

Analysis II

January 9, 2024

(Real) Analysis

- Calculus
 - Differential
 - Integral (Riemann)
- Functions and Maps
 - Measure Theory
 - (Lebesgue) Integration
- Topology
 - Completeness (as a metric space)
 - Compactness (Bolzano-Weierstrass theorem [real]) (Arzela-Ascoli)
 - Paracompactness / Metrizable / Baire Category Theorem
 - Algebraic / Combinatoric (continuous maps or functions)

Definition: Cardinality

For sets A, B , $\text{Card}(A) = \text{Card}(B)$ if there exists a one-to-one correspondence $q : A \leftrightarrow B$.

Counting, labelling, indexing, etc.

$\text{Card}(A) \leq \text{Card}(B)$ if $A \subset B$ or there exists a one-to-one mapping $A \rightarrow B$.

Definition: Countable

If $A \hookrightarrow \mathbb{N}$, then A is countable.

Theorem

The countable union of countable sets is countable.

Proof

Let $A_i = \{a_j\}_{j=1}^{\infty}$, $i = 1, 2, \dots$

$$\begin{array}{cccc} a_{11} & a_{12} & a_{13} & \cdots \\ a_{21} & a_{22} & a_{23} & \cdots \\ \vdots & & & \\ a_{k1} & a_{k2} & a_{k3} & \cdots \end{array}$$

Index by diagonalization.

Theorem

The cartesian product of countable sets is countable.

Proof

$$X \times Y = \{(x_i, y_j) : x_i \in X, y_j \in Y\}$$

$$\begin{array}{cccc}
(x_1, y_1) & (x_1, y_2) & (x_1, y_3) & \cdots \\
(x_2, y_1) & (x_2, y_2) & (x_2, y_3) & \cdots \\
\vdots & & & \\
(x_k, y_1) & (x_k, y_2) & (x_k, y_3) & \cdots
\end{array}$$

Theorem

$\text{Card}(2^X) > \text{Card}(X)$, where $2^X = \{A \subset X\}$ is the power set of X .

Proof

For all $x \in X$, $\{x\} \subset 2^X$, so $\text{Card}(X) \leq \text{Card}(2^X)$.

Assume, for sake of contradiction, that $\text{Card}(X) = \text{Card}(2^X)$.

Then, by definition, there exists a one-to-one correspondence $\phi : X \leftrightarrow 2^X$.

Set $A = \{x \in X : x \notin \phi(x)\}$, and let $a = \phi^{-1}(A)$ (i.e. $A = \phi(a)$).

If $a \in A$, then $a \notin A \subset \phi(a)$; but if $a \notin A$, then $a \in A$, a contradiction.

Theorem

$$\text{Card}(\mathbb{R}) = \text{Card}(2^{\mathbb{N}}).$$

Topology of the Real Line

Completeness (as a metric space)

$$d(a, b) = |a - b|, \quad \forall a, b \in \mathbb{R}.$$

1. $x_i \rightarrow x$ if $\forall \varepsilon > 0, \exists n \in \mathbb{N}$ such that $|x_i - x| < \varepsilon, \forall i \geq n$.
2. $\{x_i\}$ is Cauchy if $\forall \varepsilon > 0, \exists n \in \mathbb{N}$ such that $|x_i - x_j| < \varepsilon, \forall i, j \geq n$.

Definition: Open Interval

(a, b) is an open set on the real line.

There exist interior points for any subset A of real numbers.

$\forall x \in A$, x is interior if $\exists (a, b)$ such that (1) $x \in (a, b)$ and (2) $(a, b) \subset A$.

- Theorem

The union of open sets is open.

The intersection of finitely many open sets is open.

\emptyset and \mathbb{R} are open.

Definition: Limit Point

A limit point $x \in \mathbb{R}$ of a subset A is a limit point in A if for every open neighborhood U of x , $(U \setminus \{x\}) \cap A \neq \emptyset$.

Definition: Closed

A is closed if A contains all of its limit points.

- Theorem

A is closed if and only if $A^c = \mathbb{R} \setminus A$ is open.

- Proof

A closed $\implies A^c$ open.

Otherwise, $\exists x \in A^c$ such that for every neighborhood U of x , $(U \setminus \{x\}) \cap A \neq \emptyset$ which would make it a limit point of A not in A . By assumption, A contains all its limit points so this is a contradiction.

A^c open $\implies A$ closed.

For any x a limit point of A , assume otherwise that $x \in A^c$.

Then there exists some neighborhood U of x such that $U \subset A^c$ (since A^c is open).

It follows that $(U \setminus \{x\}) \cap A = \emptyset$ and x is not a limit point of A , which is a contradiction.

Definition: Sequential Compactness

A is compact if $\forall \{x_i\}$, $x_i \in A$ there exists a convergent subsequence $\{x_{i_k}\}$ and $x_{i_k} \rightarrow x \in A$.

- Theorem: Bolzano-Weierstrass

For $A \subseteq \mathbb{R}$, A is compact if and only if A is closed and bounded.

- Proof

A compact $\implies A$ closed and bounded.

Assume that A is not bounded from above.

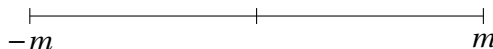
Then there exists a sequence $\{x_i\}$, $x_i \in A$ where $x_{i+1} > x_i + 1$ and $\{x_i\}$ has no convergent subsequences.

Then compactness implies closedness.

A closed and bounded $\implies A$ (sequentially) compact.

Let any $\{x_i\}$, $x_i \in A$.

Claim: $\forall \{x_i\}$ of reals, if there exists $m \in \mathbb{R}$ such that $|x_i| \leq m$, $\forall m$ then there is some convergent subsequence.



Divide and conquer: dividing the interval in half necessitates that at least one half contains infinitely many points. Repeat indefinitely.

- Theorem: Heine-Borel)

$A \subseteq \mathbb{R}$ is (sequentially) compact if and only if any open cover has a finite subcover.

- Proof

Heine-Borel Property \implies closed and bounded.

Assume that A is unbounded, $U_n = (-n, n)$ and $\{U_n\}_{n=1}^{\infty}$ an open cover for $A \subseteq \mathbb{R}$ has no finite subcover.

Assume A is not closed, then $x \in \dot{A}$ (where \dot{A} is the limit set of A) and $x \notin A$, $U_n \left\{ \left(-\infty, x - \frac{1}{n} \right) \cup \left(x + \frac{1}{n}, +\infty \right) \right\}$.

Then $\{U_n\}$ covers $\mathbb{R} \setminus \{x\} \supset A$ has no finite subcover of A .

A is bounded and closed $\implies A$ is Heine-Borel
Divide and conquer: using open sets with respect to open covers.

Definition: Cantor Set

$C = \{x \in [0, 1] : \text{the ternary expansion of } x \text{ has only the digits } \{0, 2\}\}$.
Equivalently, let $C_0 = [0, 1]$, $C_1 = [0, \frac{1}{3}] \cup [\frac{2}{3}, 1]$, $C_2 = [0, \frac{1}{9}] \cup [\frac{2}{9}, \frac{3}{9}] \cup [\frac{6}{9}, \frac{7}{9}] \cup [\frac{8}{9}, 1]$.
Then $C_n = \bigcup_{k=1}^{2^n} C_n^k$ and $C = \bigcap_{n=1}^{\infty} C_n$.
 $|C_n| = 2^n \left(\frac{1}{3}\right)^n \rightarrow 0$.

Definition: Perfectly Symmetric Sets

Let $\{\xi_n\}$ where $\xi_n \in (0, \frac{1}{2})$.
 $E_0 = [0, 1]$, $E_1 = [0, \xi_1] \cup [1 - \xi_1, 1]$, $E_2 = [0, \xi_1 \xi_2] \cup [\xi_1 - \xi_1 \xi_2, \xi_1] \cup [1 - \xi_1, 1 - \xi_1 + \xi_1 \xi_2] \cup [1 - \xi_1 \xi_2, 1]$.
Then the cantor set is given by $\xi_n = \frac{1}{3}$.
 $E_n = \bigcup_{k=1}^{2^n} E_n^k$, $|E_n^k| = \xi_1 \xi_2 \cdots \xi_n$, and $|E_n| = \sum |E_n^k| = 2^n \xi_1 \xi_2 \cdots \xi_n$.
Therefore, $E = \bigcap_{n=1}^{\infty} E_n$ and we define $|E| = \lim_{n \rightarrow \infty} |E_n| = \lim_{n \rightarrow \infty} (2^n \xi_1 \xi_2 \cdots \xi_n) = \lambda$ where $\lambda \in [0, 1)$.
Let

$$2\xi_n = \frac{\left(1 + \frac{\log(\frac{1}{n})}{n-1}\right)^{n-1}}{\left(1 + \frac{\log(\frac{1}{n})}{n}\right)^n} < 1$$

, then

$$2^n \xi_1 \cdots \xi_n = \frac{1}{\left(1 + \frac{\log(\frac{1}{n})}{n}\right)^n} \rightarrow \lambda.$$

Proof

$\lim_{n \rightarrow \infty} \left(1 + \frac{x}{n}\right)^{n/x} = e^x$, then $\lim_{y \rightarrow 0} (1 + y)^{1/y} = e$, $\log(1 + y)^{1/y} = \frac{\log(1+y)}{y} \xrightarrow{y \rightarrow 0} 1$.

Observe that

$$\left(\frac{\log(1+y)}{y}\right)' = \frac{\frac{y}{1+y} - \log(1+y)}{y^2} = \left(1 + \frac{1}{1+y} - \log(1+y)\right)' = \frac{1}{(1+y)^2} - \frac{1}{1+y} = -\frac{y}{(1+y)^2} < 0$$

Theorem

Cantor sets and perfect symmetric sets are closed, perfect, uncountable, and nowhere dense.

January 11, 2024

Last Week

Cardinality.

Topology of the reals.

- Cantor (perfect symmetric sets)

$$C_0 = [0, 1]$$

$$C_1 = [0, 1/3] \cup [2/3, 1]$$

$$C_2 = [0, 1/9] \cup [2/9, 3/9] \cup [6/9, 7/9] \cup [8/9, 1]$$

$$C_n = \bigcup_{k=1}^{2^n} C_n^k$$

$$|C_n^k| = \left(\frac{1}{3}\right)^n$$

$$C = \bigcap_{n=1}^{\infty} C_n$$

$$|C_n| = 2^n \frac{1}{3^n} = \left(\frac{2}{3}\right)^n \implies |C| = \lim_{n \rightarrow \infty} |C_n| = 0$$

Closed, no interior points and uncountable.

