilon)$ covers $\varnothing$ for arbitrarily small ε.

(1.2) Let $A \subseteq B$, Ω_A and Ω_B be collection of sequences of open intervals covering A and B respectively. Then, any cover of B must be a cover of A, that is, $\Omega_A \subseteq \Omega_B$. Therefore, $\lambda^*(A) \leq \lambda^*(B)$.

(1.3) Let $A_1, A_2, \cdots \subseteq \mathbb{R}$ and $A = \bigcup_{i=1}^{\infty} A_i$. For all i, we may find (a_{ij}, b_{ij}) covers A_i such that

$$\sum_{j=1}^{\infty} (b_{ij} - b_{ij}) \leq \lambda^*(A_i) + \varepsilon 2^{-i} \tag{2}$$

Also, $\{(a_{ij}, b_{ij})\}_{i,j}$ is a countable union of open intervals that covers A.

$$\begin{aligned} \lambda^*(A) &\leq \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} (b_{ij} - a_{ij}) & (3) \\ &\leq \sum_{i=1}^{\infty} (\lambda^*(A_i) + \varepsilon 2^{-i}) & (4) \\ &= \sum_{i=1}^{\infty} \lambda^*(A_i) + \varepsilon & (5) \end{aligned}$$

Therefore, $\lambda^*(A) \leq \sum_{i=1}^{\infty} \lambda^*(A_i)$.

(2) Note that $[a, b] \subseteq (a - \varepsilon, b + \varepsilon)$ for all $\varepsilon > 0$. Therefore,

$$\lambda^*([a, b]) \leq \inf_{\varepsilon > 0} \lambda^*(a - \varepsilon, b + \varepsilon) = b - a \tag{6}$$

Now show $\lambda^*([a, b]) \geq b - a$. We want to show that $\sum_{i=1}^{\infty} (b_i - a_i) \geq b - a$ for all possible covering of $[a, b]$, which implies the infimum of them is at least $b - a$.

Take an arbitrary covering $\{(a_i, b_i)\}_i$ of $[a, b]$. Since $[a, b]$ is compact, there exists a finite covering $[a, b] \subseteq \bigcup_{i=1}^{n} (a_i, b_i)$ (reindexed), it suffices to show the finite sum $\sum_{i=1}^{\infty} (b_i - a_i) \geq b - a$.

(1) We firstly define an *interval* to be any open, closed or half-open intervals. The *length* of an interval is the difference between two end points.

Note that if an interval I contains a finite collection of disjoint sub-intervals, then the length of I is at least the sum of lengths of sub-intervals. The equality holds when I is exactly finite union of disjoint sub-intervals.

(2) Suppose $[a, b] \subseteq \bigcup_{i=1}^{n} (a_i, b_i)$, let $I_i = [a, b] \cap (a_i, b_i)$. Easy to verify that the length of $I_i \leq$ length of $(a_i, b_i) = b_i - a_i$. Moreover, $\bigcup_{i=1}^{n} I_i = [a, b] \cup \bigcup_{i=1}^{n} (a_i, b_i) = [a, b]$.

(3) For all i, define $I'_i = I_i \backslash (I_1 \cup I_2 \cup \cdots \cup I_{i-1})$. This procedure allows us to express $[a, b]$ as a finite union of disjoint sub-intervals: $[a, b] = \bigcup_{i=1}^{n} I'_i$. Each I'_i is a finite union of disjoint intervals as well, the conventional notion of I'_i is well-defined. Then $b - a =$ sum of lengths of I'_i.

However, $\ell(I'_i) \leq \ell(I_i) \leq b_i - a_i$ and sum of lengths of $I'_i \leq$ sum of lengths of $I_i \leq \sum_{i=1}^{n} b_i - a_i$. Therefore, $b - a \leq \sum_{i=1}^{n} b_i - a_i \leq \sum_{i=1}^{\infty} b_i - a_i$. Hence, $b - a = \sum_{i=1}^{\infty} b_i - a_i$ and $\lambda^*[a, b] = b - a$ consequently. ∎

1.7 Construct Lebesgue Measure

Definition 1.9. Let X be a set with outer measure μ^*. A set $B \subseteq X$ is μ^***-measurable** if

$$\forall A \subseteq X, \mu^*(A) = \mu^*(A \cap B) + \mu^*(A \cap B^c) \tag{7}$$

Theorem 1.1. For any set X with outer measure μ^* on it, let $\mathcal{M}_{\mu^*}$ denote the set of all μ^*-**measurable** sets. Then, $\mathcal{M}_{\mu^*}$ is a σ-algebra and $\mu^*|_{\mathcal{M}_{\mu^*}}$ (μ^* restricted to $\mathcal{M}_{\mu^*}$) is a measure.

Proof. To show B is μ^*-measurable, it suffices to show that $\forall A \subseteq X, \mu^*(A) \geq \mu^*(A \cap B) + \mu^*(A \cap B^c)$, because the opposite inequality always holds by sub-additivity.

(1.1) Let $A \subseteq X$, $\mu^*(A \cap \varnothing) + \mu^*(A \cap \varnothing^c) = \mu^*(A \cap \varnothing^c) = \mu^*(A)$, therefore, $\varnothing \in \mathcal{M}_{\mu^*}$.

(1.2) Let $A \subseteq X$ and $B \in \mathcal{M}_{\mu^*}$, $\mu^*(A) = \mu^*(A \cap B) + \mu^*(A \cap B^c) = \mu^*(A \cap (B^c)^c) + \mu^*(A \cap B^c)$. Hence, $B^c \in \mathcal{M}_{\mu^*}$.

(1.3.1) Let $B_1, B_2 \in \mathcal{M}_{\mu^*}$, we are going to show $B_1 \cup B_2 \in \mathcal{M}_{\mu^*}$. Fix any $A \subseteq X$,

$$\begin{aligned} \mu^*(A \cap (B_1 \cup B_2)) &= \mu^*(A \cap (B_1 \cup B_2) \cap B_1) + \mu^*(A \cap (B_1 \cup B_2) \cap B_1^c) && (8) \\ &= \mu^*(A \cap B_1) + \mu^*(A \cap B_1^c \cap B_2) && (9) \end{aligned}$$

Moreover,

$$\mu^*(A \cap (B_1 \cup B_2)^c) = \mu^*(A \cap B_1^c \cap B_2^c) \tag{10}$$

Therefore,

$$\begin{aligned} \mu^*(A \cap (B_1 \cup B_2)) + \mu^*(A \cap (B_1 \cup B_2)^c) &= \mu^*(A \cap B_1) + \mu^*(A \cap B_1^c \cap B_2) + \mu^*(A \cap B_1^c \cap B_2^c) && (11) \\ &= \mu^*(A \cap B_1) + \mu^*(A \cap B_1^c) \text{ since } B_2 \in \mathcal{M}_{\mu^*} && (12) \\ &= \mu^*(A) \text{ since } B_1 \in \mathcal{M}_{\mu^*} && (13) \end{aligned}$$

Therefore, $\mathcal{M}_{\mu^*}$ is an algebra.

(1.3.2) Now show that $\mathcal{M}_{\mu^*}$ is a σ-algebra . For any sequence of sets $A_i \in \mathcal{M}_{\mu^*}$, we can define $B_n := A_n \backslash \cup_{j=1}^{i-1} A_j$ such that $\cup B_i = \cup A_i$. Therefore, it is suffices to show $\mathcal{M}_{\mu^*}$ is closed under countable disjoint unions.

We are going to show the union $\cup B_i$ is μ^*-measurable for any disjoint sequence of μ^*-measurable B_i's.

Claim: let $A \subseteq X$, $\mu^*(A) = \sum_{i=1}^n \mu^*(A \cap B_i) + \mu^*(A \cap (\cup_{i=1}^n B_i)^c)$. The claim can be proved by induction on n.

When $n = 1$, $\mu^*(A) = \mu^*(A \cap B) + \mu^*(A \cap B^c)$ because B_1 is μ^*-measurable.

Suppose the claim holds for n, then

$$\mu^*(A \cap (\cup_{i=1}^n B_i)^c) = \mu^*(A \cap (\cup_{i=1}^n B_i)^c \cap B_{n+1}) + \mu^*(A \cap (\cup_{i=1}^n B_i)^c \cap B_{n+1}^c) \tag{14}$$

because $B_{n+1} \in \mathcal{M}_{\mu^*}$. Moreover, since all B_i's are disjoint, $B_{n+1} \subseteq B_i^c$ for all i. Hence,

$$B_{n+1} \subseteq \cap_{i=1}^{n} B_i^c = (\cup_{i=1}^{n} B_i)^c \tag{15}$$

Also,

$$(\cup_{i=1}^{n} B_i)^c \cap B_{n+1}^c = \cap_{i=1}^{n+1} B_i^c \tag{16}$$

Consequently,

$$\mu^*(A \cap (\cup_{i=1}^{n} B_i)^c) = \mu^*(A \cap B_{n+1}) + \mu^*(A \cap (\cup_{i=1}^{n+1} B_i)^c) \tag{17}$$

Hence,

$$\begin{aligned}
\mu^*(A) &= \sum_{i=1}^{n} \mu^*(A \cap B_i) + \mu^*(A \cap (\cap_{i=1}^{n} B_i^c)) & (18)\\
&\geq \sum_{i=1}^{n} \mu^*(A \cap B_i) + \mu^*(A \cap (\cap_{i=1}^{\infty} B_i^c)) & (19)\\
&= \sum_{i=1}^{n} \mu^*(A \cap B_i) + \mu^*(A \cap (\cup_{i=1}^{\infty} B_i)^c) & (20)
\end{aligned}$$

Take $n \to \infty$

$$\begin{aligned}
\mu^*(A) &\geq \sum_{i=1}^{\infty} \mu^*(A \cap B_i) + \mu^*(A \cap (\cup_{i=1}^{\infty} B_i)^c) & (21)\\
&\geq \mu^*(A \cap \cup_{i=1}^{\infty} B_i) + \mu^*(A \cap (\cup_{i=1}^{\infty} B_i)^c) & (22)
\end{aligned}$$

Therefore, $\cup_{i=1}^{\infty} B_i$ is μ^*-measurable.

(2) Let $B_1, B_2, \ldots$ be a sequence of disjoint sets from $\mathcal{M}_{\mu^*}$. Using the above fact and take $A = \cup_{i=1}^{\infty} B_i$,

$$\mu^*(A) \geq \mu^*(\cup_{i=1}^{\infty} B_i) + \mu^*(\varnothing) = \mu^*(\cup_{i=1}^{\infty} B_i) \tag{23}$$

The opposite inequality holds by sub-additivity. Therefore, μ^* is a measure on $\mathcal{M}_{\mu^*}$. ∎

Definition 1.10. Let λ^* be the Lebesgue outer measure on $\mathbb{R}$, then the collection $\mathcal{M}_{\lambda^*}$ of λ^*-measurable sets is called the **Lebesgue σ-algebra** . The restriction $\lambda = \lambda^*|_{\mathcal{M}_{\lambda^*}}$, which is a measure on $\mathcal{M}_{\lambda^*}$, is called the **Lebesgue measure**. Any set in $\mathcal{M}_{\lambda^*}$ is called a **Lebesgue measurable set**.

Theorem 1.2. $\mathcal{B}(\mathbb{R}) \subseteq \mathcal{M}_{\lambda^*}$.

Proof. Note that $\{(-\infty, b] : b \in \mathbb{R}\}$ generates $\mathcal{B}(\mathbb{R})$, it suffices to show $\{(-\infty, b] : b \in \mathbb{R}\} \subseteq \mathcal{M}_{\lambda^*}$.

Let $B = (-\infty, b]$, we are going to show B is λ^*-measurable. Let $A \subseteq \mathbb{R}$ and (a_n, b_n) be a sequence of open intervals covers A. For every $n \in \mathbb{N}$,

$$\lambda^*((a_n, b_n) \cap B) + \lambda^*((a_n, b_n) \cap B^c) = \lambda^*((a_n, b_n) \cap (-\infty, b]) + \lambda^*((a_n, b_n) \cap (b, \infty)) \tag{24}$$

Three cases follow:

1. $b > b_n$: $\lambda^*((a_n, b_n) \cap B) + \lambda^*((a_n, b_n) \cap B^c) = \lambda^*((a_n, b_n)) = b_n - a_n$.
2. $b_n > b > a_n$: $\lambda^*((a_n, b_n) \cap B) + \lambda^*((a_n, b_n) \cap B^c) = \lambda^*((a_n, b]) + \lambda^*((b, b_n]) = b_n - a_n$.
3. $a_n > b$: $\lambda^*((a_n, b_n) \cap B) + \lambda^*((a_n, b_n) \cap B^c) = \lambda^*((a_n, b_n)) = b_n - a_n$.

Therefore,

$$\lambda^*((a_n, b_n) \cap B) + \lambda^*((a_n, b_n) \cap B^c) = b_n - a_n \tag{25}$$

By monotonicity and sub-additivity:

$$\begin{aligned}
\lambda^*(A \cap B) + \lambda^*(A \cap B^c) &\leq \lambda^*(\cup(a_n, b_n) \cap B) + \lambda^*(\cup(a_n, b_n) \cap B^c) && (26)\\
&\leq \sum \lambda^*((a_n, b_n) \cap B) + \lambda^*((a_n, b_n) \cap B^c) && (27)\\
&= \sum_{n=1}^{\infty} b_n - a_n && (28)
\end{aligned}$$

Take the infimum of all such covering, we can show

$$\lambda^*(A \cap B) + \lambda^*(A \cap B^c) \leq \lambda^*(A) \tag{29}$$

Therefore, B is μ^*-measurable and $\mathcal{M}_{\lambda^*}$ is a σ-algebra containing all such intervals and $\mathcal{B}(\mathbb{R}) \subseteq \mathcal{M}_{\lambda^*}$. ■

1.8 Lebesgue Measure on $\mathbb{R}^d$

Definition 1.11. Steps to construct Lebesgue measure on $\mathbb{R}^d$:

1. Define open cubes on $\mathbb{R}^d$ as a Cartesian product of open intervals: $Q := \prod_{i=1}^d (a_i, b_i)$. Define Lebesgue outer measure:

$$\lambda^*(A) := \inf \left\{ \sum_{n=1}^{\infty} \prod_{i=1}^{d} (b_{ni} - a_{ni}) : A \subseteq \bigcup_{n=1}^{\infty} Q_n \right\} \tag{30}$$

2. Show λ^* is an outer measure and $\lambda^*(Q) = \prod_{i=1}^d (b_i - a_i)$.
3. $\mathcal{M}_{\lambda^*}$ is the Lebesgue σ-algebra on $\mathbb{R}^d$. Restricting λ^* on $\mathcal{M}_{\lambda^*}$ defines the Lebesgue measure.
4. Show that any Borel set in $\mathbb{R}^d$ is Lebesgue measurable by showing that there is a generating set of $\mathcal{B}(\mathbb{R}^d)$ is in $\mathcal{M}_{\lambda^*}$.

1.9 Uniqueness of the Lebesgue Measure

The next goal is to prove the uniqueness of Lebesgue measure on $\mathcal{B}(\mathbb{R}^d)$ subject to the criterion that the measure of any interval (cube) is the volume in the usual sense (product of side lengths).

Theorem 1.3. Let λ be the Lebesgue measure on $\mathbb{R}^d$, then for any Lebesgue measurable set A,

1. $\lambda(A) = \inf\{\lambda(U) : \text{open } U \supseteq A\}$,
2. $\lambda(A) = \sup\{\lambda(K) : \text{compact } K \subseteq A\}$.

Proof. (1.1) WLOG $\lambda(A) < \infty$, by monotonicity, $\lambda(A) \leq \lambda(U)$ for any open cover, $\lambda(A) \leq \inf\{..\}$.

(1.2)Let $\varepsilon > 0$, $\exists$ a sequence of open intervals (R_i) such that

$$\lambda(A) \leq \sum_{i=1}^{\infty} \lambda(R_i) \leq \lambda(A) + \varepsilon \tag{31}$$

Let $U := \cup R_i$ open, hence $\inf\{..\} \leq \lambda(U) \leq \sum_{i=1}^{\infty} \lambda(R_i) \leq \lambda(A) + \varepsilon$. Since this ε can be arbitrarily small, we conclude $\inf\{..\} \leq \lambda(A)$.

(2.1) let A be a Lebesgue measurable set, assume A is bounded, so that $\lambda(A) < \infty$. Then there exists a compact $C \supseteq A$. $C \backslash A$ is Lebesgue measurable as well.

By conclusion of part (1), there exists a open set $U \supseteq C \backslash A$ such that

$$\lambda(C \backslash A) \leq \lambda(U) \leq \lambda(C \backslash A) + \varepsilon \tag{32}$$

Let $K = C \backslash U$, K is compact. Moreover, let $a \in K$, then $a \in C$ and $a \notin U$. Therefore, $a \notin C \backslash A$, it must be $x \in A$. Hence, $K \subseteq A$.

$$\begin{aligned}
\lambda(K) &= \lambda(C \backslash U) && (33)\\
&\geq \lambda(C) - \lambda(U) && (34)\\
&\geq \lambda(C) - (\lambda(C \backslash A) + \varepsilon) && (35)\\
&= \lambda(C) - \lambda(C) + \lambda(A) - \varepsilon && (36)\\
&= \lambda(A) - \varepsilon && (37)
\end{aligned}$$

Take $\varepsilon \to 0$ and $\lambda(A) \leq \sup\{..\}$. By monotonicity, $\lambda(A) \geq \sup\{..\}$.

(2.2) Other cases: suppose A is unbounded and $\lambda(A) > 0$. Take an arbitrary $b < \lambda(A)$. We will show that $\sup\{..\} \geq b$, this will prove that $\lambda(A) \leq \sup\{...\}$.

To show $\sup\{..\} \geq b$, it suffices to show that there exists a compact set $K \subseteq A$ such that $\lambda(K) \geq b$.

Let $\{C_j\}_{j=1}^{\infty}$ be a sequence of compact sets increasing to $\mathbb{R}^d$.

Then $A \cap C_j \uparrow A$ and $\lambda(A \cap C_1) < \infty$, which implies $\lambda(A) = \lim_{j \to \infty} \uparrow \lambda(A \cap C_j)$. Since $b < \lambda(A)$, there exists j such that $\lambda(A \cap C_j) \geq b$, where $A \cap C_j$ is compact. Hence, $b \leq \sup\{..\}$ and $\lambda(A) \leq \sup\{..\}$. $\lambda(A) \geq \sup\{..\}$ holds by monotonicity.

When $\lambda(A) = 0$, $0 \leq \lambda(K)$ for all K so that $0 \leq \sup\{..\}$. The opposite inequality holds by monotonicity. ∎

Lemma 1.1. For each $k \in \mathbb{Z}$, define **dyadic cubes** in $\mathbb{R}^d$ as set in the following form:

$$\prod_{i=1}^{d}[j_i 2^{-k}, (j_i+1)2^{-k}) \tag{38}$$

where $j_i \in \mathbb{Z}$ for every i. Let $\mathcal{D}$ denote the collection of dyadic cubes.

Then, any open set $U \subseteq \mathbb{R}^d$ can be expressed as a countable union of some members of $\mathcal{D}$.

A dyadic cube of side length 2^{-k} has a unique parent of side length 2^{-k+1} and a unique grandparent with side length 2^{-k+2}.

Proof. Given open set U, let $\mathcal{D}_U$ denote the set of all dyadic half open cubes D such that $D \subseteq U$ but the parent of U does not fully contain U.

Claim 1: $U = \bigcup_{D\in\mathcal{D}_U} D$. Obviously, $\bigcup_{D\in\mathcal{D}_U} \subseteq U$. To show the converse, take any $x \in U$, since U is open, there exists $D \in \mathcal{D}_U$ such that $x \in D \subseteq U$.

Let D_0 be the earliest ancestor of D such that $x \in D_0 \subseteq U$. Obviously, $D_0 \in \mathcal{D}_U$. Therefore, $U \subseteq \bigcup_{D\in\mathcal{D}_U} D$.

Claim 2: Two dyadic cubes can overlap if and only if one is the ancestor of the other. By construction, dyadic cubes in $\mathcal{D}_U$ are disjoint.

Claim 3: $\mathcal{D}_U$ is countable because $\mathcal{D}$ is itself countable. ∎

Proposition 1.4. Lebesgue measure is the only measure on $(\mathbb{R}^d, \mathcal{B}(\mathbb{R}^d))$ which assigns the *correct volume* to any d-dimensional intervals or even any d-dimensional dyadic cube.

Proof. Let λ denote the Lebesgue measure, let μ be another measure satisfying the desired property.

By lemma, for all open set U, $\mu(U) = \sum_{j=1}^{\infty} \mu(D_j) = \sum_{j=1}^{\infty} \lambda(D_j) = \lambda(U)$, where $\{D_j\}$ is a collection of disjoint dyadic cubes contains with union U. Therefore, $\lambda(A) = \mu(A)$ for all open Borel set A.

Let $A \in \mathcal{B}(\mathbb{R}^d)$, let open $U \supseteq A$, then $\mu(A) \leq \mu(U) = \lambda(U)$ for all U. Taking the infimum over all $U \supseteq A$, we conclude $\mu(A) \leq \lambda(A)$ for all Borel set A.

Next, take any bounded Borel set A, let V be a bounded open set containing A. Then,

$$\begin{aligned}
\mu(V) &= \mu(A) + \mu(V\backslash A) &(39)\\
&\leq \lambda(A) + \lambda(V\backslash A) &(40)\\
&= \lambda(V) &(41)
\end{aligned}$$

But we also know that $\mu(V) = \lambda(V)$ since V is open, the inequality holds as equality. Moreover, the previous conclusion implies $\mu(A) \leq \lambda(A)$ and $\mu(V\backslash A) \leq \lambda(V\backslash A)$, it must be $\mu(A) = \lambda(A)$ and $\mu(V\backslash A) = \lambda(V\backslash A)$. Therefore, $\mu(A) = \lambda(A)$ for all bounded Borel set A.

Lastly, any Borel set can be written as a a countable disjoint union of bounded Borel set, therefore, $\mu(A) = \lambda(A)$ for all Borel set A. ∎

Proposition 1.5. The Lebesgue outer measure on $\mathbb{R}^d$ is translation invariant. In particular, Lebesgue measure is translation invariant and any translation of Lebesgue measurable set is Lebesgue measurable.

Proof. $\lambda^*(A+x) = \lambda^*(A)$ follows the definition of λ^*: translate all covering intervals by $+x$ and the volumes of these intervals stay the same. Since λ is simply the restriction of λ^* on Lebesgue measurable sets, λ is translation invariant as well.

Now take Lebesgue measurable B, for all$A \subseteq \mathbb{R}^d$:

$$\lambda^*(A) = \lambda^*(A \cap B) + \lambda^*(A \cap B^c) \tag{42}$$

$$\implies \lambda^*(A - x) = \lambda^*((A - x) \cap B) + \lambda^*((A - x) \cap B^c) \tag{43}$$

Note that

$$(A - x) + x = A \tag{44}$$

$$(A - x) \cap B + x = A \cap (B + x) \tag{45}$$

$$(A - x) \cap B^c + x = A \cap (B + x)^c \tag{46}$$

By translational invariance of λ^*,

$$\lambda^*(A) = \lambda^*(A \cap (B + x)) + \lambda^*(A \cap (B + x)^c) \tag{47}$$

Therefore, $B + x$ is Lebesgue measurable as well. ∎

Theorem 1.4. Let μ be a non-zero measure on $(\mathbb{R}^d, \mathcal{B}(\mathbb{R}^d))$, which is finite on bounded Borel sets and translation invariant. Then, $\mu(A) = c\lambda(A)$ for all $A \in \mathcal{B}(\mathbb{R}^d)$, where λ is the Lebesgue measure.

Remark 1.1. Borel σ-algebra is closed under translation.

Proof. Let $c = \mu([0,1)^d) \in (0, \infty)$. Then $[0,1)^d$ is the disjoint union of 2^{dk} half-open dyadic intervals with side length 2^{-k}. All of these sub-intervals have the same μ since μ is translation invariant. Therefore, for every dyadic sub-interval with side length 2^{-k}, $\mu(D) = 2^{-dk}c$.

Let $\nu(A) = \frac{1}{c}\mu(A)$, then ν is a measure that is finite on bounded sets and agrees with λ on all half-open dyadic cubes. By the previous proposition, λ is the only measure assign correct volumes to dyadic cubes, therefore, $\nu = \lambda$. ∎

Theorem 1.5. Under the axiom of choice, there exists a non-Lebesgue subset of $\mathbb{R}$.

Proof. Todo. ∎

2 Functions

2.1 Measurable Functions

Definition 2.1. A function $f : (X, \mathcal{A}) \to (Y, \mathcal{B})$ is **measurable** if $f^{-1}(B) \in \mathcal{A}$ for all $B \in \mathcal{B}$.

In this course, we mainly consider functions with extended-$\mathbb{R}$ as codomain: $Y = [-\infty, \infty]$, denoted as $\mathbb{R}^*$.

Definition 2.2. The σ-algebra on $\mathbb{R}^*$ is defined to be the σ-algebra generated by $\mathcal{B}(\mathbb{R}) \cup \{-\infty\} \cup \{\infty\}$.

Proposition 2.1.

$$\begin{aligned} \sigma(\mathcal{B}(\mathbb{R}) \cup \{-\infty\} \cup \{\infty\}) = \mathcal{B}(\mathbb{R}) &\cup \{B \cup \{\infty\} : B \in \mathcal{B}(\mathbb{R})\} && (48) \\ &\cup \{B \cup \{-\infty\} : B \in \mathcal{B}(\mathbb{R})\} && (49) \\ &\cup \{B \cup \{-\infty, \infty\} : B \in \mathcal{B}(\mathbb{R})\} && (50) \end{aligned}$$

Proposition 2.2. Equivalently, f is measurable if for every $t \in \mathbb{R}$,

$$\{x \in X : f(x) \leq t\} \in \mathcal{A} \tag{51}$$

$$\{x \in X : f(x) < t\} \in \mathcal{A} \tag{52}$$

$$\{x \in X : f(x) \geq t\} \in \mathcal{A} \tag{53}$$

$$\{x \in X : f(x) > t\} \in \mathcal{A} \tag{54}$$

More generally, to determine the measurability of $f : (X, \mathcal{A}) \to (Y, \mathcal{B})$, we only need to check whether $f^{-1}(C) \in \mathcal{A}$ for all C in a generating collection $\mathcal{C}$ of $\mathcal{B}$. The converse holds true trivially.

Proof. Let $(X, \mathcal{A}), (Y, \mathcal{B})$ be two measurable spaces, let $\mathcal{C}$ be a collection of subsets of Y generates $\mathcal{B}$.

($\implies$) Let f be a measurable function, then for every $C \in \mathcal{C} \subseteq \mathcal{B}$. Obviously, $f^{-1}(C) \in \mathcal{A}$ by definition.

($\impliedby$) Suppose $f^{-1}(C) \in \mathcal{A}$ for all $C \in \mathcal{C}$. Define

$$\mathcal{B}_0 := \{B \in \mathcal{B} : f^{-1}(B) \in \mathcal{A}\} \supseteq \mathcal{C} \tag{55}$$

It's easy to check $\mathcal{B}_0$ is in fact a σ-algebra : $f^{-1}(\varnothing) = \varnothing \in \mathcal{A}$, $f^{-1}(B^c) = (f^{-1}(B))^c$, and $f^{-1}(\bigcup B_i) = \bigcup f^{-1}(B_i)$. Therefore, $\mathcal{B} \subseteq \mathcal{B}_0$ and all $B \in \mathcal{B}$ satisfies $f^{-1}(B) \in \mathcal{A}$. ∎

Example 2.1. $f(x) = \mathbb{1}\{x \in \mathbb{Q}\}$ is measurable.

2.2 Simple Functions

Definition 2.3. A function $f : (X, \mathcal{A}) \to (\mathbb{R}^*, \mathcal{B}(\mathbb{R}^*))$ is called **simple** if there exists finitely many disjoint sets $A_1, \ldots, A_n$ and real numbers $a_1, \ldots, a_n$ such that

$$f(x) = \begin{cases} a_i & \text{if } x \in A_i \\ 0 & \text{if } x \notin A_i \forall i \in [n] \end{cases} \tag{56}$$

Let $\mathbb{S}$ denote the set of simple functions, and $\mathbb{S}^+$ denote the set of non-negative simple functions.

Proposition 2.3. All simple functions are measurable.