- Perfect Symmetric Sets

$$\{\xi_k\} \in \left(0, \frac{1}{2}\right)$$

$$E_0 = [0, 1]$$

$$E_1 = [0, \xi_1] \cup [1 - \xi_1, 1]$$

$$E_2 = [0, \xi_1 \xi_2] \cup [\xi_1 - \xi_1 \xi_2, \xi_1] \cup [1 - \xi_1, 1 - \xi_1 + \xi_1 \xi_2] \cup [1 - \xi_1 \xi_2, 1]$$

$$E_n = \bigcup_{k=1}^{2^n} E_n^k$$

$$|E_n^k| \xi_1 \xi_2 \cdots \xi_n$$

$$|E_n| = 2^n \xi_1 \xi_2 \cdots \xi_n$$

$$2\xi_n = \frac{\left(1 + \frac{\log\left(\frac{1}{n}\right)}{n-1}\right)^{n-1}}{\left(1 + \frac{\log\left(\frac{1}{n}\right)}{n}\right)^n} < 1$$

$$|E_n| = \frac{1}{\left(1 + \frac{\log\left(\frac{1}{n}\right)}{n}\right)^n}$$

$$|E| = \lim_{n \rightarrow \infty} |E_n| = \frac{1}{e^{\log\left(\frac{1}{n}\right)}} = \lambda, \quad \lambda \in (0, 1)$$

Volterra's Function

$$\phi(x) = \begin{cases} x^2 \sin\left(\frac{1}{x}\right) & x \neq 0 \\ 0 & x = 0 \end{cases}$$

IMAGE HERE - graph of phi(x)

$$\phi'(x) = \begin{cases} 2x \sin\left(\frac{1}{x}\right) - \cos\left(\frac{1}{x}\right) & x \neq 0 \\ 0 & x = 0 \end{cases}$$

$$f(x) = \begin{cases} 0 & x \in E \\ \phi(x-a) & x \in (a, a+y) \\ -\phi(b-x) & x \in (b-y, b) \\ \phi(y) & x \in (a+y, b-y) \end{cases}, \quad (a, b) \in E^c$$

IMAGE HERE - f interval (a,b)

Propositions

1. $f'(x) = 0$ for $x \in E$.
2. $f'(x)$ discontinuous on E .
3. f' exists on $[0, 1]$ and is bounded.

Since $|E| > 0$, $f'(x)$ is not Riemann integrable and, therefore, the fundamental theorem of calculus does not apply.

Lebesgue Outer Measure

$$|(a, b)| = b - a.$$

Let $A \subseteq \mathbb{R}$, then $m^*(A) = \inf \{ \sum_{n=1}^{\infty} I_n : A \subseteq \bigcup_{n=1}^{\infty} I_n \}$

Question: $m^*(A \cup B) \stackrel{?}{=} m^*(A) + m^*(B)$ for $A \cap B \neq \emptyset$?

Properties

1. $A \subseteq B \implies m^*(A) \leq m^*(B)$.
2. $m^*(\emptyset) = 0$.
3. If I is an interval, then $m^*(I) = |I|$.
4. If $\{A_i\}$ is countable, $m^*(\bigcup A_i) \leq \sum m^*(A_i)$.

• Proof of 4

$\forall A_i, \exists \{I_n\}$ open intervals such that $\sum_n |I_n| < m^*(A_i) + \frac{\varepsilon}{2^i}$.

Then $\bigcup_i \bigcup_n I_n^i \supset \bigcup_i A_i$, and $\sum_{n,i} |I_n^i| = \sum_i (\sum_n |I_n^i|) \leq \sum_i (m^*(A_i) + \frac{\varepsilon}{2^i})$.

– Corollary

If A is countable, then $m^*(A) = 0$.

Thus, by contraposition, every interval is uncountable.

Proposition

For $A \subseteq \mathbb{R}$, $\forall \varepsilon > 0$, $\exists U$ open such that $A \subseteq U$ and $m^*(U) \leq m^*(A) + \varepsilon$.

Corollary

There exists G in the intersection of countable open sets such that $m^*(G) = m^*(A)$ and $G \supseteq A$.

Caratheodory Criteria

If $\forall E, m^*(E \cap A) + m^*(E \cap A^c) = m^*(E)$, then A is Lebesgue measurable.

- Remark: $m^*(E \cap A) + m^*(E \cap A^c) \leq m^*(E) \leq +\infty$

Propositions

1. If A is measurable, then A^c is measurable.
2. $m^*(A) = 0$, then A is measurable.
3. If A, B are measurable, then $A \cup B, A \cap B, A \setminus B$ are measurable.
4. If $\{A_i\}_{i=1}^k$ are disjoint and measurable, then $m^*\left(\bigcup_{i=1}^k A_i\right) = \sum_{i=1}^k m^*(A_i)$.

• Proof of 3

$$\begin{aligned} m^*(E \cap (A \cup B)) + m^*(E \cap (A \cup B)^c) &= m^*((E \cap A) \cup (E \cap B)) + m^*(E \cap A^c \cap B^c) \\ &= m^*(E \cap A) + m^*((E \cap A^c) \cap B) + m^*((E \cap A^c) \cap B^c) \\ &\leq m^*(E) \end{aligned}$$

Since $(A \cap B)^c = A^c \cup B^c$, this holds from before; similarly, $A \setminus B = A \cap B^c = A^c \cup B$.

If A, B disjoint, then

$$\begin{aligned} m^*(A \cup B) &= m^*(E \cap A) + m^*(E \cap A^c) \\ &= m^*(A) + m^*(B) \end{aligned}$$

Theorem

If $\{A_i\}$ is a countable collection of disjoint and measurable sets, then

1. $\bigcup_i A_i$ is measurable.
2. $m^*\left(\bigcup_i A_i\right) = \sum_i m^*(A_i)$.

Proof of 1

Want to show:

$$m^*\left(E \cap \left(\bigcup_{i=1}^{\infty} A_i\right)\right) + m^*\left(E \cap \left(\bigcup_{i=1}^{\infty} A_i\right)^c\right) \leq m^*(E)$$

By assumption, since the measure of E is finite, $m^*(E \cap \bigcup_{i=1}^{\infty} A_i) < +\infty$.

Claim: $\forall \varepsilon > 0, \exists k$ such that

Therefore $m^*\left(E \cap \bigcup_{i=1}^k A_i\right) \geq m^*\left(E \cap \bigcup_{i=1}^{\infty} A_i\right) - \varepsilon$.

$$m^*(E) \leq m^*\left(E \cap \bigcup_{i=1}^k A_i\right) + \varepsilon + m^*\left(E \cap \left(\bigcup_{i=1}^k A_i\right)^c\right) \leq m^*(E) + \varepsilon$$

Proof of 2

We have shown $m^*\left(\bigcup_i A_i\right) \leq \sum_{i=1}^{\infty} m^*(A_i)$.

Assume $m^*\left(\bigcup_i A_i\right) < +\infty$, then

$$\sum_{i=1}^k m^*(A_i) = m^*\left(\bigcup_{i=1}^k A_i\right) \leq m^*\left(\bigcup_i A_i\right) \implies \sum_{i=1}^{\infty} m^*(A_i) \leq m^*\left(\bigcup_i A_i\right)$$

January 16, 2024

Office Hours Tuesday / Thursday 10 AM - 11:30 AM

A note on notation: Latin characters are to be understood as countable indecies; greek as possible uncountable.

Lebesgue Outer Measure

$A \subset \mathbb{R}$

$$m^*(A) = \inf \left\{ \sum_{i=1}^{\infty} |I_i| : \bigcup_{i=1}^{\infty} I_i \supset A, I_i \text{ open intervals} \right\}$$

Properties

1. $A \subset B \implies m^*(A) \leq m^*(B)$.
2. $m^*(\emptyset) = 0$.
3. $m^*(I) = |I|$ for I an interval.
4. Countable Subadditivity: $\{A_i\}_{i=1}^{\infty} \implies m^*\left(\bigcup_{i=1}^{\infty} A_i\right) \leq \sum_{i=1}^{\infty} m^*(A_i)$.
5. $\forall A \subset \mathbb{R}, \forall \varepsilon > 0, \exists$ open neighborhood $U \supseteq A$ such that $m^*(U) \leq m^*(A) + \varepsilon$.
6. $\exists G \in \bigcap_{n=1}^{\infty} U_n, U_n \text{ open}, U_n \supseteq A \implies G \supseteq A$, such that $m^*(G) = m^*(A)$.

Measurable (Caratheodory Criterion)

$\forall A \subseteq \mathbb{R}$ is Lebesgue measurable if

$$m^*(A) = m^*(E \cap A) + m^*(E \cap A^c)$$

Essentially, $m^*(E \cap A) + m^*(E \cap A^c) \leq m^*(E) \leq +\infty$.

• Propositions

1. A measurable $\implies A^c$ measurable.
 2. $m^*(A) = 0 \implies A$ measurable.
 3. $\{A_i\}_{i=1}^{\infty}$ countable with A_i measurable, then
 - (a) $\bigcap_{i=1}^{\infty} A_i$ are measurable.
 - (b) Moreover, $A_i \cap A_j = \emptyset \implies m^*\left(\bigcup_{i=1}^{\infty} (A_i)\right) = \sum_{i=1}^{\infty} m^*(A_i)$.
 - (c) A, B measurable $\implies A \cup B, A \cap B, A \setminus B$ measurable.
 - (d) $A \cap B = \emptyset \implies m^*(A \cup B) = m^*(A) + m^*(B)$.
 - (e) $\{A_i\}_i^{\infty}$ with A_i measurable, then $\bigcup_{i=1}^{\infty} A_i$ is measurable and $A_i \cap A_j = \emptyset \implies m^*\left(\bigcup_{i=1}^{\infty} A_i\right) = \sum_{i=1}^{\infty} m^*(A_i)$.
- Proof of e $\forall E \subset \mathbb{R}, m^*\left(E \cap \left(\bigcup_{i=1}^{\infty} A_i\right)\right) + m^*\left(E \cap \left(\bigcup_{i=1}^{\infty} A_i\right)^c\right)$.
Claim: $m^*\left(E \cap \left(\bigcup_{i=1}^{\infty} A_i\right)\right) = \sum_{i=1}^{\infty} m^*(E \cap A_i)$ for $A_i \cap A_j = \emptyset$.

Then, $\forall \varepsilon > 0, \exists n \in \mathbb{N}$,

$$\begin{aligned}
& m^* \left(E \cap \left(\bigcup_{i=1}^{\infty} A_i \right) \right) = \sum_{i=1}^{\infty} m^*(E \cap A_i) \leq \sum_{i=1}^n m^*(E \cap A_i) + \varepsilon \\
\Rightarrow & m^* \left(E \cap \left(\bigcup_{i=1}^{\infty} A_i \right) \right) + m^* \left(E \cap \left(\bigcup_{i=1}^{\infty} A_i \right)^c \right) \leq m^* \left(E \cap \left(\bigcup_{i=1}^n A_i \right) \right) + m^* \left(E \cap \left(\bigcup_{i=1}^n A_i \right)^c \right) + \varepsilon \leq m^*(E) + \varepsilon \\
& \Rightarrow \bigcup_{i=1}^{\infty} A_i \text{ measurable}
\end{aligned}$$

Proof of Claim:

Step 1: A, B measurable and $A \cap B = \emptyset$. Since A is measurable,

$$\begin{aligned}
m^*(E \cap (A \cup B)) &= m^*((E \cap (A \cup B)) \cap A) + m^*((E \cap (A \cup B)) \cap A^c) \\
&= m^*(E \cap A) + m^*(E \cap A^c)
\end{aligned}$$

For $\{A_i\}_{i=1}^{\infty}$, $\bigcup_{i=1}^{\infty} A_i = \bigcup_{i=1}^{\infty} A'_i$ with $A_1 = A'_1$ and $A'_i = A_i \setminus \bigcup_{k=1}^{i-1} A_k$, $\forall i \geq 2$.

Therefore $A'_i \cap A'_j = \emptyset$ and A'_i is measurable.

$$\begin{aligned}
m^* \left(\bigcup_{i=1}^n A_i \right) &\leq m^* \left(\bigcup_{i=1}^{\infty} A_i \right) \leq \sum_{i=1}^{\infty} m^*(A_i) \\
m^* \left(\bigcup_{i=1}^n A_i \right) &= \sum_{i=1}^n m^*(A_i) \leq m^* \left(\bigcup_{k=1}^{\infty} A_k \right) < +\infty \Rightarrow \sum_{i=1}^{\infty} m^*(A_i) \leq m^* \left(\bigcup_{k=1}^{\infty} A_k \right) \leq \sum_{i=1}^{\infty} m^*(A_i)
\end{aligned}$$

Sigma Algebra and Borel Sets

Definition: Sigma Algebra

Let $S \subset 2^X$ for some set X . Then S is said to be a σ -algebra if

1. $\emptyset \in S$.
2. $A^c \in S$ if $A \in S$.
3. $\bigcup_{i=1}^{\infty} A_i \in S$ if $A_i \in S$.