Proof. For any subset of $\mathbb{R}^*$, the pre-image is either X or a union of some (potentially none) A_i's. ∎

2.3 Properties of Measurable Functions

Example 2.2. Let $f : \mathbb{R}^d \to \mathbb{R}$, then all of the following functions are measurable:

$$f(x, y) = x + y \tag{57}$$

$$f(x, y) = \max\{x, y\} \equiv x \vee y \tag{58}$$

$$f(x, y) = \min\{x, y\} \equiv x \wedge y \tag{59}$$

$$f(x, y) = x - y \tag{60}$$

$$f(x, y) = \alpha x \quad \alpha \in \mathbb{R} \tag{61}$$

Proposition 2.4 (Component-wise Measurable Functions)**.** Let $f, g : (X, \mathcal{A}) \to (\mathbb{R}^*, \mathcal{B}(\mathbb{R}^*))$ be measurable, let $h(x) = (f(x), g(x)) \in \mathbb{R}^{*2}$, then f is measurable.

Proof.

$$h^{-1}([-\infty, t] \times [-\infty, s]) = f^{-1}([-\infty, t]) \cap g^{-1}([-\infty, s]) \in \mathcal{A} \tag{62}$$

And, $\mathcal{B}(\mathbb{R}^*)$ can be generated by sets with forms $[-\infty, t] \times [-\infty, s]$. ∎

Proposition 2.5 (Composite of Measurable Functions)**.** Let $(X, \mathcal{A}), (Y, \mathcal{B}), (Z, \mathcal{C})$ be measurable spaces, let $f : X \to Y$ and $g : Y \to Z$ be measurable functions. Then, the composite $g \circ f : X \to Z$ is measurable.

Corollary 2.1. Let $f, g : X \to \mathbb{R}$ be measurable functions, then $f + g$, $f - g$, $\max\{f, g\}$, and $\min\{f, g\}$ are all measurable.

Proof. $f+g$ and $f-g$ can be written as the composition of $h_1(x) = (f(x), g(x))$ and $h_2(x, y) = x \pm y$, which are all measurable.

$f \vee g$ and $f \wedge g$ are measurable as special cases of next proposition. ∎

Proposition 2.6. Let $f_1, f_2, \ldots$ be a sequence of measurable maps from $(X, \mathcal{A}) \to (\mathbb{R}^*, \mathcal{B}(\mathbb{R}^*))$, then $\sup_n f_n$ and $\inf_n f_n$ are measurable.

Proof. Note $\{x \in X : \sup_n f_n \leq t\} = \bigcup_{n=1}^{\infty} \{x \in X : f_n \leq t\} \in \mathcal{A}$ for every t, therefore the supremum is measurable. ∎

Corollary 2.2. $\limsup f_n$ and $\liminf f_n$ are measurable.

Proof. Let $g_k = \sup_{n \geq k} f_n$, g_k is measurable. $\limsup f_n = \inf_k g_k$ is measurable as well. Similar proof for the measurability of $\liminf f_n$. ∎

Proposition 2.7. Let f and g be $\mathbb{R}^*$-valued measurable functions. Then sets

$$\{x \in A : f(x) < g(x)\}, \{x \in A : f(x) \leq g(x)\} \tag{63}$$

are measurable.

Proof.

$$\{x \in A : f(x) < g(x)\} = \bigcup_{r \in \mathbb{Q}} (\{x \in A : f(x) < r\} \cap \{x \in A : r < g(x)\}) \tag{64}$$

■

Corollary 2.3. Let $u, v : X \to \mathbb{R}^*$ be a measurable functions, then $\{x \in X : u(x) = v(x)\}$ is measurable.

Proof. Note that $\{x \in X : u(x) = v(x)\} = \{x \in X : u(x) \leq v(x)\} \cap \{x \in X : u(x) \geq v(x)\}$. ■

Corollary 2.4. Let $\{f_n\}$ be a sequence of measurable functions from $(X, \mathcal{A}) \to (\mathbb{R}^*, \mathcal{B}(\mathbb{R}^*))$. Then,

$$\{x \in X : \lim_{n \to \infty} f_n(x) \text{ exists}\} \tag{65}$$

is measurable.

Proof. Note that $\{x \in X : \lim_{n \to \infty} f_n(x) \text{ exists}\} = \{x \in X : \liminf f_n(x) = \limsup f_n(x)\}$, the result follows from previous lemma. ■

Corollary 2.5. If $\{f_n\}$ is a sequence of measurable functions such that $\lim f_n(x)$ exists for all $x \in X$, then $\lim f_n$ is a measurable function on $(X, \mathcal{A})$.

Proof. In this case, $\{x \in X : \lim_{n \to \infty} f_n(x) \text{ exists}\} = X$, and $\lim f_n = \liminf f_n$ on X. ■

Corollary 2.6. If $\{f_n\}$ is a sequence of measurable function from X to $[0, \infty]$, then $\sum_{n=1}^{\infty} f_n$ is measurable.

Proof. Follows the previous corollary directly: define $g_k = \sum_{n=1}^{k} f_n$ and $\lim_{k \to \infty} g_k = \sum_{n=1}^{\infty} f_n$. ■

3 Integrals

3.1 Integrating Simple Functions

Definition 3.1. Let $f \in \mathbb{S}^+$ with representation $\{(A_i, a_i)\}_{i=1}^{n}$. WLOG, $\bigcup_{i=1}^{n} A_i = X$. Then, define

$$\int_X f \; d\mu := \sum_{i=1}^{n} a_i \mu(A_i) \tag{66}$$

Proposition 3.1. The notion of integral on simple functions is well defined. Specifically, let $\{(A_i, a_i)\}_{i=1}^{n}$ and $\{(B_j, b_j)\}_{j=1}^{m}$ be any two representations of f, $\sum_{i=1}^{n} a_i \mu(A_i) = \sum_{j=1}^{m} b_j \mu(B_j)$.

Proof. First note that $\{A_i \cap B_j\}_{i,j}$ are disjoint sets with union X. Moreover, for any i, j, if $A_i \cap B_j \neq \varnothing$, take some $x \in A_i \cap B_j$, $f(x) = a_i = b_j$. Therefore, $a_i\mu(A_i \cap B_j) = b_i\mu(A_i \cap B_j)$ since either $a_i = b_j$ or $\mu(A_i \cap B_j) = \mu(\varnothing) = 0$.

$$\begin{aligned} \sum_{i=1}^{n} a_i\mu(A_i) &= \sum_{i=1}^{n} a_i \sum_{j=1}^{m} \mu(A_i \cap B_j) && (67) \\ &= \sum_{j=1}^{m} b_j \sum_{i=1}^{n} \mu(A_i \cap B_j) && (68) \\ &= \sum_{j=1}^{m} b_j\mu(B_j) && (69) \end{aligned}$$

■

3.2 Integrating Measurable Functions

Definition 3.2. For a non-negative measurable function $f : X \to [0, \infty]$, define its Lebesgue integral as

$$\int f\ d\mu = \sup\left\{\int g\ d\mu : g \text{ is a non-negative simple function such that } g \leq f\right\} \tag{70}$$

For any measurable $f : X \to [-\infty, \infty]$, let

$$f^+(x) = \max\{f(x), 0\} \tag{71}$$

$$f^-(x) = -\min\{f(x), 0\} \tag{72}$$

So that $f = f^+ - f^-$, and f is measurable if and only if both f^+ and f^- are measurable.

If at least one of $\int f^+\ d\mu$, $\int f^-\ d\mu$ is finite, the integral of f exists (well-defined) and is defined as

$$\int f\ d\mu = \int f^+\ d\mu - \int f^-\ d\mu \tag{73}$$

If both $\int f^+\ d\mu$ and $\int f^-\ d\mu$ are finite, f is said to be **integrable**.

3.3 Properties of Integral of Non-negative Simple Functions

Proposition 3.2 (Linearity)**.** If f, g are non-negative simple functions, then

$$\int f + g\ d\mu = \int f\ d\mu + \int g\ d\mu \tag{74}$$

Moreover, for any $\alpha \geq 0$,

$$\int \alpha f\ d\mu = \alpha \int f\ d\mu \tag{75}$$

Proof. Let f and g be simple functions represented by $\{(A_i, a_i)\}_{i=1}^n$ and $\{(B_j, b_j)\}_{j=1}^m$. WLOG, $\cup A_i = \cup B_j = X$. Then $f+g$ is a simple function with representation $\{(A_i \cap B_j, a_i + b_j)\}_{i,j}$, where $\cup_{i,j} A_i \cap B_j = X$. ■

Proposition 3.3. Let f, g be non-negative simple functions with $f \geq g$ everywhere. Then $\int f \, d\mu \geq \int g \, d\mu$.

Proof. Let f and g be simple functions represented by $\{(A_i, a_i)\}_{i=1}^n$ and $\{(B_j, b_j)\}_{j=1}^m$.

Claim: $a_i \mu(A_i \cap B_j) \geq b_j \mu(A_i \cap B_j)$ for every (i,j). If $A_i \cap B_j \neq \varnothing$, then taking some $x \in A_i \cap B_j$ implies $a_i \geq b_j$. If $A_i \cap B_j = \varnothing$, the equality holds trivially.

Note that $\int f$ and $\int g$ can be written as $\sum_{i,j} a_i \mu(A_i \cap B_j)$ and $\sum_{i,j} b_j \mu(A_i \cap B_j)$ respectively, therefore $\int f \geq \int g$ by the previous claim. ■

Proposition 3.4 (Approximation using Simple Functions)**.** Let $f : X \to [0, \infty]$ be a measurable function. Then there exists an increasing sequence of non-negative simple functions f_n such that $f_n \leq f_{n+1}$ and

$$\lim_{n\to\infty} f_n(x) = f(x) \tag{76}$$

for all x.

Proof. For each n and $1 \leq k \leq n2^n$, let

$$A_{n,k} = \left\{ x \in X : \frac{k-1}{2^n} \leq f(x) < \frac{k}{2^n} \right\} \tag{77}$$

Define

$$f_n(x) = \begin{cases} \frac{k-1}{2^n} & \text{if } x \in A_{n,k} \\ n & \text{otherwise} \end{cases} \tag{78}$$

That is, for a $x \in X$, if $\frac{k-1}{2^n} \leq f(x) < \frac{k}{2^n}$ for some k, we take $f_n(x) = \frac{k-1}{2^n}$; if $f(x) \geq n$, we define $f_n(x) = n$. Clearly, each f_n is a simple function.

Claim 1: $f_n \leq f_{n+1}$. Easy to verify.

Claim 2: $\lim_{n\to\infty} f_n(x) = f(x)$. Let $x \in X$, (i) if $f(x) = \infty$, then $f_n(x) = n$ for all $n \in \mathbb{N}$ and $\lim_{n\to\infty} f_n(x) = \infty = f(x)$.

(ii) if $f(x) < \infty$, then $\exists n_0$ such that $f(x) < n_0$. For every $n \geq n_0$, $x \in A_{n,k}$ for some k such that $f_n(x) = \frac{k-1}{2^n}$ and $\frac{k-1}{2^n} \leq f(x) < \frac{k}{2^n}$. Therefore, for all $n \geq n_0$, $|f_n(x) - f(x)| < \frac{1}{2^n}$, which implies $\lim_{n\to\infty} f_n(x) = f(x)$. ■

Proposition 3.5 (Monotone Convergence 1: $\mathbb{S}_+ \uparrow \mathbb{S}_+$)**.** Let f_n be a sequence of non-negative simple functions that increase to another non-negative simple function f at each point, then

$$\int f \, d\mu = \lim_{n\to\infty} \int f_n \, d\mu \tag{79}$$

Proof. By monotonicity, $f_n \le f$ for all n and $\int f \, d\mu \ge \lim \int f_n \, d\mu$.

Fix $0 < \varepsilon < 1$ and define $g = (1-\varepsilon)f$. Suppose f is represented by (A_i, a_i). Then for every n, i, define

$$A_{n,i} = \{x \in A_i : f_n(x) \ge (1-\varepsilon)a_i\} \tag{80}$$

Define

$$g_n(x) = \begin{cases} (1-\varepsilon)a_i & \text{if } x \in A_{n_i} \\ 0 & \text{otherwise} \end{cases} \tag{81}$$

In order to show $\int f \, d\mu \le \lim \int f_n \, d\mu$, we are constructing this g_n satisfying

$$(1-\varepsilon)\int f \, d\mu \le \lim \int g_n \, d\mu \le \lim \int f_n \, d\mu \le \int f \, d\mu \tag{82}$$

where the last equality has been shown above. The equality can then be shown by taking $\varepsilon \to 0$ and using Squeeze theorem. Note that $(1-\varepsilon)\int f \, d\mu \not\le \int g_n \, d\mu$, only the limit does.

By construction, $g_n \le f_n$ and $\int g_n \, d\mu \le \int f_n \, d\mu$ as a result.

$$\begin{aligned}
\lim_n \int f_n \, d\mu &\ge \lim_n g_n \, d\mu &(83)\\
&= \lim_n \sum_{i=1}^{K} (1-\varepsilon)a_i \mu(A_{n,i}) &(84)\\
&= \sum_{i=1}^{K} (1-\varepsilon)a_i \lim_n \mu(A_{n,i}) &(85)\\
&= \sum_{i=1}^{K} (1-\varepsilon)a_i \mu(A_i) \text{ Since for all } i,\ A_{n,i} \uparrow A_i \text{ as } n \to \infty. &(86)\\
&= (1-\varepsilon)\int f \, d\mu &(87)
\end{aligned}$$

Taking $\varepsilon \to 0$ completes the proof. ■

Proposition 3.6 (Monotone Convergence 2: $\mathbb{S}_+ \uparrow$ Measurable)**.** Let $f : X \to [0, \infty]$ be a measurable function. Let f_n be a sequence of non-negative simple functions such that $f_n \uparrow f$ point-wise. Then

$$\int f \, d\mu = \lim_{n\to\infty} \int f_n \, d\mu \tag{88}$$

Proof. The proof follows the previous proposition and the definition of $\int f \, d\mu$. Since $f_n \uparrow f$, $f_n \le f$ and $\int f_n \le \int f$ for all n. $\int f_n$ is a bounded monotone sequence, therefore $\lim \int f_n$ exists and $\le \int f$.

To show the other equality, it suffices to prove $\lim \int f_n \ge \int g$ for any non-negative simple functions $g \le f$.

Define $g_n = \min\{g, f_n\}$, easy to show that $g_n(x) \leq g_{n+1}(x)$.

$$\lim_{n\to\infty} g_n(x) = \lim_{n\to\infty} \min\{g, f_n\} \tag{89}$$
$$= \min\{g(x), f(x)\} \tag{90}$$
$$= g(x) \tag{91}$$

since $f_n \uparrow f$ and $g \leq f$.

By the previous proposition, $\int g\ d\mu = \lim \int g_n\ d\mu$ since g_n and g are non-negative simple functions. Since $g_n \leq f_n$ everywhere, so $\int g_n\ d\mu \leq \int f_n\ d\mu$. Taking limit on both sides implies $\int g \leq \lim \int f_n$. ∎

Proposition 3.7 (Vector Space Properties for Non-negative Integrable Functions)**.** Let $f, g : X \in [0, \infty]$ be integrable (of course, measurable as well) functions and $\alpha \geq 0$. Then

1. $\int f + g\ d\mu = \int f\ d\mu + \int g\ d\mu$.
2. $\int \alpha f\ d\mu = \alpha \int f\ d\mu$.
3. If $f \geq g$ everywhere, then $\int f\ d\mu \geq \int g\ d\mu$.

Proof. We know that there exists sequences of non-negative simple functions f_n and g_n such that $f_n \uparrow f$ and $g_n \uparrow g$. Note that $f_n + g_n$ is a sequence of simple functions increases to $f + g$. Therefore,

$$\int (f+g) d\mu = \lim_{n\to\infty} \int (f_n + g_n)\ d\mu \tag{92}$$
$$= \lim_{n\to\infty} \left(\int f_n\ d\mu + \int g_n\ d\mu \right) \tag{93}$$
$$= \lim_{n\to\infty} \int f_n\ d\mu + \lim_{n\to\infty} \int g_n\ d\mu \tag{94}$$
$$= \int f\ d\mu + \int g\ d\mu \tag{95}$$

Similarly, taking $\alpha f_n \uparrow \alpha f$ leads to the second result.

Finally, if $f \geq g$ everywhere, then

$$\{h \in \mathbb{S}_+ \text{ and } h \leq g\} \subseteq \{h \in \mathbb{S}_+ \text{ and } h \leq f\} \tag{96}$$

Therefore, the supremum of integrals of functions from a larger collection is larger. ∎

3.4 Linearity of Lebesgue Integral for Arbitrary Integrable Functions

Theorem 3.1 (Vector Space Property of Integral Functions)**.** Let $(X, \mathcal{A}, \mu)$ be a measure space, let $f, g : X \to \mathbb{R}^*$ be integrable functions, let $\alpha \in \mathbb{R}$. Then, $f+g$ and αf are integrable, and

$$\int f + g d\mu = \int f d\mu + \int g d\mu \tag{97}$$

$$\int \alpha f d\mu = \alpha \int f d\mu \tag{98}$$

Proof. It's easy to check that $(f+g)^+ \leq f^+ + g^+$ and $(f+g)^- \leq f^- + g^-$. By monotonicity, $\int (f+g)^+ d\mu, \int (f+g)^- d\mu < \infty$. Therefore, $f+g$ is integrable.

Moreover, $f + g = f^+ - f^- + g^+ - g^- \iff f + g + f^- + g^- = f^+ + g^+$. We can apply the linearity of non-negative integrable functions to derive the result.

When $\alpha \geq 0$, $(\alpha f)^+ = \alpha f^+$ and $(\alpha f)^- = \alpha f^-$. The proof for cases with $\alpha < 0$ is similar. ∎

Corollary 3.1. Let f, g be integrable functions such that $f \geq g$, then $\int f \ d\mu \geq \int g \ d\mu$.

Proof. Let $h = f - g = f + (-1)g \geq 0$, which is integrable by the previous theorem. And $\int h \ d\mu \geq 0$ since its the supremum of integrals for simple functions less than h, which includes the zero function (has zero integral). ∎

Lemma 3.1. A function f is integrable if and only if $|f|$ is integrable.

Proof. Note that $|f| = f^+ + f^-$, and $\int f^+ + f^- \ d\mu < \infty$ by the integrability of f. Therefore, $|f|$ is integrable.

Moreover, $|f|^+ = f^+ + f^-$, therefore, the integrability of $|f|$ implies both $\int f^+ \ d\mu$ and $\int f^- \ d\mu$ are finite. ∎

Proposition 3.8. All integrable function f satisfies the triangle inequality

$$\left| \int f \ d\mu \right| \leq \int |f| \ d\mu \tag{99}$$

Proof.

$$\begin{aligned}
\left| \int f \ d\mu \right| &= \left| \int f^+ - f^- \ d\mu \right| && (100) \\
&= \left| \int f^+ \ d\mu - \int f^- \ d\mu \right| && (101) \\
&\leq \left| \int f^+ \ d\mu \right| + \left| \int f^- \ d\mu \right| && (102) \\
&= \int f^+ \ d\mu + \int f^- \ d\mu && (103) \\
&= \int |f| \ d\mu && (104)
\end{aligned}$$

∎

4 Limit Theorems (i.e., when we can exchange limits and integrals)

Theorem 4.1 (Monotone Convergence Theorem)**.** Let $(X, \mathcal{A}, \mu)$ be a measure space, let $f_n : X \to [0, \infty]$ be a non-decreasing sequence of measurable functions converge to f. Then,

$$\int f \, d\mu = \lim_{n\to\infty} \int f_n \, d\mu \tag{105}$$

Proof. f measurable since $f = \lim_n f_n = \liminf_n f_n$. Moreover, $\int f_n \, d\mu$ is a non-decreasing sequence to the limit $\int f \, d\mu$, therefore $\int f \, d\mu \geq \lim_n \int f_n \, d\mu$.

For each $n \in \mathbb{N}$, there exists a non-decreasing sequence of non-negative simple functions $g_{n,k}$ converges to f_n. Define

$$h_n = \max\{g_{1,n}, g_{2,n}, \ldots, g_{n,n}\} \tag{106}$$

Note that h_n is a non-decreasing sequence since

$$\begin{aligned} h_{n+1} &= \max\{g_{1,n+1}, g_{2,n+1}, \ldots, g_{n+1,n+1}\} && (107)\\ &\geq \max\{g_{1,n+1}, g_{2,n+1}, \ldots, g_{n,n+1}\} && (108)\\ &\geq \max\{g_{1,n}, g_{2,n}, \ldots, g_{n,n}\} = h_n && (109)\end{aligned}$$

Moreover, for any $m \in \mathbb{N}$, for any $n \geq m$,

$$h_n(x) = \max\{g_{1,n}, g_{2,n}, \ldots, g_{n,n}\} \geq g_{m,n} \tag{110}$$

Therefore, by taking the limit $n \to \infty$,

$$\lim_{n\to\infty} h_n(x) \geq \lim_{n\to\infty} g_{m,n} = f_m \tag{111}$$

Taking limit $m \to \infty$ on both sides

$$\begin{aligned} \lim_n h_n(x) = \lim_m \lim_n h_n(x) &\geq \lim_m f_m = f && (112)\\ \implies \int \lim_n h_n(x) \, d\mu &\geq \int f \, d\mu && (113)\end{aligned}$$

Note that, by construction,

$$h_n = \max\{g_{1,n}, g_{2,n}, \ldots, g_{n,n}\} \leq \max\{f_1, \ldots, f_n\} = f_n \tag{114}$$

Therefore,

$$\int \lim_{n\to\infty} f_n(x) \, d\mu \geq \int f \, d\mu \tag{115}$$

■

Corollary 4.1. Let (f_n) be a sequence (not necessarily increasing) non-negative measurable functions, then

$$\int \sum_{n=1}^{\infty} f_n \ d\mu = \sum_{n=1}^{\infty} \int f_n \ d\mu \tag{116}$$

Theorem 4.2 (Fatou's Lemma)**.** Let f_n be a sequence of non-negative measurable functions, then

$$\int \liminf_{n\to\infty} f_n \ d\mu \leq \liminf_{n\to\infty} \int f_n \ d\mu \tag{117}$$

Proof. Define $g_n = \inf_{k\geq n} f_k$, then g_n is an increasing sequence of non-negative functions. By construction, $\int g_n \ d\mu \leq \inf_{k\geq n} \int f_k \ d\mu$. By MCT,

$$\int \liminf_{n\to\infty} f_n \ d\mu = \int \lim_{n\to\infty} g_n \ d\mu \tag{118}$$

$$= \lim_{n\to\infty} \int g_n \ d\mu \tag{119}$$

$$\leq \lim_{n\to\infty} \inf_{k\geq n} \int f_k \ d\mu \tag{120}$$

$$= \liminf_{n\to\infty} \int f_n \ d\mu \tag{121}$$

■

Theorem 4.3 (Lebesgue's Dominated Convergence Theorem)**.** Let $(X, \mathcal{A}, \mu)$ be a measure space, let f and f_n be $\mathbb{R}^*$-valued measurable functions on X such that $f_n \to f$ point-wise. If there exists a non-negative integrable function g such that $|f_n| \leq g$ for all n, then, all f and f_n are integrable, moreover,

$$\int f \ d\mu = \lim_{n\to\infty} \int f_n \ d\mu \tag{122}$$

Proof. Since $|f_n| \leq g$, all f_n are integrable. The limit f also satisfies $|f| \leq g$ and is integrable.

For now, assume f_n are $\mathbb{R}$-valued instead of $\mathbb{R}^*$-valued.

Note that $f + g = \lim_{n\to\infty} f_n + g$ is non-negative (because of the dominance) and integrable, by Fatou's lemma

$$\int f + g \ d\mu = \int \liminf f + g \ d\mu \leq \liminf \int f_n + g \ d\mu \tag{123}$$

$$= \liminf \int f_n \ d\mu + \int g \ d\mu \tag{124}$$

$$\implies \int f \ d\mu \leq \liminf \int f_n \ d\mu \tag{125}$$

Similarly, $g - f = \lim_{n\to\infty} g - f_n$ is non-negative and integrable as well, by Fatou's lemma

$$\int g - f \ d\mu = \int \liminf g - f_n \ d\mu \leq \liminf \int g - f_n \ d\mu \tag{126}$$

$$\implies - \int f \ d\mu \leq - \liminf \int f_n \ d\mu \tag{127}$$

$$\implies \int f \ d\mu \geq \limsup \int f_n \ d\mu \tag{128}$$

Also, $\liminf \int f_n \ d\mu \leq \limsup \int f_n \ d\mu$, therefore,

$$\liminf \int f_n \ d\mu \geq \int f \ d\mu \geq \limsup \int f_n \ d\mu \geq \liminf \int f_n \ d\mu \tag{129}$$

$$\implies \int f \ d\mu = \lim \int f_n \ d\mu \tag{130}$$

■

Proposition 4.1 (A Stronger Result)**.** Given assumptions of the dominated convergence theorem, f_n L^1-converges to f.

$$\lim_{n\to\infty} \int |f_n - f| \ d\mu = 0 \tag{131}$$

Proof. Note that $|f_n - f| \to 0$ point-wise, and $|f_n - f| \leq 2g$. The dominated convergence theorem suggests $\lim_{n\to\infty} \int |f_n - f| \ d\mu = \int 0 \ d\mu = 0$. ■

4.1 The Notion of Almost Everywhere

Definition 4.1. Let $(X, \mathcal{A}, \mu)$ be a measure space, a set $N \subseteq X$ (not necessarily measurable) is called "**negligible** w.r.t. μ" if $N \subseteq A$ for some $A \in \mathcal{A}$ with $\mu(A) = 0$.

A property is said to hold **almost everywhere** w.r.t. μ (denoted as μ-a.e.) if the set on which this property fails is negligible.

Proposition 4.2. Let $f : X \to [0, \infty]$ be an integrable function, then f is finite μ-a.e.

Proof. Let $A := f^{-1}(\infty)$, define $h_n(x) := n\mathbb{1}\{x \in A\}$. Clearly, h_n is a simple function $\leq f$ for every n, by monotonicity, $\int f \ d\mu \leq \int h_n \ d\mu = n\mu(A)$. Taking $n \to \infty$ leads to a contradiction. ■

Corollary 4.2. If $f : X \to \mathbb{R}^*$ is integrable w.r.t. μ, then $|f| < \infty$ μ-a.e.

Proof. f is integrable implies $\int f^+ \ d\mu, \int f^- \ d\mu < \infty$. Then, by the previous proposition, $f^+ < \infty$ except for a negligible set A, and $f^- < \infty$ expect for a negligible set B. Therefore, $|f| = \infty$ on set $A \cup B$, which is negligible as well. ■

Proposition 4.3. Let $f : X \to [0, \infty]$ be measurable, then

$$\int f \ d\mu = 0 \iff f = 0 \ \mu - a.e. \tag{132}$$

Proof. ($\Longrightarrow$) Suppose $f = 0$ a.e., for every simple function $g \leq f$, let (a_i, A_i) be the representation of g, then $\int g \, d\mu = 0$ by definition. Suppose $a_i > 0$ for some A_i, then $f(x) \geq a_i > 0$ for all $x \in A_i$, since $f = 0$ a.e., $\mu(A_i) = 0$. Therefore, $\int g \, d\mu = 0$, so is the integral of f.

($\Longleftarrow$), suppose $\int f \, d\mu = 0$, note that

$$\{x : f(x) > 0\} = \bigcup_{n=1}^{\infty} \{x : f(x) > 1/n\} \tag{133}$$

Define $A_n = \{x : f(x) > 1/n\}$, then A_n is an increasing sequence of sets, therefore, suppose there exists some A_n with $\mu(A_n) > 0$, define $g(x) = \frac{1}{n}\mathbb{1}\{x \in A_n\}$. $f \geq g$ by construction, so that $\int f \, d\mu \geq \int g \, d\mu = \frac{1}{n}\mu(A_n) > 0$. This leads to a contradiction, so all $\mu(A_n) = 0$, and $\mu(\{x : f(x) > 0\}) = \lim_n \mu(A_n) = 0$. ∎

Corollary 4.3. Let $f : X \to \mathbb{R}^*$ be a measurable function,

$$f = 0 \ \mu - a.e. \implies \int f \, d\mu = 0 \tag{134}$$

Proof. $f = 0$ a.e. implies $f^+, f^- = 0$ a.e., apply the previous proposition, $\int f^+ \, d\mu = \int f^- \, d\mu = 0$, so is $\int f \, d\mu$.