• Equivalently, $\bigcap_{i=1}^{\infty} A_i \in S$ if $A_i \in S$.

Theorem:

The collection \mathcal{L} of all Lebesgue measurable sets is a σ -algebra.

Definition: Borel Set

Let B be the σ -algebra generated by open sets of reals (i.e. the smallest σ -algebra containing all open sets of reals). Then $b \in B$ is called a Borel set.

Remark

B is generated by $\{(a, +\infty) : a \in \mathbb{R}\}$.

1. $(a, +\infty)^c = (-\infty, a]$.
2. $\bigcap_{n=1}^{\infty} \left(a - \frac{1}{n}, +\infty\right) = [a, +\infty)$.
3. $[a, +\infty)^c = (-\infty, a)$.
4. $(-\infty, b) \cap (a, +\infty) = (a, b)$.
5. $(-\infty, b] \cap [a, +\infty) = [a, b]$.

Theorem:

Any Borel set is Lebesgue measurable.

Proof

It suffices to demonstrate that $(a, +\infty)$ is measurable $\forall a \in \mathbb{R}$.

$\forall E \subset \mathbb{R}$, we want to show that $m^*(E \cap (a, +\infty)) + m^*(-\infty, a]) \leq m^*(E)$.

Then, $\forall \varepsilon > 0$, $\exists \mathcal{C} = \{I_i\}$ with I_i open intervals such that $\sum_{I_i \in \mathcal{C}} |I_i| \leq m^*(E) + \varepsilon/2$. Set

$$\begin{aligned}\mathcal{C}^\ell &= \{I \in \mathcal{C} : x < a, \forall x \in I\} \\ \mathcal{C}^r &= \{I \in \mathcal{C} : x > a, \forall x \in I\} \\ \mathcal{C}^m &= \{I \in \mathcal{C} : a \in I\} = \{I_k\}\end{aligned}$$

Then $\mathcal{AC} = \mathcal{C}^\ell \cup \mathcal{C}^r \cup \mathcal{C}^m$.

$\forall I_k \in \mathcal{C}^m = \{I_k\}$, $I_k = (c_k, d_k)$ for some $c_k, d_k \in \mathbb{R}$, define

$$\begin{aligned}I_k^\ell &= \left(c_k, a + \frac{\varepsilon}{2^{k+1}}\right) \\ I_k^r &= (a, d_k)\end{aligned}$$

Let $\mathcal{C}^m = \{I_k^\ell\} \cup \{I_k^r\} = \overline{\mathcal{C}}^{m\ell} \cup \overline{\mathcal{C}}^{mr}$. Then

$$\begin{aligned}\mathcal{C}^\ell \cup \overline{\mathcal{C}}^{m\ell} &\text{ covers } E \cap (-\infty, k] \\ \mathcal{C}^r \cup \overline{\mathcal{C}}^{mr} &\text{ covers } E \cap (k, +\infty) \\ \mathcal{C}^\ell \cup \mathcal{C}^r \cup \mathcal{C}^m &\text{ covers } E\end{aligned}$$

Observe that

$$|I_k^\ell| + |I_k^r| \leq |I_k| + \frac{\varepsilon}{2^{k+1}}$$

Therefore

$$m^*(E \cap (a, +\infty)) \leq \sum_{I \in \mathcal{C}^R + \bar{\mathcal{C}}^{mr}} |I|$$

$$m^*(E \cap [-\infty, a]) \leq \sum_{I \in \mathcal{C}^\ell + \bar{\mathcal{C}}^{m\ell}} |I|$$

Therefore

$$\begin{aligned} m^*(E \cap (a, +\infty)) + m^*(E \cap (-\infty, a]) &\leq \sum_{I \in \mathcal{C}^r \cup \bar{\mathcal{C}}^{mr}} |I| + \sum_{I \in \mathcal{C}^\ell \cup \bar{\mathcal{C}}^{m\ell}} |I| \\ &= \sum_{I \in \mathcal{C}^r} |I| + \sum_{I \in \mathcal{C}^\ell} |I| + \sum_k (|I_k^\ell| + |I_k^r|) \\ &\leq \sum_{I \in \mathcal{C}} |I| + \sum_{k=1}^{+\infty} \frac{\varepsilon}{2^{k+1}} \\ &\leq m^*(E) + \frac{\varepsilon}{2} + \frac{\varepsilon}{2} \\ &\leq m^*(E) + \varepsilon \end{aligned}$$

Lebesgue Measurable vs Borel

Theorem

The following statements are equivalent

1. A is measurable.
2. $\forall \varepsilon > 0, \exists U$ open, $U \supset A$ such that $m(U \setminus A) < \varepsilon$.
3. $\forall \varepsilon > 0, \exists C$ closed, $C \subset A$ such that $m(A \setminus C) < \varepsilon$.
4. $\forall A \in \mathbb{R}, \exists \bigcap_{n=1}^{\infty} U_n = F \in \mathcal{B}, U_n$ open, $U_n \supset A$ such that $F \supset A$ and $m(F \setminus A) = 0$.
5. $\exists \{C_n\}, C_n$ closed and $C_n \subset A$ such that $G = \bigcup_{n=1}^{\infty} C_n \subset A$ and $m(A \setminus G) = 0$.

Corollary

Every measurable set is the union of a Borel set and a measure zero set.

Proof 1 Implies 2

Step 1: if $m(A) < \infty$, then for $\varepsilon > 0, \exists U$ open and $U \supset A$, then

$$m(U) \leq m(A) + \varepsilon \iff m(U \setminus A) = m(U) - m(A) \leq \varepsilon$$

Step 2: let $A_n = A \cap (-n, n), n \in \mathbb{N}$.

Then $m(A_n) \leq 2n < +\infty$.

For each $A_n, \exists U_n$ open with $U_n \supset A_n$ and $m(U_n \setminus A_n) < \frac{\varepsilon}{2^n}$

Let $U = \bigcup_{n=1}^{\infty} U_n$ and $A = \bigcup_{n=1}^{\infty} A_n$.
Now verify that

$$m(U \setminus A) = m\left(\bigcup_{n=1}^{\infty} U_n \setminus \bigcup_{n=1}^{\infty} A_n\right) = m\left(\bigcup_{n=1}^{\infty} U_n \setminus A_n\right) \leq \sum_{n=1}^{\infty} m(U_n \setminus A_n) \leq \varepsilon$$

Proof 2 Implies 3

Write

$$A \setminus C = A \cap C^c = C^c \cap A = C^c \setminus A^c$$

Apply (2).

Proof 3 Implies 4

U_n comes from 2.

Proof 4 Implies 5

Follows from 4.

Proof 5 Implies 1

$A = G \cup (A \setminus G) \implies A$ is measurable.

Example: Non-measurable Set

Define $x \sim y$ if $x - y \in \mathbb{Q}$, $\forall x, y \in \mathbb{R}$.

Let $A = \{x \in (0, 1) : x \text{ is a representative of each class } \mathbb{R} / \sim\} \subset (0, 1) \subset \mathbb{R}$.

Claim: A is not Lebesgue measurable.

Let $(-1, 1) \supset S = \bigcup_{r \in \mathbb{Q} \cap (0, 1)} (A + r) \supset (0, 1)$, and observe that $\mathbb{Q} \cap (0, 1)$ is countable.

So $(A + r) \cap (A + s) = \emptyset$ for $s \neq r$.

Then $1 < m(S) < 2$, so $m(A) = 0$ and $m(A) > 0$ are both contradictions.

January 18, 2024

Abstract measure theory.

Definition: Topological Space

A set X equipped with a collection of subsets $\tau \subset 2^X$ where τ is a topology if

1. $\emptyset, X \in \tau$
2. Union of subsets in τ remains in τ .
3. Intersection of finitely many subsets in τ remains in τ .

Any subset of τ is called an open set of X .

Definition: Measure Space

For a set X with $\Lambda \subset 2^X$ a σ -algebra such that

1. $\emptyset \in \Lambda$
2. $A^c \in \Lambda$ if $A \in \Lambda$.
3. $\bigcup_{i=1}^{\infty} A_i \in \Lambda$ if $A_i \in \Lambda$.
4. Remark: Borel Sigma Algebra

The σ -algebra generated by τ for a topological space (X, τ) .

The measure space (X, Λ, μ) , $\Lambda \subset 2^X$ a σ -algebra equipped with set function $\mu : \Lambda \rightarrow [0, +\infty]$ such that

1. $\mu(\emptyset) = 0$
2. $\mu\left(\bigcup_{i=1}^{\infty} A_i\right) = \sum_{i=1}^{\infty} \mu(A_i)$ for $A_i \in \Lambda$ and $A_i \cap A_j = \emptyset$ for all $i \neq j$ (countable additivity).

Proposition: Monotonicity

$$A, B \in \Lambda, A \subseteq B \implies \mu(A) \leq \mu(B).$$

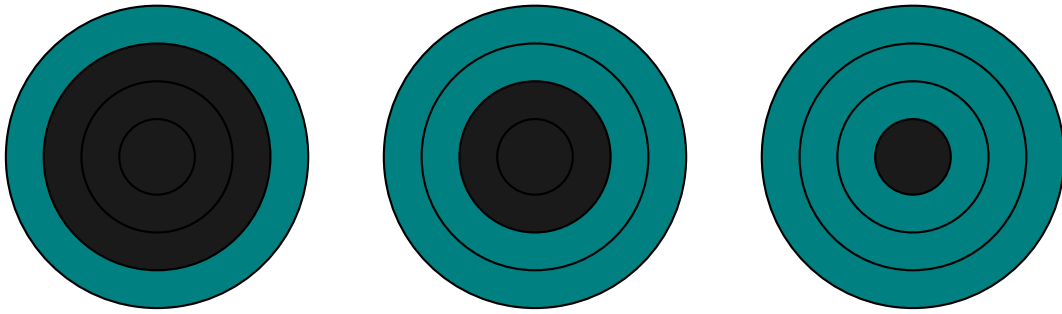
Proposition: Countable Subadditivity

$$\mu\left(\bigcup A_i\right) \leq \sum \mu(A_i) \text{ if } A_i \in \Lambda$$

Proposition: Monotone Convergence

Given $A_i \in \Lambda$ such that $A_i \subset A_{i+1}$ where $A = \bigcup_{i=1}^{\infty} A_i$, then $\mu(A_i) \rightarrow \mu(A)$.

Similarly, if $A_i \supset A_{i+1}$ such that $A = \bigcap_{i=1}^{\infty} A_i$, then $\mu(A_i) \rightarrow \mu(A)$ if $\mu(A_k) < +\infty$ for some $k = 1, 2, 3, \dots$



$$\text{Given } A'_i = \begin{cases} A_1 & i = 1 \\ A_i \setminus \bigcup_{j=1}^{i-1} A_j & i > 1 \end{cases}, \bigcup_{i=1}^{\infty} A_i = \bigcup_{i=1}^{\infty} A'_i \text{ and}$$

$$\mu(A) \sum_{i=1}^{\infty} A'_i = \lim_{n \rightarrow \infty} \sum_{i=1}^{\infty} \mu(A'_i)$$

and

$$\sum_{i=1}^n \mu(A'_i) = \mu(A_1) + (\mu(A_2) - \mu(A_1)) + (\mu(A_3) - \mu(A_2)) + \dots + (\mu(A_n) - \mu(A_{n-1})) = \mu(A_n)$$

Similarly, $A_1 \setminus A = \bigcup_{i=2}^{\infty} (A_i \setminus A_{i-1})$ where $\mu(A_1) < +\infty$ gives

$$\mu(A_1) - \mu(A) = \mu(A_1) + \sum_{i=2}^{\infty} (\mu(A_i) - \mu(A_{i-1})) = \lim_{n \rightarrow \infty} \mu(A_n)$$

Definition: Complete Measure Space

A measure space (X, Λ, μ) is complete if $\forall A \in \Lambda$ with $\mu(A) = 0$, then $\forall B \subset A$ and $B \in \Lambda$.

Example

The Lebesgue measure space on the reals $(\mathbb{R}, \mathcal{L}, m)$ is complete.

Theorem: Completion of a Measure Space

Given a measure space (X, Λ, μ) , then there exists $(X, \bar{\Lambda}, \bar{\mu})$ such that

1. $\Lambda \subset \bar{\Lambda}$.
2. If $A \in \Lambda$, then $\bar{\mu}(A) = \mu(A)$.
3. $(X, \bar{\Lambda}, \bar{\mu})$ is complete.

Proof (Construction)

Let $\bar{\Lambda} = \{A \cup Z : A \in \Lambda, \exists D \in \Lambda, m(D) = 0, Z \subset D\}$ and $\bar{\mu}(A \cup Z) := \mu(A)$.

Verify:

1. $\bar{\Lambda}$ is a σ -Algebra.
 - (a) If $A \cup Z \in \bar{\Lambda}$, then $(A \cup Z)^c \in \bar{\Lambda}$.
 - (b) If $A_i \cup Z_i \in \bar{\Lambda}$, then $\bigcup (A_i \cup Z_i) \in \bar{\Lambda}$.
2. $\bar{\mu}$ is a well-defined measure on $\bar{\Lambda}$.
3. $(X, \bar{\Lambda}, \bar{\mu})$ is complete.

• Proof of 1

Given $A \in \Lambda$ and $Z \subset D$ where $\mu(D) = 0$ and $D \in \Lambda$, we know $D^c \subset Z^c$ and $Z^c = D^c \cup (Z^c \cap D)$. Therefore

$$(A \cup Z)^c = A^c \cap Z^c = A^c \cap (D^c \cup (Z^c \cap D)) = (A^c \cap D^c) \cup (A^c \cap Z^c \cap D) \in \bar{\Lambda}$$

Since $A^c \cap D^c \in \Lambda$ and $A^c \cap Z^c \cap D \in D$

Since $\bigcup A_i \in \Lambda$ and $\bigcup Z_i \subset \bigcup D_i$,

$$\bigcup_{i=1}^{\infty} (A_i \cup Z_i) = \left(\bigcup_{i=1}^{\infty} A_i \right) \cup \left(\bigcup_{i=1}^{\infty} Z_i \right) \in \bar{\Lambda}$$

- Proof of 2

Given $A_1 \cup Z_1 = A_2 \cup Z_2$, $A_1 \subset A_2 \cup Z_2 \subset A_2 \cup D_2$ implies $\mu(A_1) \leq \mu(A_2)$.

Then, $\mu(A_2) \leq \mu(A_1) \implies \mu(A_1) = \mu(A_2)$. So $\bar{\mu}$ is well defined.

Given $\{A_i \cup Z_i\}$ with $(A_i \cup Z_i) \cap (A_j \cup Z_j) = \emptyset$ for all $i \neq j$,

$$\bar{\mu}\left(\bigcup_{i=1}^{\infty} (A_i \cup Z_i)\right) = \bar{\mu}\left(\left(\bigcup_{i=1}^{\infty} A_i\right) \cup \bigcup_{i=1}^{\infty} Z_i\right) = \mu\left(\bigcup_{i=1}^{\infty} A_i\right) = \sum_{i=1}^{\infty} \mu(A_i) = \sum_{i=1}^{\infty} \bar{\mu}(A_i \cup Z_i)$$

So $\bar{\mu}$ is countably additive and therefore a measure.

Borel Measure and Radon Measure

Given a measure space (X, Λ, μ) and an underlying topology (X, τ) ,

Definition: Borel Measure

μ is a Borel measure if all borel sets $\tau \subset \Lambda$.

Definition: Locally Finite Measure

μ is locally finite if $\forall x \in X, \exists U \subset X$ a neighborhood such that $\mu(U) < +\infty$.

Definition: Borel Regularity

μ is Borel regular if $\forall A \in \Lambda, \exists B$ a Borel set such that $B \supseteq A$ and $\mu(B) = \mu(A)$.

Definition: Radon Measure

μ is a Radon measure if

1. it is a Borel measure.
2. $\mu(K) \leq +\infty$ for K compact.
3. $\mu(V) = \sup\{\mu(K) : K \subset V, K \text{ compact}\}$, V open.
4. $\mu(A) = \inf\{\mu(V) : A \subset V, V \text{ open}\}$, $\forall A \in \Lambda$.

- Example 1

Lebesgue measure.

- Example 2

Point charge: $\mu(\{x\}) = 1$ and $\mu(A) = 0$ if $x \notin A$.

Theorem:

Let (X, Λ, μ) be a Borel regular measure space where the underlying topology (X, τ) is a metric space. Then

1. For $A \in \Lambda$ with $\mu(A) < +\infty$, $\forall \varepsilon > 0$, $\exists C \subseteq A$ closed such that $\mu(A \setminus C) < \varepsilon$.

2. For $A \in \Lambda$, $\exists \{V_i\}$ open sets such that $A \subset \bigcup_{i=1}^{\infty} V_i$ and $\mu(V_i) < +\infty$. Then $\forall \varepsilon > 0$, $\exists U$ open with $A \subset U$ and $\mu(U \setminus A) < \varepsilon$.

Proof

Given $\mu(A) < +\infty$, $\nu(B) = \mu(B \cap A) < +\infty$, $\forall B \in \Lambda$ and (X, Λ, ν) .

Let $F = \{B \in \Lambda : \forall \varepsilon > 0, \exists C \subset B \text{ closed, with } \nu(B \setminus C) < \varepsilon\}$.

Note that closed sets are in F .

Claim 1: the Borel σ -algebra is in F .

Claim 2: if $A_i \in F$, $\bigcup A_i, \bigcap A_i \in F$.

Given claim 2, $\forall U$ open, U^c is closed. Then $U_\varepsilon = \{x \in U : \text{dist}(x, U^c) \leq \varepsilon\}$ is closed and, therefore, $U = \bigcup_{i=1}^{\infty} U_{1/i}$.

So, given $A_i \in F$, $\exists C_i \subset A_i$ closed where $\nu(A_i \setminus C_i) < \varepsilon/2^{i+1}$. We want to show that $\nu(\bigcap A_i \setminus \bigcap C_i) < \varepsilon$.

Then, for $x \in \bigcap A_i \setminus \bigcap C_i$, $x \in A_i$ for all i and $x \notin C_{i_0}$ for some i_0 .

Therefore $x \in A_{i_0}$, $x \notin C_{i_0}$, and $x \in A_{i_0} \setminus C_{i_0}$. It follows that

$$\begin{aligned} \bigcap_{i=1}^{\infty} A_i \setminus \bigcap_{i=1}^{\infty} C_i &\subset \bigcup_{i=1}^{\infty} (A_i \setminus C_i) \\ \nu\left(\bigcap_{i=1}^{\infty} A_i \setminus \bigcap_{i=1}^{\infty} C_i\right) &\leq \sum_{i=1}^{\infty} \nu(A_i \setminus C_i) < \varepsilon \end{aligned}$$

Therefore

$$\nu\left(\bigcup_{i=1}^{\infty} A_i \setminus \bigcup_{i=1}^n C_i\right) \rightarrow \nu\left(\bigcup_{i=1}^{\infty} A_i \setminus \bigcup_{i=1}^{\infty} C_i\right) \leq \nu\left(\bigcup_{i=1}^{\infty} (A_i \setminus C_i)\right) < \frac{\varepsilon}{2}$$

so $\exists N \gg 1$ such that $\nu\left(\bigcup_{i=1}^{\infty} A_i \setminus \bigcup_{i=1}^N C_i\right) < \varepsilon$ with $\bigcup_{i=1}^N C_i$ closed.

Restatement

For A Borel,

$$\varepsilon > \nu(A \setminus C) = \mu((A \setminus C) \cap A) = \mu(A \setminus C)$$

January 23, 2024

Review - Abstract Measure

Given (X, Λ, μ) where $\Lambda \subseteq 2^X$ is a σ -algebra, $\mu : \Lambda \rightarrow [0, +\infty]$

$$1. \mu(\emptyset) = 0.$$

$$2. m\left(\bigcup A_i\right) = \sum \mu(A_i), A_i \cap A_j = \emptyset.$$

Properties of a Measure

Monotonicity

$$\mu(A) \leq \mu(B), A, B \in \Lambda, A \subseteq B$$

Countable Subadditivity

$$\mu\left(\bigcup A_i\right) \leq \sum \mu(A_i)$$

Monotone Convergence

$$A_i \subset A_{i+1}, A_i \rightarrow \bigcup A_i \implies \mu(A) = \mu\left(\bigcup A_i\right).$$

$$A_i \supset A_{i+1}, A_i \rightarrow \bigcap A_i \implies \mu(A_i) \rightarrow \mu\left(\bigcap A_i\right) \text{ if } \mu(A_1) < \infty$$

- Example

$$A_n = (n, +\infty) \text{ gives } \bigcap A_n = \emptyset$$

Completeness of a Measure

(X, Λ, μ) is complete if $\forall A \in \Lambda$ with $\mu(A) = 0$, then $\forall B \in \Lambda$ if $B \subseteq A$.

Theorem:

Given (X, Λ, μ) , there exists $(X, \overline{\Lambda}, \overline{\mu})$ such that $\Lambda \subset \overline{\Lambda}$ and $\overline{\mu}(A) = \mu(A)$ if $A \in \Lambda$.

$$\overline{\Lambda} = \{A \cup Z : A \in \Lambda, Z \subset D, D \in \Lambda \text{ with } \mu(D) = 0\}$$

$$\overline{\mu}(A \cup Z) = \mu(A)$$

$(X, \overline{\Lambda}, \overline{\mu})$ is complete.

Measure Space with Topology

Given a topological space (X, τ) , a measure space (X, Λ, μ)

Definition: Locally Finite

The measure μ is locally finite if $\forall x \in X$, there exists an open neighborhood U of x such that $U \in \Lambda$ and $\mu(U) < +\infty$.

Definition: Borel Measure

μ is a Borel measure if the Borel σ -algebra generated by τ , \mathcal{B} , is a subset of Λ .

Definition: Borel Regular

$\forall A \in \Lambda$, $\exists B \in \mathcal{B}$ such that $B \supset A$ and $\mu(B) = \mu(A)$.

Definition: Radon Measure

1. Borel.
2. $\mu(K) < +\infty$ for K compact.
3. $\mu(V) = \sup\{\mu(K) : K \text{ compact}, K \subset V\}$, $\forall V$ open.
4. $\mu(A) = \inf\{\mu(V) : V \text{ open}, A \subset V\}$, $\forall A \in \Lambda$.