Note the converse is not true, it is possible that $f^+ \, d\mu = \int f^- \, d\mu \neq 0$ such that $\int f \, d\mu = 0$. ∎

Corollary 4.4. Let $f, g : X \to \mathbb{R}^*$ be integrable functions, then

$$f = 0 \ \mu - a.e. \implies \int f \, d\mu = \int g \, d\mu \tag{135}$$

Proof. Let $\tilde{f} = f(x)\mathbb{1}\{x \in \mathbb{R}\}$ and $\tilde{g} = g(x)\mathbb{1}\{x \in \mathbb{R}\}$, we are doing this to avoid subtracting infinity from infinity. $|\tilde{f}|$ and $|\tilde{g}|$ are bounded by $|f|$ and $|g|$ and are integrable. Moreover, $f = \tilde{f} = g = \tilde{g}$ a.e. by construction. Lastly, since $|\tilde{f}|, |\tilde{g}| < \infty$, we can write

$$\int \tilde{f} - \tilde{g} \, d\mu = \int \tilde{f} \, d\mu - \int \tilde{g} \, d\mu = 0 \tag{136}$$

$$\implies \int f \, d\mu = \int \tilde{f} \, d\mu = \int g \, d\mu = \int \tilde{g} \, d\mu \tag{137}$$

∎

Proposition 4.4. Monotone convergence theorem and dominated convergence theorem holds even if $f_n \to f$ a.e. In DCT, we can also have $|f_n| \leq g$ a.e.

Proof for MCT. Suppose $f_n \geq 0$ a.e.

$$A = \{x : f_n(x) \geq 0 \ \forall n \wedge \lim_{n\to\infty} f_n(x) = f(x)\} \tag{138}$$

Therefore, $A^c = \bigcup_n \{x : f_n(x) < 0\} \cup \{x : \lim_{n\to\infty} f_n(x) \neq f(x)\}$, which is a countable union of measure zero sets, hence $\mu(A^c) = 0$.

Define $\tilde{f}_n = \mathbb{1}_A f_n$ and $\tilde{f} = \mathbb{1}_A f$, apply the original version of MCT on $\tilde{f}_n$ and f, then exert the fact that $\int \tilde{f}_n \; d\mu = \int f_n \; d\mu$ and $\int \tilde{f} \; d\mu = \int f \; d\mu$. ■

5 Integral of Complex-Valued Functions

Definition 5.1. A function $f : X \to \mathbb{C}$ is called **measurable** if both $\Re(f)$ and $\Im(f)$ (both are real-valued functions) are measurable. Similarly, f is **integrable** if both its real and imaginary parts are integrable.

Define

$$\int f \; d\mu = \int \Re(f) \; d\mu + i \int \Im(f) \; d\mu \tag{139}$$

Proposition 5.1. Let f, g be integrable complex-valued functions, then

1. $\int (f+g) \; d\mu = \int f \; d\mu + \int g \; d\mu$.
2. for all $\alpha \in \mathbb{C}$, $\int (\alpha f) \; d\mu = \alpha \int f \; d\mu$.

Proposition 5.2 (Triangle Inequality)**.** Let $f : X \to \mathbb{C}$ be an integrable function, then

$$\left| \int f \; d\mu \right| \leq \int |f| \; d\mu \tag{140}$$

Proof. Note that there exists $\alpha \in \mathbb{C}$ with $|\alpha| = 1$ such that

$$\left| \int f \; d\mu \right| = \alpha \int f \; d\mu \tag{141}$$

To see this point, let $z = re^{i\theta} \in \mathbb{C}$ so that $|z| = r$, let $\alpha = e^{-i\theta}$, which satisfies $\alpha z = r = |z|$.

Therefore,

$$\left| \int f \; d\mu \right| = \alpha \int f \; d\mu \tag{142}$$

$$= \int (\alpha f) \; d\mu \tag{143}$$

$$= \int \Re(\alpha f) \; d\mu + i \int \Im(\alpha f) \; d\mu \tag{144}$$

$$\implies \int \Im(\alpha f) \; d\mu = 0 \tag{145}$$

Therefore,

$$\left| \int f \; d\mu \right| = \int \Re(\alpha f) \; d\mu \leq \int |\alpha f| \; d\mu = \int |f| \; d\mu \tag{146}$$

where the last step holds because $|\alpha| = 1$. ■

6 Convergence of Measurable Functions

Definition 6.1. Let $(X, \mathcal{A}, \mu)$ be a measure space, let $\{f_n\}_n$ be a sequence of real-valued measurable functions on X, let $f : X \to \mathbb{R}$ be a measurable function.

Then $f_n \to f$ **in measure** if for every $\varepsilon > 0$,

$$\lim_{n\to\infty} \mu(\{x : |f_n(x) - f(x)| > \varepsilon\}) = 0 \tag{147}$$

Remark 6.1. Convergence almost everywhere does not imply convergence in measure.

Counter-example. ∎

Remark 6.2. Convergence in measure does not imply convergence almost everywhere (even if we are considering a finite measure).

Counter-example. ∎

Proposition 6.1. Let μ be a finite measure, then convergence a.e. implies convergence in measure.

Proof. Suppose $f \to f_n$ a.e. Let $\varepsilon > 0$. Note that if there exists x such that $|f_n - f(x)| \geq \varepsilon$ for infinitely many n, then $f_n \not\to f$ at x. Therefore,

$$\mu(\{x : |f_n(x) - f(x)| > \varepsilon \text{ for infinitely many } n\}) \leq \mu(\{x : f_n(x) \not\to f(x)\}) = 0 \tag{148}$$

Further, note that

$$\{x : |f_n(x) - f(x)| > \varepsilon \text{ for infinitely many } n\} = \bigcap_{n=1}^{\infty} \underbrace{\bigcup_{k=n}^{\infty} \{x : |f_k(x) - f(x)| > \varepsilon\}}_{B_n} \tag{149}$$

Where $x \in B_n$ indicates there exists a $k \geq n$ such that $|f_k(x) - f(x)| > \varepsilon$. If we take the intersection of all B_n, it means for all $n \in \mathbb{N}$, there exists $k \geq n$ such that $|f_k(x) - f(x)| > \varepsilon$, which is equivalent to saying there are infinitely many k such that $|f_k(x) - f(x)| > \varepsilon$.

Clearly $B_1 \supseteq B_2 \supseteq \dots$, there must exist some B_i such that $\mu(B_i)$ since μ is a finite measure.

Therefore,

$$0 = \mu(\{x : |f_n(x) - f(x)| > \varepsilon \text{ for infinitely many } n\}) = \lim_{n\to\infty} \mu(B_n) \tag{150}$$

Hence, $\lim_{n\to\infty} \mu(B_n) = 0$. However, $B_n \supseteq \{x : |f_n(x) - f(x)| > \varepsilon\}$, therefore,

$$\lim_{n\to\infty} \{x : |f_n(x) - f(x)| > \varepsilon\} = 0 \tag{151}$$

∎

Proposition 6.2. Let f_n be a sequence of measurable real-valued functions converge to a measurable f in measure, then there exists a subsequence of f_n converges to f a.e.

Proof. Suppose $f_n \to f$ in measure, take $\varepsilon = 1$, there exists infinitely many n_1 such that

$$\mu(\{x : |f_{n_1} - f(x)| > 1\}) < 2^{-1} \tag{152}$$

Then for every k, we can choose $n_k > n_{k-1}$ such that

$$\mu(\underbrace{\{x : |f_{n_k} - f(x)| > \frac{1}{k}\}}_{A_k}) < 2^{-k} \tag{153}$$

Let $B = \bigcap_{j=1}^{\infty} \bigcup_{k=j}^{\infty} A_k$, define $B_j = \bigcup_{k=j}^{\infty} A_k$. Note that for all j, $B \subseteq B_j$, therefore,

$$\mu(B) \leq \mu(B_j) = \mu(\bigcup_{k=j}^{\infty} A_k) \leq \sum_{k=j}^{\infty} \mu(A_k) < \sum_{k=j}^{\infty} 2^{-j+1} \tag{154}$$

Take $j \to \infty$, $\mu(B) = 0$. If $x \notin B$, $x \in B^c = \bigcup_{j=1}^{\infty} \bigcap_{k=j}^{\infty} A_k^c$, which means $\exists j$ such that $x \in A_k^c$ for all $k \geq j$. That is

$$\exists j \ s.t. \ \forall k \geq j \ \ |f_{n_k} - f(x)| \leq \frac{1}{k} \tag{155}$$

Therefore, this subsequence n_k converges t o $f(x)$ a.e. ■

Lemma 6.1 (Borel-Cantelli Lemma)**.** If $A_1, A_2, \cdots$, is a sequence of measurable sets such that

$$\sum_{k=1}^{\infty} \mu(A_k) < \infty \tag{156}$$

then

$$\mu(\{x : x \in \text{ infinitely many } A_k\}) = 0 \tag{157}$$

Proof. Define

$$B = \bigcap_{n=1}^{\infty} \bigcup_{k=n}^{\infty} A_k \tag{158}$$

Easy to verify that $x \in B$ if and only if $x \in$ infinitely many A_k. For every j,

$$B \subseteq \bigcup_{k=j}^{\infty} A_k \tag{159}$$

Hence

$$\mu(B) \leq \mu\left(\bigcup_{k=j}^{\infty} A_k\right) \leq \sum_{k=j}^{\infty} \mu(A_k) \to 0 \text{ as } j \to \infty \tag{160}$$

Therefore, $\mu(B) = 0$. ■

Theorem 6.1 (Egorov's Theorem)**.** Let $(X, \mathcal{A}, \mu)$ be a measure space with $\mu(X) < \infty$. Let f_n be a sequence of measurable $\mathbb{R}$-valued functions converging a.e. to a $\mathbb{R}$-valued function f.

Then for all $\varepsilon > 0$, $\exists$ a set $B \in \mathcal{A}$ such that

1. $\mu(B^c) < \varepsilon$,
2. and $f_n \to f$ uniformly on B.

Proof. Let $\varepsilon > 0$.

For all $n \in \mathbb{N}$, define

$$g_n(x) := \sup_{k \geq n} |f_k(x) - f(x)| \tag{161}$$

since $f_n \to f$ a.e., $g_n(x)$ is finite a.e. Moreover, $g_n(x) \to 0$ a.e. as $n \to \infty$ (both holds where $f_n \to f$).

Since $\mu(X) < \infty$, $g_n(x) \to 0$ in measure by previous results. Then, for every $k \in \mathbb{N}$, there exists n_k such that

$$\mu\left(\left\{x : g_{n_k}(x) > \frac{1}{k}\right\}\right) < \frac{\varepsilon}{2^k} \tag{162}$$

Since there are infinitely many n_k to choose, we may choose an increasing sequence of n_k's. Define

$$B^c = \left\{x : g_{n_k}(x) > \frac{1}{k} \text{ for some } k\right\} \tag{163}$$

Then,

$$\mu(B^c) = \mu\left(\bigcup_{k=1}^{\infty} \left\{x : g_{n_k}(x) > \frac{1}{k}\right\}\right) \tag{164}$$

$$\leq \sum_{k=1}^{\infty} \frac{\varepsilon}{2^k} = \varepsilon \tag{165}$$

Lastly, we can show that $f_n \to f$ uniformly on B. Note that for every $\delta > 0$, take $k_\delta \geq \frac{1}{\delta}$, if $x \in B$, then $g_{n_{k_\delta}}(x) \leq \frac{1}{k_\delta} < \delta$. Therefore, $\sup_{n \geq n_{k_\delta}} |f_n(x) - f(x)| < \delta$.

Therefore, $\forall x \in B, n \geq n_{n_\delta}$, $|f_n(x) - f(x)| < \delta$ and $f_n \to f$ uniformly on B. ■

Definition 6.2. A sequence of measurable $\mathbb{R}$-valued functions f_n converges to a $\mathbb{R}$-valued measurable function f in L^1 if

$$\lim_{n \to \infty} \int |f_n - f| \; d\mu = 0 \tag{166}$$

Proposition 6.3 (Markov Inequality)**.** If $g \geq 0$, then for all $t \geq 0$,

$$\mu\left(\{x : g(x) \geq t\}\right) \leq \frac{\int g \ d\mu}{t} \tag{167}$$

In probabilistic notations:

$$P(g \geq t) \leq \frac{\mathbb{E}[g]}{t} \tag{168}$$

Proof. Define $h(x) := t\mathbb{1}\{g \geq t\}$, obviously, $h \leq g$.

$$\int h \ d\mu = t\mu(\{x : g(x) \geq t\}) \leq \int g \ d\mu \tag{169}$$

The result follows. ∎

Proposition 6.4. $f_n \overset{L^1}{\to} f \implies f_n \overset{\mu}{\to} f$.

Proof. Let $\varepsilon > 0$, apply Markov inequality on every $|f_n - f|$:

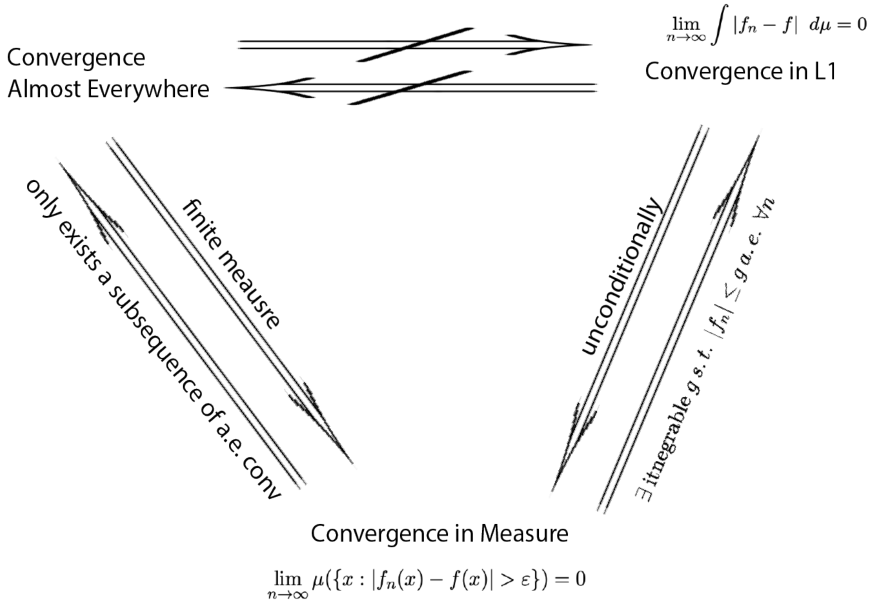
$$\mu\left(\{x : |f_n(x) - f(x)| \geq \varepsilon\}\right) \leq \frac{\int |f_n - f| \ d\mu}{\varepsilon} \to 0 \text{ as } n \to \infty \tag{170}$$

Therefore, $f_n \overset{\mu}{\to} f$. ∎

Remark 6.3.

1. $f_n \overset{a.e.}{\to} f \not\Longrightarrow f_n \overset{L^1}{\to} f$.
2. $f_n \overset{L^1}{\to} f \not\Longrightarrow f_n \overset{a.e.}{\to} f$.
3. $f_n \overset{\mu}{\to} f \not\Longrightarrow f_n \overset{a.e.}{\to} f$.

Figure 1: Modes of Convergences



Proposition 6.5 (Dominated Convergence Theorem II)**.** Suppose $f_n \xrightarrow{\mu} f$, and $\exists$ integrable g such that $|f_n| \leq g$ a.e. for all n. Then, $f_n \xrightarrow{L^1} f$, in particular, $\int f_n \ d\mu \to \int f \ d\mu$.

Proof. Suppose, for contradiction, $f_n \not\to f$ in L^1. Equivalently, there exists ε and a subsequence f_{n_k} such that for all k:

$$\int |f_{n_k} - f| \ d\mu \geq \varepsilon \quad (\dagger) \tag{171}$$

But the convergence in measure implies $f_{n_k} \to f$ in measure as well. Then there exists a subsequence n_{k_ℓ} such that $f_{n_{k_\ell}} \to f$ almost everywhere.

By the previous dominated convergence theorem, $\lim_{\ell\to\infty} \int \left| f_{n_{k_\ell}} - f \right| \ d\mu = 0$, contradicts ($\dagger$). ∎

7 Normed Space

Definition 7.1. Let V be a vector space over $\mathbb{R}$ (over $\mathbb{C}$), a **norm** on V is a function $||\cdot|| : V \to \mathbb{R}$ such that

1. $||x|| \geq 0 \ \forall x \in V$,
2. $||x|| = 0 \iff x = 0$,
3. $||ax|| = |a| \, ||x||$ for all $a \in \mathbb{R} (\in \mathbb{C})$,
4. (Triangle Inequality) $||x + y|| \leq ||x|| + ||y|| \ \forall x, y \in V$.

Example 7.1. For $V = \mathbb{R}^n$, <u>for every $p \geq 1$</u>, the L^p norm is defined as

$$||x||_{L^p} = \left(\sum_{i=1}^{n} |x_i|^p \right)^{1/p} \tag{172}$$

Note: for $p < 1$, the triangle inequality fails.

Example 7.2. Let $C[a,b]$ denote the collection of continuous functions from $[a,b]$ to $\mathbb{R}$, where $[a,b]$ is a compact interval.

The sup norm is defined as

$$||f||_\infty = \sup_{x \in [a,b]} |f(x)| \tag{173}$$

The 1-norm is defined as

$$||f||_1 = \int_{[a,b]} |f| \ d\lambda \tag{174}$$

Definition 7.2. Let S be a set, a **metric** d on S is a function $d : S \times S \to \mathbb{R}$ such that for all $x, y, z \in S$:

1. $d(x,y) \geq 0$,
2. $d(x,y) = 0 \iff x = y$,
3. $d(x,y) = d(y,x)$,
4. $d(x,y) \leq d(x,z) + d(y,z)$.

Proposition 7.1. A norm induces a metric: $d(x,y) := ||x - y||$.

Note: the converse is false, i.e., there are metrics not induced by any norm. For example, $d(x,y) := \mathbb{1}\{x = y\}$ is in general not induced by any norm.

Definition 7.3. Let S be a set with a metric d, a sequence of points x_n converges to $x \in S$ if

$$\lim_{n \to \infty} d(x_n, x) = 0 \tag{175}$$

A sequence is **Cauchy** with respect to d if $\forall \varepsilon > 0, \exists n_0 \in \mathbb{N} \ s.t. \ \forall m, n \geq n_0, d(x_m, x_n) < \varepsilon$.

Definition 7.4. A metric space w.r.t d is **complete** if every Cauchy sequence w.r.t. d converges to somewhere in the space.

Example 7.3. $C[a,b]$ with the supremum norm is complete.

Example 7.4. $C[a,b]$ with L^1 norm is not complete.

Proof. Using counter-example: for $[a,b] = [-1,1]$,

$$f_n(x) = \begin{cases} 0 & \text{if } x \in [-1,0] \\ nx & \text{if } x \in (0,1/n) \\ 1 & \text{if } x \in [1/n,1] \end{cases} \tag{176}$$

The sequence of f_n is Cauchy but converges to $f = \mathbb{1}\{x \geq 0\} \notin C[a,b]$. ■

Proposition 7.2. $C[a,b]$ under sup-norm is complete.

Proof. Suppose f_n is a Cauchy sequence in $C[a,b]$ under supremum norm. For all $x \in [a,b]$,

$$f_n(x) - f_m(x) \leq ||f_n - f_m||_\infty \to 0 \tag{177}$$

since f_n is Cauchy. Therefore, $f_n(x)$ is a Cauchy sequence in $\mathbb{R}$ and $\lim_{n\to\infty} f_n(x)$ exists. Define f to be the point-wise limit of f_n.

Claim: $f \in C[a,b]$ and $f_n \to f$ in sup-norm.

For all $\varepsilon > 0$, there exists N, such that for all $m, n \geq N$,

$$||f_m - f_n||_\infty < \varepsilon \tag{178}$$

Therefore, for all $x \in [a,b]$, $|f_n(x) - f_m(x)| < ||f_m - f_n||_\infty < \varepsilon$.

Fixing n, take $m \to \infty$, this shows for all $n \geq N$, for all $x \in [a,b]$

$$|f(x) - f_n(x)| = \lim_{m\to\infty} |f_m(x) - f_n(x)| \leq \varepsilon \tag{179}$$

Therefore, for all $n \geq N$, $||f - f_n||_\infty \leq \varepsilon$. Hence $f \to f_n$ in sup-norm.

Now show the continuity of f: take $x_0 \in [a,b]$, given $\varepsilon > 0$, since $f_n \to f$ in sup-norm, there exists N such that for all $n \geq N$,

$$||f - f_n||_\infty \leq \frac{\varepsilon}{3} \tag{180}$$

In particular, $||f - f_N||_\infty \leq \frac{\varepsilon}{3}$.

Moreover, since f_N is continuous, $\exists \delta > 0$ such that $|x - x_0| < \delta \implies |f_N(x) - f_N(x)| < \varepsilon/3$ for every x. Take any $x \in \mathcal{B}_\delta(x_0)$, by triangle inequality,

$$\begin{aligned} |f(x) - f(x_0)| &\leq |f(x) - f_N(x)| + |f_N(x) - f_N(x_0)| + |f_N(x_0) - f(x_0)| \quad (181) \\ &\leq \frac{\varepsilon}{3} + \frac{\varepsilon}{3} + \frac{\varepsilon}{3} = \varepsilon \quad (182) \end{aligned}$$

Hence, $f \in C[a,b]$. ■

8 Functional Analysis: L^p Spaces

We will firstly define $\mathcal{L}^p$ spaces, which is a little simpler than L^p spaces.

Definition 8.1. Let $(X, \mathcal{A}, \mu)$ be a measure space, for every $1 \leq p < \infty$, the $\mathcal{L}^p(X, \mathcal{A}, \mu, \mathbb{R})$ space is the collection of all measurable functions $f : X \to \mathbb{R}$ such that

$$\int |f|^p \, d\mu < \infty \tag{183}$$

Similarly, $\mathcal{L}^p(X, \mathcal{A}, \mu, \mathbb{C})$ denotes the collection of all measurable functions $f : X \to \mathbb{C}$ such that $\int |f|^p \, d\mu < \infty$.

Thought out this notes, we use $\mathcal{L}^p$ to denote $\mathcal{L}^p(X, \mathcal{A}, \mu, \mathbb{R})$ or $\mathcal{L}^p(X, \mathcal{A}, \mu, \mathbb{C})$.

Proposition 8.1 ($\mathcal{L}^p$ space is a vector space)**.** Note that $0 \in \mathcal{L}^p$, and if $f \in \mathcal{L}^p$ and $\alpha \in \mathbb{R}/\mathbb{C}$, then

$$\int |\alpha f|^p \, d\mu = |\alpha|^p \int |f|^p \, d\mu < \infty \tag{184}$$

Therefore, $\alpha f \in \mathcal{L}^p$.

For all $x \in X$,

$$\begin{aligned}
|f(x) + g(x)|^p &\leq (|f(x)| + |g(x)|)^p && (185)\\
&\leq (2 \max\{|f(x)|, |g(x)|\})^2 && (186)\\
&\leq 2^p \max\{|f(x)|^p, |g(x)|^p\} && (187)\\
&\leq 2^p(|f(x)|^p + |g(x)|^p) && (188)\\
\implies \int |f + g|^p \, d\mu < \infty & && (189)\\
\implies f + g \in \mathcal{L}^p & && (190)
\end{aligned}$$

Hence, $\mathcal{L}^p$ is a vector space.

Definition 8.2. Let $\mathcal{L}^\infty(X, \mathcal{A}, \mu, \mathbb{R}/\mathbb{C})$ be the set of all bounded measurable $f : X \to \mathbb{R}/\mathbb{C}$.

Definition 8.3. For $f \in \mathcal{L}^p$ with $p < \infty$, define

$$||f||_p = \left(\int |f|^p \, d\mu \right)^{\frac{1}{p}} \tag{191}$$

for $p = \infty$, $||f||_\infty$'s definition is a little bit more complicated, for continuous functions, it collides with the sup-norm. However, it's not the same as sup-norm for discontinuous functions.

Definition 8.4. Given a measure space $(X, \mathcal{A}, \mu)$, a set B is called **μ-null/negligible** if $B \subseteq A$ for some $A \in \mathcal{A}$ with $\mu(A) = 0$.

A subset $N \subseteq X$ is called **locally μ-null** if $\forall A \in \mathcal{A}$ with $\mu(A) < \infty$, $A \cap N$ is μ-null.

A property of elements of X is said to hold **locally a.e.** if the set on which it fails is locally μ-null.

We use this notion of locally null to circumvent non-sigma finite cases.

Definition 8.5. For $f \in \mathcal{L}^\infty$, define

$$||f||_\infty = \inf \{M \geq 0 : \text{the set of all } x \text{ with } |f(x)| > M \text{ is locally } \mu\text{-null.}\} \tag{192}$$

this is called the **essential supremum** of $|f|$. Equivalently, $||f||_\infty$ is the infimum of M such that $|f(x)| \leq M$ locally a.e.

Note that $||f||_\infty$ is only a semi-norm, we may modify a function on a measure-zero set without changing the value of $||f||_\infty$.

Our previous definitions of semi-norms on $\mathcal{L}^p$ spaces satisfy

$$||f||_p = 0 \iff \int |f|^p \, d\mu = 0 \iff |f|^p = 0 \; a.e. \iff f = 0 \; a.e. \tag{193}$$

This definition of semi-norm on $\mathcal{L}^\infty$ ensures $||f||_\infty = 0 \iff f = 0 \; a.e.$.

Example 8.1. Take $X = [0, 1]$ and $\mu = \lambda$,

$$f(x) = \begin{cases} x & \text{if } x \neq \frac{1}{2} \\ 2 & \text{otherwise} \end{cases} \tag{194}$$

Then $||f||_\infty = 1$ but $\sup f = 2$. To see this, note that $\{x : |f(x)| > 1\} = \{1/2\}$ has zero measure. However, for any $M < 1$, the same has non-zero Lebesgue measure.

Proposition 8.2.

$$\mu\left(\{x : |f(x)| > ||f||_\infty\}\right) \text{ is locally } \mu\text{-null.} \tag{195}$$

$$\mu\left(\{x : |f(x)| > c\}\right) \text{ is not locally } \mu\text{-null } \forall c < ||f||_\infty \tag{196}$$

Lemma 8.1. Countable union of locally μ-null sets is locally μ-null.

Proposition 8.3. $||f||_p$ and $||f||_\infty$ are semi-norms.

Definition 8.6. Given $p \in (1, \infty)$, the **conjugate exponent** q is defined as

$$\frac{1}{p} + \frac{1}{q} = 1 \tag{197}$$

That is,

$$q = \frac{p}{p-1} \tag{198}$$

For $p = \infty$, $q = 1$.

Lemma 8.2 (Young's Inequality)**.** Take $p \in (1, \infty)$, let q be the conjugate exponent of p, then for all $x, y \geq 0$,

$$xy \leq \frac{x^p}{p} + \frac{y^q}{q} \tag{199}$$

Proof. ■

Theorem 8.1 (Hölder's Inequality)**.** Let $(X, \mathcal{A}, \mu)$ be a measure space, take $1 \leq p \leq \infty$, and q be it's conjugate exponent. Take $f \in \mathcal{L}^p$, $g \in \mathcal{L}^q$, then

$$fg \in \mathcal{L}^1 \tag{200}$$

and

$$||fg||_1 \leq ||f||_p ||g||_q \tag{201}$$

Example 8.2. Take $X = \{x_1, \cdots, x_n\}$ and μ to be the counting measure on X. Let $p = q = 2$ and $f, g \in \mathcal{L}^2$. Define $v = (f(x_1), \ldots, f(x_n)) \in \mathbb{R}^n$ and $u = (g(x_1), \ldots, g(x_n)) \in \mathbb{R}^n$.

$$||fg||_1 = \sum_{i=1}^{n} \mu(\{x_i\}) \, |f(x_i)g(x_i)| = \sum_{i=1}^{n} |f(x_i)g(x_i)| \tag{202}$$

Therefore,

$$|\langle v, u \rangle| = \left| \sum_{i=1}^{n} f(x_i)g(x_i) \right| \leq ||fg||_1 \tag{203}$$

In this finite dimensional case with counting measure,

$$||f||_2 = \sqrt{\sum_{i=1}^{n} \mu(\{x_i\}) f(x_i)^2} = \sqrt{\sum_{i=1}^{n} f(x_i)^2} = ||v||_2 \tag{204}$$

The same holds for g, in this case Hölder's inequality reduces to cauchy-Switchz inequality.

Proof. ■

Theorem 8.2 (Minkowski's Inequality)**.** Let $(X, \mathcal{A}, \mu)$ be a measure space. Take $1 \leq p \leq \infty$. If $f, g \in \mathcal{L}^p(X, \mathcal{A}, \mu)$, then $f + g \in \mathcal{L}^p$ and $||f + g||_p \leq ||f||_p + ||g||_p$.

Proof. First, suppose that $p \in (1, \infty)$. Let q be the conjugate exponent of p. We have already shown that $\mathcal{L}^p$ is a vector space, so $f + g \in \mathcal{L}^p$.