Theorem:

If X is a metric space equipped with a Borel regular (X, Λ, μ) , then

1. $\forall A \in \Lambda, \mu(A) < +\infty, \forall \varepsilon > 0, \exists C$ closed where $C \subset A$ and $\mu(C \setminus A) < \varepsilon$.
2. If $\exists \{V_i\}, V_i$ open and $\mu(V_i) < +\infty$, and $A \in \Lambda$ with $A \subset \bigcup V_i$, then $\exists U$ open such that $A \subset U$ and $\mu(U \setminus A) < \varepsilon$.

Proof of 1

Define $\nu(B) = \mu(B \cap A)$ such that (X, Λ, ν) is a new measure space.

Define $F = \{B \in \Lambda : \forall \varepsilon > 0, \exists C \text{ closed}, C \subset B, \nu(B \setminus C) < \varepsilon\}$, all closed sets in F .

Claim 1: $\bigcap A_i, \bigcap A_i \in F$ if $A_i \in F$.

Claim 2: U is open.

$U = \bigcup U_i, U_i = \{x \in U : \text{dist}(x, U^c) \leq \frac{1}{i}\}$, therefore $B \subset F$.

IMAGE HERE - 1

If A is Borel, then $\forall \varepsilon > 0, \exists C$ closed with $C \subset A$ and $\mu(A \setminus C) < \varepsilon$.

To finish, $\forall A \in \Lambda$ by Borel Regularity of μ , $\exists B \in \mathcal{B}$ such that $B \supset A$ and $\mu(B) = \mu(A)$.

Note also that this requires $\mu(B \setminus A) = 0$ since $\mu(A) < +\infty$.

IMAGE HERE - 2

Then $B \setminus A \in \Lambda, \exists D \in \mathcal{B}$ such that $D \supset B \setminus A$ and $\mu(D) = \mu(B \setminus A) = 0$. Then

$$\begin{aligned} B \cap A^c &= B \setminus A \subset D \\ (B \cap A^c)^c &\supset D^c \\ B \cap (B^c \cup A) &\supset D^c \cap B \\ A &\supset B \setminus D \end{aligned}$$

$$A \setminus (B \setminus D) = A \cap (B \cap D^c)^c = A \cap (B^c \cup D) = \overbrace{(A \cap B^c)}^{\emptyset} \cup A \cap D = A \cap D \subset D$$

Therefore $B \setminus D \subset A$, and $\mu(A \setminus (B \setminus D)) = 0$.

$B \setminus D \in \mathcal{B}, \forall \varepsilon > 0, \exists C$ closed such that $C \subset B \setminus D \subset A, \mu((B \setminus D) \setminus C) < \varepsilon$.

This implies that $\mu(A \setminus C) = \mu(A \setminus (B \setminus D)) + \mu((B \setminus D) \setminus C) < \varepsilon$.

Proof of 2

Consider $V_i \setminus A$ where $\mu(V_i \setminus A) \leq \mu(V_i) < +\infty$.

By (1), $\exists C_i$ closed with $C_i \subset V_i \setminus A$ and $\mu((V_i \setminus A) \setminus C_i) < \varepsilon/2^{i+1}$. Write

$$(V_i \setminus A) \setminus C_i = (V_i \setminus A) \cap C_i^c = V_i \cap A^c \cap C_i^c = (V_i \cap C_i^c) \cap A^c = (V_i \setminus C_i) \setminus A$$

Note that $V_i \setminus C_i$ is open, since C_i is closed.

Define $U = \bigcup (V_i \setminus C_i) \supset A$. Then,

$$U \setminus A = \left(\bigcup (V_i \setminus C_i) \right) \setminus A = \bigcup ((V_i \setminus C_i) \setminus A)$$

Therefore $\mu(U \setminus A) \leq \varepsilon \sum_{i=1}^{\infty} \frac{1}{2^{i+1}} = \varepsilon$.

Remark

$X = \bigcup V_i$, V_i open and $\mu(V_i) < +\infty$.

Then $\forall A \in \Lambda$, $\forall \varepsilon > 0$, $\exists U$ open such that $U \supset A$ and $\mu(U \setminus A) < \varepsilon$.

For A^c , $\exists U \supset A^c (\implies U^c \subset A)$, $\mu(U \setminus A^c) < \varepsilon$. So

$$U \cap A = U \setminus A^c = A \setminus U^c = A \cap U$$

and $\mu(A \setminus U^c) < \varepsilon$, $U^c \subset A$ with U^c closed.

Corollary

For \mathbb{R}^n , a measure is Radon if and only if it is locally finite and Borel regular.

• Proof

(\implies)

Let $B(r, x_0) = \{x \in \mathbb{R}^n : |x - x_0| < r\}$ and $\overline{B(r, x_0)} = \{x \in \mathbb{R}^n : |x - x_0| \leq r, \text{ compact}\}$.

Then $\mu(B(r, x_0)) \leq \mu(\overline{B(r, x_0)}) < +\infty$. So μ is locally finite.

For $A \in \Lambda$, we may assume without loss of generality that $\mu(A) < +\infty$.

Then $\forall i$, $\exists U_i$ open where $U_i \supset A$ and $\mu(A) \leq \mu(U_i) \leq \mu(A) + \frac{1}{i} < +\infty$.

Set $G = \bigcap U_i \in \mathcal{B}$, then $\mu(G) = \mu(A)$.

(\impliedby)

1. Borel regular implies Borel.

2. For K compact, $\forall x \in K \ni U_x$ open where $\mu(U_x) < +\infty$.

$\{U_\lambda\}_{\lambda \in k}$ is an open cover. Therefore there is a finite subcover $\{U_{\lambda_i}\}_{i=1}^k$ where

$$\mu(K) \leq \mu\left(\bigcup_{i=1}^k U_{\lambda_i}\right) \leq \sum_{i=1}^k \mu(U_{\lambda_i}) < +\infty$$

3. $\forall V$ open, $B(i) = B(i, 0)$, $V \cap B(i)$, $\mu(V \cap B(i)) < +\infty$, $\exists C_i$ closed where $C_i \subset V \cap B(i)$ so C_i is bounded and therefore compact.

So $\mu(C_i) \leq \mu((V \cap B(i)) \setminus C_i) < \frac{1}{i}$ and $\mu(V \cap B(i)) \leq \mu(C_i) + \frac{1}{i}$.

Then $\mu(V) = \lim_{i \rightarrow \infty} \mu(V \cap B(i)) = \lim_{i \rightarrow \infty} \mu(C_i)$, and $C_i \subset V \cap B(i) \subset V$ compact.

Therefore $\mu(V) = \sup\{\mu(K) : K \text{ compact}, K \subset V\}$.

4. $\forall A \in \Lambda$, $\forall i$, $\exists U_i$ open where $U_i \supset A$ and $\mu(U_i \setminus A) < \frac{1}{i}$

This implies that $\mu(A) \leq \mu(U_i) \leq \mu(A) + \frac{1}{i}$ and therefore $\mu(A) = \inf\{\mu(U) : U \supset A, U \text{ open}\}$.

Caratheodory Construction

Definition: Outer Measure

$$\mu^*(A), \forall A \in 2^X$$

1. $\mu^*(\emptyset) = 0$.

$$2. \mu^*(A) \leq \mu^*(B) \text{ if } A \subseteq B.$$

$$3. \mu^*\left(\bigcup A_i\right) \leq \sum \mu^*(A_i), \forall A_i \in 2^X \text{ (countable subadditivity)}$$

Define $\Lambda = \{A \in 2^X : \mu^*(E) = \mu^*(E \cap A) + \mu^*(E \cap A^c), \forall E \in 2^X\}$.

Then $\mu(A) = \mu^*(A)$ if $A \in \Lambda$.

(X, Λ, μ) is complete.

January 25, 2024

Theorem: Caratheodory Construction

Outer Measure

$$\mu^* : 2^X \rightarrow [0, +\infty].$$

$$1. \mu^*(\emptyset) = 0$$

$$2. \text{ Monotonicity: } \mu^*(A) \leq \mu^*(B), A \subseteq B$$

$$3. \text{ Countable Subadditivity: } \mu^*\left(\bigcup_i A_i\right) \leq \sum_i \mu^*(A_i).$$

Caratheodory Criterion

$A \subset X$ is measurable if $\forall E \in X$,

$$\mu^*(E) = \mu^*(E \cap A) + \mu^*(E \cap A^c)$$

Theorem

The collection Λ of all measurable sets is a σ -algebra.

(X, Λ, μ) is a complete measure space (cf. proof of Lebesgue completeness).

Hausdorff Measure

$\forall A \subseteq \mathbb{R}^n, \forall s \geq 0, H_s^\delta(A) = \inf\left\{\sum_i (d(E_i))^s : \bigcup_i E_i \supset A, d(E_i) \leq \delta\right\}$ where $d(E_i)$ is the diameter of E_i .

Notice that $H_s^{\delta_1}(A) \leq H_s^{\delta_2}(A)$ if $\delta_2 \leq \delta_1$.

Let $H_s^*(A) = \lim_{\delta \rightarrow 0} H_s^\delta(A), \forall A \in 2^{\mathbb{R}^n}$.

Claim: H_s^* is an outer measure.

- Verify

$$1. H_s^*(\emptyset) = 0.$$

$$2. H_s^*(A) \leq H_s^*(B), \forall A \subseteq B \subseteq \mathbb{R}^n.$$

$$3. \text{ Given } A_i \subset \mathbb{R}^N,$$

$\exists \delta_0 > 0$ such that $\forall \delta < \delta_0$, $H_s^* \left(\bigcup_i A_i \right) \leq H_s^\delta \left(\bigcup_i A_i \right) + \frac{\varepsilon}{2}$.

Then $\forall \delta < \delta_0$ fixed, $\forall A_i$, $\exists \{E_i^j\}$ such that $\bigcup_j E_i^j \supset A_i$, $\sum_j (d(E_i^j))^s \leq H_s^\delta(A_i) + \frac{\varepsilon}{2^{i+1}}$, and $d(E_i^j) \leq \delta$. So

$$\begin{aligned} H_s^\delta \left(\bigcup_i A_i \right) &\leq \sum_{i,j} (d(E_i^j))^s \\ &= \sum_i \left(\sum_j (d(E_i^j))^s \right) \\ &= \sum_i \left(H_s^\delta(A_i) + \frac{\varepsilon}{2^{i+1}} \right) \\ &= \sum_i H_s^\delta(A_i) + \frac{\varepsilon}{2} \end{aligned}$$

and

$$H_s^* \left(\bigcup_i A_i \right) \leq \sum_i H_s^\delta(A_i) + \varepsilon \leq \sum_i H_s^*(A_i) + \varepsilon, \quad \forall \varepsilon > 0.$$

Then, since H_s^* is an outer measure, it is a measure by the Caratheodory construction.

Definition: Hausdorff Measure

The Hausdorff Measure $H_s : \Lambda \rightarrow [0, +\infty)$ on a σ -algebra $\Lambda \subset 2^{\mathbb{R}^n}$.

Not Locally Finite

Consider $B(0,1) = \{x : |x| < 1\}$.

Then $H_s(B(0,1)) = \infty$ for $s < n$.

That is, the Hausdorff measure is not locally finite for $s < n$.

Complete

The Hausdorff measure, by the Caratheodory construction, is complete.

Symmetry

1. Translation Invariance: $H_s(A+x) = H_s(A)$.
2. Rotation Invariance: $H_s(RA) = H_s(A)$.
3. Scaling: $H_s(\lambda A) = \lambda^s H_s(A)$.

Open Balls Measurable

What about $B(0,1) \subset \mathbb{R}^n$. For $\delta > 0$,

$$H_s^*(E \cap B(0,1)) + H_s^*(E \cap B(0,1)^c) \leq H_s^*(E \cap B(0,1-\delta)) + H_s^*(E \cap (B(0,1) \setminus B(0,1-\delta))) + H_s^*(E \cap B(0,1)^c)$$

Want to show that for all $\varepsilon > 0$, this is $\leq H_s^*(E) + \varepsilon$.