Note that

$$1/p + 1/q = 1 \implies (p + q)/(pq) = 1 \implies p + q = pq \implies p = (p - 1)q \tag{205}$$

Therefore,

$$\int (|f + g|^{p-1})^q \; d\mu = \int |f + g|^p \; d\mu < \infty \tag{206}$$

Therefore, $|f+g|^{p-1} \in \mathcal{L}^q$. By Hölder's inequality,

$$\int |f+g|^p \ d\mu = \int |f+g|\,|f+g|^{p-1} \ d\mu \tag{207}$$

$$\leq \int |f|\,|f+g|^{p-1} \ d\mu + \int |g|\,|f+g|^{p-1} \ d\mu \tag{208}$$

$$\leq ||f||_p |||f+g|^{p-1}||_q + ||g||_p |||f+g|^{p-1}||_q \tag{209}$$

where

$$|||f+g|^{p-1}||_q = \left(\int (|f+g|^{p-1})^q\right)^{1/q} = \left(\int |f+g|^p\right)^{1/q} \tag{210}$$

If $||f+g||_p = 0$, we are done. Suppose not, divide $(\int |f+g|^p \ d\mu)^{1/q}$ on both sides,

$$\frac{\int |f+g|^p \ d\mu}{(\int |f+g|^p \ d\mu)^{1/q}} \leq ||f||_p + ||g||_p \tag{211}$$

$$\implies (\int |f+g|^p \ d\mu)^{1-1/q} = (\int |f+g|^p \ d\mu)^{1/p} = ||f+g||_p \leq ||f||_p + ||g||_p \tag{212}$$

When $p = 1$,

$$||f+g||_1 = \int |f+g| \ d\mu \leq \int (|f| + |g|) \ d\mu = ||f||_1 + ||g||_1 \tag{213}$$

When $p = \infty$, define

$$N_1 = \{x : |f(x)| > ||f||_\infty\} \tag{214}$$

$$N_2 = \{x : |g(x)| > ||g||_\infty\} \tag{215}$$

Then N_1 and N_2 are locally μ-null, so is $N_1 \cup N_2$. For $x \notin N_1 \cup N_2$,

$$|f(x) + g(x)| \leq |f(x)| + |g(x)| \leq ||f||_\infty + ||g||_\infty \tag{216}$$

■

*Note that $||\cdot||_p$ is a **semi-norm** on $\mathcal{L}^p$, to make it a norm, we introduce the L^p space.*

Definition 8.7. For $1 \leq p < \infty$, define the class of zero vectors

$$\mathcal{N}^p := \{f \in \mathcal{L}^p : f \text{ is measurable and } f = 0 \ a.e.\} \tag{217}$$

which is a subspace of $\mathcal{L}^p$. Define L^p to be the quotient space:

$$L^p(X, \mathcal{A}, \mu) := \mathcal{L}^p(X, \mathcal{A}, \mu)/\mathcal{N}^p(X, \mathcal{A}, \mu) \tag{218}$$

That is, an element $[f] \in L^p$ (an equivalent class) is the collection of all $g \in \mathcal{L}^p$ such that $f - g = 0$

almost everywhere:

$$L^p \ni [f] := \{g \in \mathcal{L}^p : f - g \in \mathcal{N}^p\} \tag{219}$$

Then L^p is a vector space over $\mathbb{R}$ or $\mathbb{C}$, and $||\cdot||_p$ is well-defined: for any f, for all $g \in [f]$, $||f||_p = ||g||_p$ since $f = g$ almost everywhere so their integrals are the same. Most importantly, $||\cdot||_p$ is a norm on L^p.

For $p = \infty$, we define

$$\mathcal{N}^\infty := \{f : f \text{ is bounded, measure and } f = 0 \ a.e.\} \tag{220}$$

Then $L^\infty := \mathcal{L}^p / \mathcal{N}^p$.

Note that L^p for $1 \le p \le \infty$ is also a vector space with equivalence relations. In general, we treat L^p as a space of functions instead of a space of classes of functions.

Proposition 8.4. Convergence in L^p ($1 \le p < \infty$) implies convergence in measure.

Proof. By Markov's inequality,

$$\mu(\{x : |f_n(x) - f(x)| > \varepsilon\}) = \mu(\{x : |f_n(x) - f(x)|^p > \varepsilon^p\}) \tag{221}$$

$$\le \frac{\int |f_n - f|^p \ d\mu}{\varepsilon^p} \to 0 \text{ as } n \to \infty \tag{222}$$

■

Corollary 8.1. Let $f_n \to f$ in L^p with $1 \le p < \infty$, then there exists a subsequence $f_{n_k} \to f$ a.e.

Proof. As convergence in L^p implies convergence in measure, which further implies existence of a.e. converging subsequences. ■

Theorem 8.3. For any $1 \le p \le \infty$, the $||\cdot||_p$ norm on L^p is complete.

Proof. For $1 \le p < \infty$, let (f_n) be a Cauchy sequence in L^p.

Step 1: Find a subsequence (f_{n_k}) such that $||f_{n_k} - f_{n_{k+1}}||_p \le 2^{-k}$ for all k. By Cauchy property, we may find n_1 such that $||f_{n_1} - f_n|| \le 2^{-1}$ for all $n \ge n_1$. Also, find a $n_2 \ge n_1$ such that $||f_{n_2} - f_n|| \le 2^{-2}$ for all $n \ge n_2$, etc.

Step 2: construct the limit Define

$$A_k := \{x : |f_{n_k}(x) - f_{n_{k+1}}(x)| > 2^{-k/2}\} \tag{223}$$

Then, by Markov's inequality,

$$\mu(A_k) \le \frac{\int |f_{n_k} - f_{n_{k+1}}|^p \ d\mu}{(2^{-k/2})^p} \tag{224}$$

$$\le \frac{2^{-kp}}{(2^{-k/2})^p} = 2^{-kp/2} \tag{225}$$

Thus, $\sum_{k=1}^{\infty} \mu(A_k) < \infty$. Define

$$B := \{x : x \in \text{ infinitely many} A_k\} = \bigcap_{k=1}^{\infty} \bigcup_{j=k}^{\infty} A_j \tag{226}$$

By Borel-Cantelli lemma, $\mu(B) = 0$. Take any $x \notin B$, then for sufficiently large k,

$$\left| f_{n_k}(x) - f_{n_{k+1}} \right| \leq 2^{-k/2} \tag{227}$$

This shows for all $x \notin B$, the constructed $(f_{n_k}(x))$ is a Cauchy sequence in $\mathbb{R}$, therefore, it's convergent.

Define the almost point-wise limit

$$f(x) := \begin{cases} \lim_{k\to\infty} f_{n_k}(x) & \text{if } x \notin B \\ 0 & \text{if } x \in B \end{cases} \tag{228}$$

Step 3: Show $f_n \to f$ in L^p. Note that $f_{n_k} \to f$ almost everywhere, so that $|f|^p \to |f_{n_k}|^p$. By Fatou's lemma,

$$\int |f|^p \; d\mu \leq \liminf_{k\to\infty} \int |f_{n_k}|^p \; d\mu \tag{229}$$

But the Cauchy property of f_n implies that $\sup_n ||f_n||_p < \infty$ (find n such that $||f_n - f_m||_p \leq 1$ for all $m \geq n$. Thus, $\forall m \geq n$, $||f_m||_p \leq ||f_n - f_m||_p + ||f_n||_p \leq 1 + ||f_n||_p$. Therefore, $||f||_p < \infty$.

For any $\varepsilon > 0$, we can find N so large that $||f_n - f_m||_p < \varepsilon$ for all $n, m \geq N$ since f_n is Cauchy. By Fatou's lemma, for all $n \geq N$,

$$\int |f_n - f|^p \; d\mu \leq \liminf_{n\to\infty} \int |f_n - f|^p \; d\mu \tag{230}$$

But when k is so large that $n_K \geq N$, we have

$$\int |f_n - f_{n_k}|^p \; d\mu = ||f_n - f_{n_k}||_p^p \leq \varepsilon^p \tag{231}$$

Thus, fo all $n \geq N$, $||f - f_n||_p \leq \varepsilon$. ∎

Proof. for $p = \infty$ case. Let f_n be Cauchy in L^∞, as before, find a subsequence f_{n_k} such that

$$||f_{n_k} - f_{n_{k+1}}||_\infty \leq 2^{-k} \quad \forall k \tag{232}$$

Then for all k, there exists a locally μ-null set N_k such that for all $x \notin N_k$.

$$\left| f_{n_k}(x) - f_{n_{k+1}}(x) \right| \leq 2^{-k} \tag{233}$$

Let $N = \bigcup_{k=1}^{\infty} N_k$, so that N is locally μ-null as well. Then for all $x \notin N$, $f_{n_k}(x)$ is a Cauchy sequence of real numbers, define $f(x) = \lim_k f_{n_k}(x)$ outside N and $f(x) = 0$ on N.

Claim: $f_n \to f$ in L^∞. Note that for all $x \notin N$, for all k,

$$|f(x) - f_{n_k}(x)| \leq \sum_{j=k}^{\infty} \left| f_{n_j}(x) - f_{n_{j+1}}(x) \right| \leq \sum_{j=k}^{\infty} 2^{-j} = 2^{-k+1} \tag{234}$$

Thus, $||f - f_{n_k}||_\infty \leq 2^{-k+1}$.

Take any $\varepsilon > 0$, find N so large that $\forall m, n \geq N$, $||f_m - f_n||_\infty \leq \varepsilon$. Then find k so large that $n_k \geq N$ and $2^{-k+1} \leq \varepsilon$. Then for all $n \geq N$,

$$||f - f_n||_\infty \leq ||f - f_{n_k}||_\infty + +||f_{n_k} - f_n|| \leq 2\varepsilon \tag{235}$$

Taking $\varepsilon' = \varepsilon/2$ concludes $f_n \to f$ in L^∞. ■

9 Signed and Complex Measures

Definition 9.1. The **variation** of a complex measure μ is defined as

$$|\mu|(A) := \sup \left\{ \sum_{i=1}^{n} |\mu(A_i)| : A_1, \ldots, A_n \in \mathcal{A} \text{ disjoint s.t. } \bigcup_{i=1}^{n} A_i = A \right\} \tag{236}$$

Note that the supremum is taken over all *finite partitions of* A. It is easy to check that if μ is a finite signed measure, this definition of variation is the same as the previous one.

Lemma 9.1. Suppose $\mu : \mathcal{A} \to [0, \infty]$ is a function such that (i) $\mu(\varnothing) = 0$ and (ii) is finite additivity (that is, $\mu(A \cup B) = \mu(A) + \mu(B)$ for all disjoint A and B). Moreover, if $\lim_{n\to\infty} \mu(A_n) = 0$ for all $A_n \searrow \varnothing$, then μ is a measure.

Proof. It suffices to check the countable additivity of μ, let $B_1, B_2, \ldots$ be a disjoint sequence of sets in $\mathcal{A}$.

Let $B = \bigcup_i B_i$ and define $A_n := B \setminus \bigcup_{i=1}^{n-1} B_i$. Easy to check $A_n \searrow \varnothing$. Therefore, by finite additivity of μ: $\mu(A_n) = \mu(B) - \sum_{i=1}^{n-1} \mu(B_i) \to 0$. Taking $n \to \infty$ implies $\mu(B) = \sum_{i=1}^{\infty} \mu(B_i)$. ■

Proposition 9.1. Let μ be a complex measure, then $|\mu|$ is a measure.

Proof. Obviously, $|\mu|(\varnothing) = 0$.

Take any disjoint $A, B \in \mathcal{A}$. Now show the finite additivity of $|\mu|$: let $C_1, \ldots, C_n$ be a measurable disjoint partition of $A \cup B$, so $(C_i \cap A)$ and $(C_i \cap B)$ are partitions of A and B respectively.

$$|\mu|(A) + |\mu|(B) \geq \sum |\mu(C_i \cap A)| + \sum |\mu(C_i \cap B)| \tag{237}$$

$$\geq \sum |\mu(C_i \cap A) + \mu(C_i \cap B)| \tag{238}$$

$$= \sum |\mu(C_i)| \because C_i \subseteq A \cup B \tag{239}$$

$$\geq |\mu|(A \cup B) \tag{240}$$

Conversely, let $C_1, \ldots, C_n$ be a partition of A and $D_1, \ldots, D_m$ be a partition of B, then $C_1, \ldots, C_n, D_1, \ldots, D_m$ is a partition of $A \cup B$.

$$|\mu|(A \cup B) \geq \sum_{i=1}^{n} |\mu(C_i)| + \sum_{i=1}^{m} |\mu(D_i)| \tag{241}$$

Taking supremum of partitions (C_i) for A and (D_i) for B,

$$|\mu|(A \cup B) \geq |\mu|(A) + |\mu|(B) \tag{242}$$

Therefore, $|\mu|$ is finitely additive.

Now take a $A_n \searrow \varnothing$ in $\mathcal{A}$, using the Jordan decomposition: $\mu = \mu_1 - \mu_2 + i\mu_3 - i\mu_4$ where μ_i are measures. By triangle inequality in $\mathbb{C}$,

$$|\mu(A)| \leq \sum_{i=1}^{4} \mu_i(A) \tag{243}$$

then for all measurable partitions $A_1, \ldots, A_n$ of A,

$$\sum_{j=1}^{n} |\mu(A_j)| \leq \sum_{i=1}^{4} \sum_{j=1}^{n} \mu_i(A_j) = \sum_{i=1}^{4} \mu_i(A) \tag{244}$$

Taking supremum of all such partitions,

$$|\mu|(A) \leq \sum_{i=1}^{4} \mu_i(A) \tag{245}$$

Since $A_n \searrow \varnothing$) implies $\mu_i(A_n) \to 0$ as μ_i's are finite measures (there is no ∞ in $\mathbb{C}$), $|\mu|(A_n) \to 0$. By Previous lemma, $|\mu|$ is a measure. ■

Proposition 9.2 (Completeness of Total Variation)**.** The total variation is a norm on the space of finite signed/complex measures.

Proof. Obviously, $||\mu||$ is a norm. Now show the completeness.

Let $\{\mu_n\}$ be a Cauchy (in total variation) sequence of measures, for all $A \in \mathcal{A}$, $|\mu(A)| \leq |\mu|(A)$ since A is a trivial partition of A.