- Lemma 1

$$H_s^*(E \cap B(0, 1 - \delta)) + H_s^*(E \cap B(0, 1)^c) = H_s^*(E \cap (B(0, 1 - \delta) \cup B(0, 1)^c)) \leq H_s^*(E)$$

- Lemma 2

$$H_s^*(E \cap (B(0, 1) \setminus B(0, 1 - \delta))) < \varepsilon.$$

- Lemma 1'

If $A, B \subset \mathbb{R}^n$, $\text{dist}(A, B) > 0$, then $H_s^*(A \cup B) = H_s^*(A) + H_s^*(B)$.

Since $\{E_i\}$ covering $A \cup B$, $d(E_i) < \frac{1}{4}\text{dist}(A, B)$ gives

$$\delta < \frac{1}{4}\text{dist}(A, B) \iff \{E_j^A\} \cup \{E_k^B\}$$

if and only if $\{E_j^A\}$ covers A and $\{E_k^B\}$ covers B . Therefore,

$$\begin{aligned} \sum_i (d(E_i))^s &= \sum_j (d(E_j^A))^s + \sum_k (d(E_k^B))^s \\ \inf \left\{ \sum_i (d(E_i))^s \right\} &= \inf \left\{ \sum_j (d(E_j^A))^s \right\} + \inf \left\{ \sum_k (d(E_k^B))^s \right\} \end{aligned}$$

and $H_s^\delta(A \cup B) = H_s^\delta(A) + H_s^\delta(B)$.

Thus $H_s^*(A \cup B) = H_s^*(A) + H_s^*(B)$.

Let $T_i = E \cap \left(B\left(0, 1 - \frac{1}{i+1}\right) \right) \setminus B\left(0, 1 - \frac{1}{i}\right)$.

IMAGE HERE - 1 CONCENTRIC RINGS

We want to show that $H_s^*\left(E \cap \left(B(0, 1) \setminus B\left(0, \frac{1}{i}\right)\right)\right) < \varepsilon$ for $i \gg 1$. Then

$$\begin{aligned} \bigcup_{k=1} T_k &= (B(0, 1) \setminus \{0\}) \cap E \\ \bigcup_{k=i} T_k &= \left(B(0, 1) \setminus B\left(0, 1 - \frac{1}{i}\right) \right) \cap E \end{aligned}$$

Claim: $\sum_i H_s^*(T_i) < +\infty$. It suffices to prove this claim.

$$\sum_{i \text{ even}}^{2k} H_s^*(T_i) = H_s^*\left(\bigcup_{i \text{ even}}^{2k}\right) \leq H_s^*(E) < +\infty$$

$$\sum_{i \text{ odd}}^{2k+1} H_s^*(T_i) = H_s^*\left(\bigcup_{i \text{ odd}}^{2k+1}\right) \leq H_s^*(E) < +\infty$$

Then $\sum_i^k H_s^*(T_i) < \infty$.

Borel

Take a countable, dense set $\{q_i\} \subset \mathbb{R}^n$ and $\left\{B\left(q_i, \frac{1}{k}\right)\right\}_{i,k}$.

Claim: $\forall V \subseteq \mathbb{R}^n$ open, then $V = \bigcup_l B\left(q_{i_l}, \frac{1}{k_l}\right)$.

Then $\mathcal{B} \subseteq \Lambda$ and the Hausdorff measure is Borel.

Borel Regular

$\forall A \subset \Lambda$, $\exists B \in \mathcal{B}$ such that $B \supset A$ and $H_s(B) = H_s(A)$.

$\forall \delta = \frac{1}{j}$, $\{E_i^j\}$ E_i^j closed balls with $d(E_i^j) < \frac{1}{j}$,

$$\sum_i (d(E_i))^\delta \leq H_s^\delta(A) + \frac{1}{j}$$

Take $B = \bigcap_j \left(\bigcup_i E_i^j\right) \in \mathcal{B}$ since $B = \bigcap_j \bigcup_i E_i^j \supset A$. Then

$$\begin{aligned} H_s^\delta(B) &\leq H_s^\delta\left(\bigcup_i E_i^j\right) \\ &\leq \sum_i H_s^\delta(E_i^j) \\ &\leq \sum_i (d(E_i^j))^\delta \\ &\leq H_s^\delta(A) + \frac{1}{j} \end{aligned}$$

and in the limit as $j \rightarrow \infty$

$$H_s^*(A) \leq H_s^*(B) \leq H_s^*(A)$$

Fractional or Hausdorff Dimension

Theorem:

$$1. H_s^*(A) < +\infty \implies H_t^*(A) = 0, \forall t > s \geq 0.$$

$$2. H_t^s > 0 \implies H_s(A) = \infty, \forall 0 \leq s < t$$

Proof

$$\begin{aligned} H_s^\delta(A) &\sim \sum_i (d(E_i))^\delta \\ &= \sum_i (d(E_i))^t (d(E_i))^{s-t} \end{aligned}$$

So $s < t$ gives $\geq \delta^{s-t}$.

In the other direction, when $s < t$

$$\begin{aligned} \sum_i (d(E_i))^t &= \sum_i (d(E_i))^s (d(E_i))^{t-s} \\ &\leq \delta^{t-s} \sum_i (d(E_i))^s \end{aligned}$$

Definition: Hausdorff Dimension

Given $A \subset \mathbb{R}^n$,

$$\begin{aligned}\dim_H(A) &= \sup \{s : H_s^*(A) = \infty\} \\ &= \sup \{s : H_s^*(A) > 0\} \\ &= \inf \{s : H_s^*(A) = 0\} \\ &= \inf \{s : H_s^*(A) < +\infty\}\end{aligned}$$

Example 1

\mathbb{R}^n has n Hausdorff dimension.

Consider the n -cube with sides d , $C(d)$. Then

$$H_s(C(d)) = C(n, s)d^s$$

So $C(n, s) = C(n, s)2^{nk} \frac{1}{(2^k)^s} = C(n, s)2^{(n-1)k}$.

If $s < n$, this tends to infinity as $k \rightarrow \infty$.

If $s > n$ it tends to 0.

Example 2

Cantor set has Hausdorff dimension $\frac{\log(2)}{\log(3)}$.

$$\bigcup_{k=1}^{2^n} C_n^k = \frac{\log(2)}{\log(3)}$$

where $|C_n^k| = \frac{1}{3^n}$, so $H_s^\delta(C^n) \sim \frac{2^n}{(3^n)^s} = \left(\frac{2}{3}\right)^n$.

Example 3

The Koch snowflake has dimension $\frac{\log(4)}{\log(3)}$.

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Lemma:

Given a measure space (X, Λ, μ) and an extended real-valued function $f : X \rightarrow [-\infty, +\infty]$, the following are equivalent

1. $\forall \alpha \in \mathbb{R}, \{x \in X : f(x) > \alpha\} \in \Lambda$.
2. $\forall \alpha \in \mathbb{R}, \{x \in X : f(x) \geq \alpha\} \in \Lambda$.
3. $\forall \alpha \in \mathbb{R}, \{x \in X : f(x) < \alpha\} \in \Lambda$.
4. $\forall \alpha \in \mathbb{R}, \{x \in X : f(x) \leq \alpha\} \in \Lambda$.
5. $\forall U \subset \mathbb{R}$ open, $f^{-1}(U) \in \Lambda$ and $f^{-1}(\pm\infty) \in \Lambda$.

Proof 1 Implies 2

$$\{x \in X : f(x) \geq \alpha\} = \bigcap_{n=1}^{\infty} \left\{x \in X : f(x) > \alpha - \frac{1}{n}\right\}.$$

Proof 2 Implies 3

$$\{x \in X : f(x) < \alpha\} = \{x \in X : f(x) \geq \alpha\}^c$$

Proof 3 Implies 4

$$\{x \in X : f(x) \leq \alpha\} = \bigcap_{n=1}^{\infty} \left\{x \in X : f(x) < \alpha + \frac{1}{n}\right\}$$

Proof 4 Implies 1

$$\{x \in X : f(x) > \alpha\} = \{x \in X : f(x) \leq \alpha\}^c$$

Proof of 5

$\forall U \subset \mathbb{R}$ open, $V = \bigcup_i I_i$ disjoint open intervals.

Therefore $f^{-1}((a, b)) = \{x \in X : f(x) > a\} \cap \{x \in X : f(x) < b\}$.

Similarly, $f^{-1}(-\infty) = \bigcap_n \{x \in X : f(x) < -n\}$ and $f^{-1}(\infty) = \bigcap_n \{x \in X : f(x) > n\}$.

Proof 5 Implies 1

$$\{x \in X : f(x) > \alpha\} = f^{-1}((\alpha, +\infty)) \cup f^{-1}(+\infty) \in \Lambda.$$

Definition: Measurable Function

For a measure space (X, Λ, μ) , an extended real-valued function $f : X \rightarrow [-\infty, +\infty]$ is said to be measurable if one or all of (1)-(5) hold.

Remark:

If (X, Λ, μ) is Borel, then continuous functions are always measurable.

Remark:

The characteristic function

$$\chi_A = \begin{cases} 1 & x \in A \\ 0 & x \notin A \end{cases}$$

is measurable if $A \in \Lambda$.

Definition: Simple Functions

The function ϕ is simple if

$$\phi(x) = \sum_{i=1}^k \lambda_i \chi_{A_i}, \quad \lambda_i \in \mathbb{R}, A_i \in \Lambda$$

Proposition:

Given a measure space (X, Λ, μ) and measurable, real-valued f, g ,

- $f \pm g$ is measurable.

$$\{x \in X : f(x) + g(x) < \alpha\} = \bigcup_{r \in \mathbb{Q}} (\{x \in X : f(x) < r\} \cup \{x \in X : g(x) < \alpha - r\}).$$

- f^2 is measurable

$$\forall \alpha \geq 0, \{x \in X : f^2(x) < \alpha\} = \{x \in X : f(x) < \sqrt{\alpha}\} \cap \{x \in X : f(x) > -\sqrt{\alpha}\}.$$

- $f \cdot g$ is measurable

$$f(x) \cdot g(x) = \frac{1}{2} ((f+g)^2 - f^2 - g^2).$$

Definition: Almost Everywhere Equality

Measurable functions f and g on the space (X, Λ, μ) are the same almost everywhere with respect to μ (written μ -a.e.) if

$$\mu(\{x \in X : f(x) \neq g(x)\}) = 0$$

Proposition:

For a complete measure space (X, Λ, μ) , if f and g are equal μ -a.e., then f is measurable if and only if g is measurable.

Proof

$$\begin{aligned} \{x \in X : f(x) > \alpha\} &= (\{x \in X : f(x) > \alpha\} \cap \{x \in X : f(x) = g(x)\}) \cup \{x \in X : f(x) > \alpha\} \cap \underbrace{\{x \in X : f(x) \neq g(x)\}}_{\mu=0} \\ &= (\{x \in X : g(x) > \alpha\} \cap \{x \in X : f(x) = g(x)\}) \cup \{x \in X : f(x) > \alpha\} \cap \underbrace{\{x \in X : f(x) \neq g(x)\}}_{\mu=0} \end{aligned}$$

Proposition:

Given $\{f_k(x)\}$ measurable.

1. $g_n(x) = \sup\{f_1(x), f_2(x), \dots, f_n(x)\}$ and $h_n(x) = \inf\{f_1(x), f_2(x), \dots, f_n(x)\}$ measurable.
2. $g(x) = \sup\{f_n(x)\}$ and $h(x) = \inf\{f_n(x)\}$ measurable.
3. $\limsup_{n \rightarrow +\infty} f_n(x) = \inf_n \sup\{f_n(x), f_{n+1}(x), \dots\}$ and $\liminf_{n \rightarrow +\infty} f_n(x) = \sup_n \inf\{f_n(x), f_{n+1}(x), \dots\}$ measurable.
4. $f_n(x) \rightarrow f(x)$ pointwise $\implies f$ measurable.

Proof of A

$$\begin{aligned} \{x \in X : g_n(x) > \alpha\} &= \bigcup_{k=1}^n \{x \in X : f_k(x) > \alpha\} \\ \{x \in X : h_n(x) < \alpha\} &= \bigcup_{k=1}^n \{x \in X : f_k(x) < \alpha\} \end{aligned}$$

Proof of B

$$\begin{aligned}\{x \in X : g(x) > \alpha\} &= \bigcup_n \{x \in X : f_n(x) > \alpha\} \\ \{x \in X : h(x) < \alpha\} &= \bigcup_n \{x \in X : f_n(x) < \alpha\}\end{aligned}$$

Definition: Almost Everywhere Convergence

For $f_n(x)$ measurable, $f_n(x) \rightarrow f(x)$ μ -a.e. in X if $f_n(x) \rightarrow f(x)$ in $A \subset X$ pointwise where $\mu(X \setminus A) = 0$.

Proposition:

On a complete measure space (X, Λ, μ) with f_n measurable and $f_n(x) \rightarrow f(x)$ μ -a.e. in X , $f(x)$ is measurable.

Proof

$f_n(x) \rightarrow f(x)$ pointwise in A and $\mu(A^c) = 0$.

$$\{x \in X : f(x) > \alpha\} = (\{x \in X : f(x) > \alpha\} \cap A) \cup (\{x \in X : f(x) > \alpha\} \cap A^c).$$

Theorem:

With (X, Λ, μ) a measure space and f measurable, there exist simple functions ϕ_n such that

1. $|\phi_n(x)| \leq |\phi_{n+1}(x)|$.
2. $\phi_n(x) \rightarrow f(x)$ pointwise in X .
3. If f is bounded, then $\phi_n(x) \rightrightarrows f(x)$ in X .

Proof

Consider $(-\infty, -n] \cup (-n, n) \cup [n, +\infty)$, and define $N_n = \{x \in X : f(x) \leq -n\}$ and $P_n = \{x \in X : f(x) \geq n\}$.

Then $\bigcap_n (N_n \cup P_n) = \emptyset$.

Define

$$\begin{aligned}A_{n,k} &= \left\{x \in X : \frac{k-1}{2^n} < f(x) \leq \frac{k}{2^n}\right\}_{k=-1, -2, \dots, -n2^n+1} \\ A_{n,0} &= \left\{x \in X : \frac{-1}{2^n} < f(x) < 0\right\} \\ A_{n,1} &= \left\{x \in X : 0 < f(x) < \frac{1}{2^n}\right\} \\ A_{n,k} &= \left\{x \in X : \frac{k-1}{2^n} \leq f(x) < \frac{k}{2^n}\right\}_{k=2, 3, \dots, n2^n}\end{aligned}$$

and set

$$\phi_n(x) = -n\chi_{N_n} + \sum_{k=0}^{-n2^n+1} \frac{k}{2^n} \chi_{A_{n,k}} + \sum_{k=1}^{n2^n} \frac{k-1}{2^n} \chi_{A_{n,k}} + n\chi_{P_n}$$

Claim:

1. $\forall x \in X, \phi_n(x) \rightarrow f(x)$.
2. if $\exists N \in \mathbb{N}$ such that $|f(x)| < N \implies \phi_n(x) \rightrightarrows f(x)$ in X .

Proof

$$|\phi_n(x) - f(x)| \leq \frac{1}{2^n}, \forall x \in X \setminus (U_n \cup P_n)$$

Note $\forall x \in X, \exists m \in \mathbb{N}$ such that $x \notin N_m \cup P_m$. So $|f(x)| < m$.

Then boundedness implies $\exists N$ such that $N_N \cup P_N = \emptyset$.

Therefore $\forall x \in X, |\phi_n(x) - f(x)| < \frac{1}{2^n}, \forall n \geq N$.

Theorem: Egoroff

Given a measure space (X, Λ, μ) , $\mu(X) < +\infty$ and $f_n \rightarrow f$ μ -a.e. in X , then $\forall \delta > 0, \exists A \in \Lambda$ such that $\mu(X \setminus A) < \delta$ and $f_n(x) \rightarrow f(x)$ in A .

Recall: Pointwise Convergence

$\forall x \in X, f_n(x) \rightarrow f(x)$ if $\forall \varepsilon > 0, \exists N \in \mathbb{N}$ such that $|f_n(x) - f(x)| < \varepsilon, \forall n \geq N$.

$$B_{N,\varepsilon} = \{x \in X : \exists N \in \mathbb{N}, |f_n(x) - f(x)| < \varepsilon, \forall n \geq N\}$$

In negation, $\exists \varepsilon > 0$ such that $\forall N \in \mathbb{N}, \exists m \geq N$ such that $|f_m(x) - f(x)| \geq \varepsilon$.

$$A_{N,\varepsilon} = B_{N,\varepsilon}^c = \{x \in X : \exists m \geq N, |f_m(x) - f(x)| \geq \varepsilon\}$$

$$\text{Then } \{x \in X : f_n(x) \rightarrow f(x)\} = \bigcap_{\varepsilon > 0} \bigcup_N B_{N,\varepsilon} = \bigcap_{\varepsilon_i \rightarrow 0} \bigcup_i B_{N_i, \varepsilon_i}$$

$$\text{and } \{x \in X : f_n(x) \not\rightarrow f(x)\} = \bigcup_{\varepsilon > 0} \bigcap_N A_{N,\varepsilon} = \bigcup_{\varepsilon_i \rightarrow 0} \bigcap_i A_{N_i, \varepsilon_i} \text{ where } \varepsilon_i = \frac{1}{i}.$$

February 2, 2024

Review: Measurable Function

An extended, real-valued function $f : X \rightarrow [-\infty, +\infty]$ is measurable if one or all of the following hold

1. $\forall \alpha \in \mathbb{R}, \{x : f(x) > \alpha\} \in \Lambda$.
2. $\forall \alpha \in \mathbb{R}, \{x : f(x) \geq \alpha\} \in \Lambda$.
3. $\forall \alpha \in \mathbb{R}, \{x : f(x) < \alpha\} \in \Lambda$.
4. $\forall \alpha \in \mathbb{R}, \{x : f(x) \leq \alpha\} \in \Lambda$.
5. $\forall V \subseteq \mathbb{R}$ open, $f^{-1}(V) = \{x : f(x) \in V\}$ and $f^{-1}(-\infty), f^{-1}(+\infty) \in \Lambda$.

Properties

1. For $f = g$ μ -a.e., f is measurable if and only if g is measurable.
2. For f, g measurable, $f + g$ and $f \cdot g$ are measurable.
3. For $\{f_n\}$ measurable,
 - (a) $\sup_{n \leq k} \{f_n\}$ and $\inf_{n \leq k} \{f_n\}$ are measurable.
 - (b) $\sup_n \{f_n\}$ and $\inf_n \{f_n\}$ are measurable.
 - (c) $\limsup_{n \rightarrow \infty} f_n$ and $\liminf_{n \rightarrow \infty} f_n$ are measurable.

(d) if $f_n \rightarrow f$ μ -a.e. in X , then f is measurable.

Examples

Characteristic Functions

$$\chi_A = \begin{cases} 1 & x \in A \\ 0 & x \notin A \end{cases}, \quad A \in \Lambda$$

Simple Functions

$$\sum_{i=1}^k \alpha_i \chi_{A_i}, \quad \alpha_i \in \mathbb{R}, A_i \in \Lambda, A_j \cap A_k = \emptyset$$

Step Functions

$$\sum_{i=1}^k \alpha_i \chi_{I_i}, \quad I_i \text{ interval}$$

Theorem:

On a measure space (X, Λ, μ) , suppose f is measurable.
There exists a sequence of simple functions $\{\phi_n\}$ such that

1. $\phi_n \rightarrow f$ pointwise.
2. $\phi_n \rightrightarrows f$ for f bounded.

Proof

Let $N_n = \{x : f(x) \leq -n\}$ and $A_{n,k} = \{x : \frac{k-1}{2^n} < f(x) \leq \frac{k}{2^n}\}$. Then

$$\begin{aligned} A_{n,0} &= \left\{x : -\frac{1}{2^n} < f(x) < 0\right\} \\ A_{n,1} &= \left\{x : 0 < f(x) < \frac{1}{2^n}\right\} \\ A_{n,k} &= \left\{x : \frac{k-1}{2^n} < f(x) < \frac{k}{2^n}\right\} \\ P_n &= \{x : f(x) \geq n\} \end{aligned}$$

and

$$\phi_n = -n\chi_{N_n} + \sum_{k=-n2^n+1}^D \frac{k}{2^n} \chi_{A_{n,k}} + \sum_1^{n2^n} \chi_{A_{n,k}} + n\chi_{P_n}$$

So

$$|\phi_n(x) - f(x)| \leq \frac{1}{2^n}, \quad x \in X \setminus (N_n \cup P_n), \quad \bigcap_n (N_n \cap P_n) = \emptyset$$

Egoroff Theorem

Given (X, Λ, μ) where $\mu(X) < +\infty$, if

1. $f_n(x) \rightarrow f(x)$ μ -a.e. in X and
2. f_n, f μ -a.e. finite.

Then, $\forall \delta > 0, \exists A \in \Lambda$ with $\mu(A) < \delta$ such that $f_n(x) \rightrightarrows f(x)$ on A^c .

Proof

Define $D = \{x : f_n(x) \rightarrow f(x)\} = X$.

Then $\forall \varepsilon > 0, \exists m \in \mathbb{N}$ such that $|f_n(x) - f(x)| < \varepsilon, \forall n \geq m$.

Say that the universal quantifier \forall is equivalent to grand intersection and the existential quantifier \exists is equivalent to grand union. Then

$$D_{m,\varepsilon} = \{x : |f_n(x) - f(x)| < \varepsilon, \forall n \geq m\}$$

and

$$\bigcap_{\varepsilon > 0} \bigcup_m D_{m,\varepsilon} = X.$$

The negation is

$$D_{n,\varepsilon}^c = \{x : \exists n \geq m, |f_n(x) - f(x)| \geq \varepsilon\}$$

Then injection is equivalent to the complement.

Set $\varepsilon_i = \frac{1}{i}$ such that

$$D = \bigcap_i \bigcup_m D_{m,1/i}$$

$$\emptyset = D^c = \bigcup_i \bigcap_m D_{m,1/i}^c$$

So $\bigcap_m D_{m,1/i}^c = \emptyset$,

$$D_{m,1/i}^c = A_{m,1/i} = \left\{x : \exists n \geq m, |f_n(x) - f(x)| \geq \frac{1}{i}\right\}$$

and $A_{n,1/i} \supset A_{n+1,1/i} \supset \dots$. Therefore

$$\mu(A_{n,1/i}) \rightarrow \mu\left(\bigcap_m A_{m,1/i}\right) = 0$$

for $\mu(X) < +\infty$.