For any $m, n \in \mathbb{N}, A \in \mathcal{A}$, $\mu_m - \mu_n$ is a signed measure,

$$|\mu_m(A) - \mu_n(A)| \leq |\mu_m - \mu_n|(A) \tag{246}$$
$$\leq ||\mu_m - \mu_n|| \tag{247}$$

Therefore, $\{\mu_n(A)\}$ is a Cauchy sequence in $\mathbb{R}$ for all $A \in \mathcal{A}$. Define μ as the "set-wise" limit of

μ_n:

$$\mu(A) := \lim_{n\to\infty} \mu_n(A) \tag{248}$$

Now show μ is a measure: observe that $\mu_n \to \mu(A)$ uniformly over all $A \in \mathcal{A}$ by Equation (247). The finite additivity of μ follows its definition.

Fix arbitrary $A_n \searrow \varnothing$, show that $\mu(A_n) \to 0$. Take any $\varepsilon > 0$, find N so large that $|\mu_N(A) - \mu(A)| < \varepsilon$ for all A by uniform convergence.

Find j_0 so large such that for all $j \geq j_0$, $|\mu_N(A_j)| < \varepsilon/2$. For all $j \geq j_0$,

$$|\mu(A_j)| \leq |\mu(A_j) - \mu_N(A_j)| + |\mu_N(A_j)| < \varepsilon \tag{249}$$

Lastly, we show $||\mu_n - \mu|| \to 0$. Take any partition $A_n, \ldots, A_k$ of X, take any $\varepsilon > 0$, the Cauchy property of $\{\mu_n\}$ provides a N so large that for all $m, n \geq N$, $||\mu_m - \mu_n|| < \varepsilon$.

$$\sum_{j=1}^{k} |\mu_m(A_j) - \mu_n(A_j)| \leq ||\mu_m - \mu_n|| < \varepsilon \tag{250}$$

Take $m \to \infty$,

$$\sum_{j=1}^{k} |\mu(A_j) - \mu_n(A_j)| \leq \varepsilon \tag{251}$$

Since above inequality holds for all partitions of X, $||\mu - \mu_m|| < \varepsilon$. ■

9.1 Integration w.r.t. Signed and Complex Measures

Definition 9.2. Let $\mu = \mu^+ - \mu^-$ be a signed measure and its corresponding Jordan decomposition, define

$$\int f \ d\mu = \int f \ d(\mu^+ - \mu^-) = \int f \ d\mu^+ - \int f \ d\mu^- \tag{252}$$

Easy to check that $f \mapsto \int f \ d\mu$ and $\mu \mapsto \int f \ d\mu$ are linear maps.

When μ is a complex measure: $\mu = \mu' + i\mu''$, define

$$\int f \ d\mu = \int f \ d\mu' + i \int f \ d\mu'' \tag{253}$$

10 Radon-Nikodym Theorem

Definition 10.1. Let $(X, \mathcal{A})$ be a measurable space, let μ, ν be two measures on this space, ν is **absolutely continuous** w.r.t. μ if for every $A \in \mathcal{A}$:

$$\mu(A) = 0 \implies \nu(A) = 0 \tag{254}$$

denoted as $\nu \ll \mu$.

Theorem 10.1 (Radon-Nikodym)**.** Let $(X, \mathcal{A})$ be a measurable space, let μ, ν be two σ-finite measures. Suppose ν is absolutely continuous w.r.t. μ, then there exists a measurable map $g : X \to [0, \infty)$ such that

$$\nu(A) = \int_A g \; d\mu \tag{255}$$

for every $A \in \mathcal{A}$.

Interpretations Let χ_A denote the indicator function of set A, recall that $\int_A f \; d\mu \equiv \int f\chi_A \; d\mu$. Then, $\nu(A) = \int_A 1 \; d\nu = \int \chi_A \; d\nu = \int g\chi_A \; d\mu$ for all A. Moreover, for any integrable f,

$$\int f \; d\nu = \int fg \; d\mu \tag{256}$$

This allows us to denote g as $\frac{d\nu}{d\mu}$.

Example 10.1. Suppose $(X, \mathcal{A})$ is a metric space (take $(\mathbb{R}, \mathcal{B}(\mathbb{R}))$ here), suppose g is continuous w.r.t. the metric, let $A = B(x, \varepsilon)$ be the ε-open ball around $x \in X$, then for sufficiently small ε:

$$\nu(A) = \nu(B(x, \varepsilon)) \tag{257}$$

$$\int_A g \; d\mu \approx g(x) \int_A \; d\mu = g(x)\mu(B(x, \varepsilon)) \tag{258}$$

That is,

$$\frac{d\nu}{d\mu} = g(x) \approx \frac{\nu(B(x, \varepsilon))}{\mu(B(x, \varepsilon))} \tag{259}$$

Actually,

$$g(x) = \lim_{\varepsilon \to 0} \frac{\nu(B(x, \varepsilon))}{\mu(B(x, \varepsilon))} \tag{260}$$

Therefore, the Radon-Nikodym derivative $\frac{d\nu}{d\mu}$ captures the relative growth rate of ν to μ when we initially apply them on a small ball and expand the radius of this ball.

Lemma 10.1. Let $(X, \mathcal{A})$ be a measurable space, let ν be a measure on it, let ν be a finite measure. Then, $\nu \ll \mu$ if and only if

$$\forall \varepsilon > 0, \; \exists \delta > 0 \; s.t. \; \mu(A) < \delta \implies \nu(A) < \varepsilon \; \forall A \in \mathcal{A} \tag{261}$$

Recall the definition of uniform continuity and $\frac{df(x)}{dx}$.

Proof. ($\Longleftarrow$) Suppose $\mu(A) = 0$, $\nu(A) < \varepsilon$ for all $\varepsilon > 0$, it must be $\nu(A) = 0$.

($\implies$) Suppose $\nu \ll \mu$, suppose the condition fails, $\exists \varepsilon > 0$ such that $\forall \delta > 0$, $\exists A$ with $\mu(A) < \delta$ but $\nu(A) \geq \varepsilon$.

We can find a sequence $A_1, A_2, \ldots$ such that $\mu(A_j) < \delta_j = 2^{-j}$ for all j and $\nu(A_j) \geq \varepsilon$. It follows $\sum \mu(A_j) < \infty$. By Borel-Cantelli lemma,

$$\mu\left(\bigcap_{j=1}^{\infty} \bigcup_{k=j}^{\infty} A_k\right) = 0 \tag{262}$$

Define $B_j = \bigcup_{k=j}^{\infty} A_k$ and $B = \bigcap_{j=1}^{\infty} B_j$. Since $B_j \searrow B$ and ν is a finite measure, $\nu(B) = \lim_j \nu(B_j)$. But for any j, $\nu(B_j) \geq \nu(A_j) \geq \varepsilon$. Therefore, $\nu(B) \geq \varepsilon$, which contradicts $\nu \ll \mu$. ■

Proof of Radon-Nikodym Theorem. Let ν, μ be finite measures, let

$$\mathcal{F} := \left\{ f : X \to [0, \infty] : f \text{ measurable and } \int_A f \, d\mu \leq \nu(A) \ \forall A \in \mathcal{A} \right\} \tag{263}$$

We are choosing the largest $g \in \mathcal{F}$ as $\frac{d\nu}{d\mu}$.

Claim: $f, g \in \mathcal{F} \implies f \vee g \equiv \max\{f, g\} \in \mathcal{F}$.

Proof. Let $B := \{x : f(x) \geq g(x)\}$, for any $A \in \mathcal{A}$,

$$\int_A f \vee g \, d\mu = \int_{A \cap B} f \vee g \, d\mu + \int_{A \cap B^c} f \vee g \, d\mu \tag{264}$$

$$= \int_{A \cap B} f \, d\mu + \int_{A \cap B^c} g \, d\mu \leq \nu(A \cap B) + \nu(A \cap B^c) = \nu(A) \tag{265}$$

■

Let $(f_n) \in \mathcal{F}$ be a sequence such that

$$\lim_{n \to \infty} \int f_n \, d\mu = \sup\{\int f \, d\mu : f \in \mathcal{F}\} \tag{266}$$

For every $n \in \mathbb{N}$, take $g_n(x) = \max_{j \leq n} f_j(x)$, $g_n \in \mathcal{F}$ by previous claim. Moreover, $g_n(x) \uparrow$ for all $x \in X$.

$$\int f_n \, d\mu \leq \int g_n \, d\mu \leq \sup\{\int f \, d\mu : f \in \mathcal{F}\} \tag{267}$$

By squeeze theorem, $\lim_{n \to \infty} \int g_n \, d\mu = \sup\{\int f \, d\mu : f \in \mathcal{F}\}$.

Define $g(x) = \lim_{n \to \infty} g_n(x)$, which alway exists but is potentially infinity. By MCT,

$$\int g \, d\mu = \lim_{n \to \infty} \int g_n \, d\mu = \sup\{\int f \, d\mu : f \in \mathcal{F}\} \tag{268}$$

Note that $\forall A \in \mathcal{A}$,

$$\int_A g \; d\mu = \lim_{n\to\infty} \int_A g_n \; d\mu \leq \nu(A) \tag{269}$$

So $g \in \mathcal{F}$ and attains the supremum, in terms of integral, over $\mathcal{F}$.

Claim: $\forall A \in \mathcal{A}$, $\int_A g \; d\mu = \nu(A)$.

Proof. Define $\nu_0(A) = \nu(A) - \int_A g \; d\mu$. Since ν is a measure and $A \mapsto \int_A g \; d\mu$ is also a finite measure. Therefore, ν_0 is a finite signed measure. Moreover, since $g \in \mathcal{F}$, $\nu_0(A) \geq 0$ for all $A \in \mathcal{A}$.

Suppose, for contradiction, $\nu_0(A) > 0$ for some $A \in \mathcal{A}$. It must be $\nu_0(X) > 0$. But $\mu(X) < \infty$, there exists $\varepsilon > 0$ such that $\nu_0(X) > \varepsilon\mu(X)$. Note that $\nu_0 - \varepsilon\mu$ is a finite signed measure, let (P, N) be the Hahn decomposition of $\nu_0 - \varepsilon\mu$. Then for any $A \in \mathcal{A}$,

$$\begin{aligned}
\nu(A) &= \int_A g \; d\mu + \nu_0(A) && (270)\\
&\geq \int_A g \; d\mu + \nu_0(A \cap P) && (271)\\
&= \int_A g \; d\mu + \underbrace{\nu_0(A \cap P) - \varepsilon\mu(A \cap P)}_{\geq 0} + \varepsilon\mu(A \cap P) && (272)\\
&\geq \int_A g \; d\mu + \varepsilon\mu(A \cap P) && (273)\\
&= \int_A g + \varepsilon\chi_{A\cap P} \; d\mu && (274)
\end{aligned}$$

Therefore, $g + \varepsilon\chi_{A\cap P} \in \mathcal{F}$. Take $A = X$:

$$\int g + \varepsilon\chi_{A\cap P} \; d\mu = \int g \; d\mu + \varepsilon\mu(P \cap A) \geq \int g \; d\mu \tag{275}$$

Suppose, for contradiction, $\mu(P) \leq 0$, it must be $\mu(P) = 0$, by absolute continuity, $\nu \ll \mu$, $\nu(P) = 0$ as well. Then, since $\int_P g \; d\mu$ is bounded on a measure zero set, it must be zero,

$$\nu_0(P) = \nu(P) - \int_P g \; d\mu = 0 \tag{276}$$

Thus

$$\begin{aligned}
&(\nu_0 - \varepsilon\mu)(P) = 0 && (277)\\
\implies &(\nu_0 - \varepsilon\mu)(X) = (\nu_0 - \varepsilon\mu)(P) + (\nu_0 - \varepsilon\mu)(N) \leq 0 && (278)
\end{aligned}$$

Contradicts $\nu_0(X) \geq \varepsilon\mu(X)$, therefore, $\mu(P) > 0$.

This leads to a contradiction since $g + \varepsilon\chi_{A\cap P}$ has strictly larger integral than g. Therefore, $\nu_0 = 0$. ■

Suppose μ and ν are σ-finite. Let $B_1, B_2, \dots \in \mathcal{A}$ be a partition pf X such that $\mu(B_n), \nu(B_n)$ are finite. Moreover, define $\mu_n(A) := \mu(A \cap B_n)$ and $\nu_n(A) := \nu(A \cap B_n)$, both of μ_n and ν_n are finite on X (in particular, on B_n) and $\nu_n \ll \mu_n$.

For every $n \in \mathbb{N}$, there exists measurable $g_n : X \to [0, \infty]$ such that

$$\nu_n(A) = \int_A g_n \, d\mu \tag{279}$$

Therefore,

$$\begin{aligned} \nu(A \cap B_n) &= \int g_n \chi_{A \cap B_n} \, d\mu & (280) \\ &= \int g_n \chi_{B_n} \chi_A \, d\mu & (281) \\ &= \int_A g_n \chi_{B_n} \, d\mu & (282) \end{aligned}$$

Let $g = \sum_{n=1}^{\infty} g_n \chi_{B_n}$, then

$$\begin{aligned} \nu(A) &= \sum_{n=1}^{\infty} \nu(A \cap B_n) & (283) \\ &= \sum_{n=1}^{\infty} \int g_n \chi_{B_n} \chi_A \, d\mu & (284) \\ &= \sum_{n=1}^{\infty} \chi_A \int g_n \chi_{B_n} \, d\mu & (285) \\ &= \int \chi_A \sum_{n=1}^{\infty} g_n \chi_{B_n} \, d\mu & (286) \\ &= \int_A g \, d\mu & (287) \\ & & (288) \end{aligned}$$

Since $g_n < \infty$ everywhere for all n, so is g. ■

Remark 10.1 (Uniqueness of Radon-Nikodym Derivative)**.** Let g and h be two Radon-Nikodym derivatives of ν w.r.t. μ.

Case 1: suppose $\nu(X) < \infty$, then for all $A \in \mathcal{A}$, by definitoin,

$$\int_A g \, d\mu = \nu(A) = \int_A h \, d\mu \tag{289}$$

Let $B := \{x, g(x) > h(x)\}$, $(g - h)\chi_A \geq 0$ and $(g - h)\chi_A = 0$ a.e. on A. Similarly, $(h - g)\chi_{A^c} \geq 0$ and $(h - g)\chi_{A^c} = 0$ a.e. on A^c. Add them together, $g - h = 0$ a.e. on X.

Case 2: suppose ν is σ-finite, let $B_1, B_2, \dots$ be disjoint measurable sets such that $\nu(B_n) < \infty$ and $\cup_n B_n = X$. Since $g = h$ a.e. on every B_n as shown before, $g = h$ a.e. on X.