Thus, $\forall i, \exists m_i$ such that $\mu(A_{m_i,1/i}) < \frac{\delta}{2^{i+1}}$. It follows that $A = \bigcup_i (A_{m_i,1/i})$,

$$\mu(A) \leq \sum \mu(A_{m_i,1/i}) < \delta$$

and

$$x \in A^c = \bigcap_i A_{m_i, 1/i}^c = \bigcap_i D_{m_i, 1/i} = \bigcap_i \left\{ x : |f_n(x) - f(x)| < \frac{1}{i}, \forall n \geq m_i \right\}$$

Finally, this implies $f_n(x) \Rightarrow f(x)$ in A^c .

Example

Take $f_n = \chi_{[n, n+1]}$ on \mathbb{R} , then $f_n(x) \rightarrow 0$ in \mathbb{R} but $A \subset \mathbb{R}$, $\mu(A) < \frac{1}{2}$, $A^c \cap [n, n+1] \neq \emptyset$, $\forall n$.
That is, $\forall n$, $\exists x \in A^c$ such that $f_n(x) = 1$ but $f(x) = 0$.
Therefore $f_n(x) \not\Rightarrow f(x)$ on \mathbb{R} .

Definition: Essential Bounds

On a measure space (X, Λ, μ) with f measurable, define $\|f\|_\infty = \inf\{M : \mu(\{x : |f(x)| > M\}) = 0\}$.
This is the L^∞ -norm.

Proposition:

$f_n \Rightarrow f$ on A where $\mu(A^c) = 0$ if and only if $\|f_n - f\|_\infty \rightarrow 0$.

Proof

(\Rightarrow)

$\forall \varepsilon > 0$, $\exists m \in \mathbb{N}$ such that $|f_n(x) - f(x)| < \frac{\varepsilon}{2}$, $\forall x \in A$.

Claim: $\|f_n(x) - f(x)\|_\infty < \varepsilon$, $\forall n \geq m$.

$$\|f_n(x) - f(x)\|_\infty = \inf\{M : \mu(\{x : |f_n(x) - f(x)| > M\}) = 0\}$$

Where $\{x : |f_n(x) - f(x)| > n\} \subset A^c$ and $n \geq m$ and $M \geq \varepsilon/2$.

(\Leftarrow)

Recall: Urysohn's Lemma

For X locally compact and Hausdorff, $K \subset U$ for K compact and U open, $\exists \phi$ continuous such that $\phi = \begin{cases} 1 & K \\ 0 & U^c \end{cases}$.

Theorem: Vitali-Lusin

On measure space (X, Λ, μ) with X locally compact and Hausdorff and μ a Radon measure.

For f measurable, μ -a.e. finite and vanishing outside A where $\mu(A) < +\infty$,

$\forall \varepsilon > 0$, $\exists g$ continuous with compact support such that $\mu(\{x : f(x) \neq g(x)\}) < \varepsilon$.

Proof

1. $\exists C \subset A$ compact with $\mu(A \setminus C) < \varepsilon$.
2. For A compact with $\mu(A) < +\infty$, $\exists U \supset A$ open neighborhood with compact closure and $\mu(U \setminus A) < \varepsilon$.
3. $\phi_n = -n\chi_{N_n} + \sum_{-n2^n+1}^0 \frac{k}{2^n} \chi_{A_{n,k}} + \sum_1^{n2^n} \frac{k-1}{2^n} \chi_{A_{n,k}} + n\chi_{P_n}$

Since we may minimize $\mu(N_n \cup P_n) < \varepsilon$,

$$\phi_n = \sum_{-n2^n+1}^0 \frac{k}{2^n} \chi_{A_{n,k}} + \sum_1^{n2^n} \frac{k-1}{2^n} \chi_{A_{n,k}}$$

Take $C_{1,k} \subset A_{1,k}$ compact with $\mu(C_{1,k}) \geq \mu(A_{1,k}) - 2^{-1}2^{-|k|+1}\varepsilon$. Write

$$C_1 = \bigcup_k C_{1,k}$$

and inductively define $C_{n-1,k}$ and $C_{n-1} = \bigcup_k C_{n-1,k}$ such that $C_{n,k} \subset A_{n,k} \cap C_{n-1}$ compact and

$$\mu(C_{n,k}) \geq \mu(A_{n,k} \cap C_{n-1}) - 2^{-1}2^{-|k|+1}\varepsilon$$

Define, by Urysohn's Lemma,

$$\tilde{\chi}_{A_{n,k}} := \begin{cases} 1 & C_{n,k} \\ 0 & U^c \cup \bigcup_{l \neq k} C_{n,l} \end{cases}$$

where $C_n \subset C_{n-1}$, $C = \bigcap C_n$, $C_n = \bigcup_k C_{n,k}$.
Then define

$$g_n := \sum_{-n2^n+1}^0 \frac{k}{2^n} \tilde{\chi}_{A_{n,k}} + \sum_1^{n2^n} \frac{k-1}{2^n} \tilde{\chi}_{A_{n,k}}$$

Then $g_n = \phi_n$ on C for all n .

Therefore $g_n = \phi_n \Rightarrow \hat{g} = f$ on C .

By uniform convergence, \hat{g} is continuous on C .

So, again by Urysohn's Lemma, $g = \phi \hat{g}$ and $\{x : g \neq f\} = U \setminus C$.

February 8, 2024

Midterm Review

Problem 2

Given a finite measure space (X, Λ, μ) , $\mu(X) < +\infty$ and a function f which is μ -a.e. finite.
Monotone Convergence Theorem:

1. $A_1 \subset A_2 \subset \dots$, then $\mu(\bigcup_i A_i) = \lim_{i \rightarrow \infty} \mu(A_i)$.
2. $A_1 \supset A_2 \supset \dots$, then $\mu(\bigcap_i A_i) = \lim_{i \rightarrow \infty} \mu(A_i)$ for $\mu(A_1) < +\infty$.

If $A_k = \{x : |f(x)| > k\}$ and

$$F = \bigcap_{k=1}^{\infty} A_k$$

then $\mu(F) = \lim_{k \rightarrow \infty} \mu(A_k) = 0$ since $\mu(X) < +\infty$.

If instead we consider A_k^c , then

$$\bigcup_k A_k^c = X \setminus F$$

Problem 3

1. Borel

Given $(\alpha, +\infty)$, we want $\forall E \subset \mathbb{R}$

$$m^*(E \cap (\alpha, +\infty)) + m^*(E \cap (-\infty, \alpha]) \leq m^*(E)$$

$\forall \varepsilon > 0, \exists \{I_i\}$ pen intervals

$$\bigcup_i I_i \supset E \quad \sum_i |I_i| \leq m^*(E) + \varepsilon/2$$

Divide $\{I_i\}$ into 3 groups,

$$C^\ell = \{I \in \{I_i\} : I \text{ is to the left of } \alpha\}$$

$$C^r = \{I \in \{I_i\} : I \text{ is to the right of } \alpha\}$$

$$C^m = \{I \in \{I_i\} : \alpha \in I\}$$

Then, $\forall I_k^m \in C^m = \{I_k^m\}$, and

$${}^\ell I_k^n = \left(a_k, \alpha + \frac{2}{2^{k+2}} \right)$$

$${}^r I_k^n = \left(\alpha - \frac{2}{2^{k+2}}, b_k \right)$$

$${}^m I_k^n = (a_k, b_k)$$

where also

$$A_n \supset (\alpha, +\infty)^c \quad A_n = \left(-\infty, \alpha + \frac{1}{2^n} \right)$$

$$B_n \supset (\alpha, +\infty) \quad B_n = \left(\alpha + \frac{1}{2^n}, +\infty \right)$$

$$A_n \cap B_n = \left(\alpha - \frac{1}{2^n}, \alpha + \frac{1}{2^n} \right)$$

So ${}^\ell I_k^n \cup {}^r I_k^n = I_k^n$, and $|{}^\ell I_k^n| + |{}^r I_k^n| = |I_k^n| + \frac{\varepsilon}{2^{k+1}}$.

Finally

$$\begin{aligned} m^*(E \cap (\alpha, +\infty)) + m^*(E \cap (-\infty, \alpha]) &\leq \sum_{I \in C^r} |I| + \sum_k |{}^r I_k^n| + \sum_{I \in C^\ell} |I| + \sum_k |{}^\ell I_k^n| \\ &\leq \sum_{I \in C^r} |I| + \sum_{I \in C^\ell} |I| + \sum_k |I_k^n| + \frac{\varepsilon}{2} \\ &\leq m^*(E) + \frac{\varepsilon}{2} + \frac{\varepsilon}{2} \end{aligned}$$

2. $\mu(K) < +\infty$ for $K \subset \mathbb{R}$ compact.

K is bounded, $k \in (-M, M)$ for large M .

Therefore $\mu(K) \leq 2M < +\infty$.

3. $\forall U \subset \mathbb{R}$ open, we want to show $\exists K_n$ compact such that $K_n \subset U$ and $\mu(K_n) \rightarrow \mu(U)$.

Let $U = \bigcup_i I_i$ a union of countably many disjoint open intervals (e.g. $I_i = (a_i, b_i)$).

Then $m(U) = \sum_i m(I_i)$.

Set $I_i^n = \left[a_i + \frac{1}{n2^{i+1}}, b_i - \frac{1}{n2^{i+1}} \right]$. Then

$$\sum_i^k |I_i^n| \geq \sum_i^k |I_i| - \frac{1}{n}, \quad \forall k$$

It follows that

$$\sum_{i=1}^k |I_i| \rightarrow \sum_{i=1}^{\infty} |I_i|, \quad \text{as } k \rightarrow +\infty$$

and

$$K_k^n = \bigcup_{i=1}^k I_i^n \subset U \quad \text{compact}$$

$$m(U) \geq m(K_k^n) = \sum_{i=1}^n |I_i^n| \geq \underbrace{\sum_{i=1}^{\infty} |I_i|}_{m(U)} - \frac{1}{n}$$

Alternatively, we have the theorem that if X is a metric space and μ is Borel regular on (X, Λ) , then

(a) $A \in \Lambda$, $\mu(A) < +\infty$, $\forall \varepsilon > 0$, $\exists C$ closed with $C \subset A$ such that $\mu(A \setminus C) < \varepsilon$.

(b) $\exists \{U_i\}$, $\mu(U_i) < +\infty$, U_i open where $A \subset \bigcup_i U_i$, $\forall \varepsilon > 0$ there exists V open such that $V \supset A$ and $\mu(V \setminus A) < \varepsilon$.

With the corollary that for μ on \mathbb{R}^n , μ is Radon if and only if it is locally finite and Borel regular.

4. For $A \in \Lambda$, $m(A) = \inf\{m(V) : V \supset A, V \text{ open}\}$

Recall Borel regularity: $\forall A \in \Lambda$, there is some Borel set $B \supset A$ with $m(B) = m(A)$.

We may assume $m(A) < +\infty$. Then, $\forall \varepsilon > 0$, there is some collection of open intervals $\{I_i^n\}$ containing A where

$$\sum_i |I_i^n| \leq m(A) + \varepsilon$$

Set $\varepsilon = \frac{1}{n}$ and let $U^n = \bigcup_i I_i^n \supset A$ open. Then

$$m(A) \leq m(U^n) \leq \sum_i |I_i^n| \leq m(A) + \frac{1}{n}$$

If $B = \bigcap_n U_n$, then $\lim_{n \rightarrow \infty} m(U^n) = m(A)$ and $m(B) = m(A)$.

Problem 4

Given $f : \mathbb{R} \rightarrow \mathbb{R}$, continuous outside a measure zero set D .

That is, $\bar{f} : \mathbb{R} \setminus D \rightarrow \mathbb{R}$ is continuous.

$\forall V \subset \mathbb{R}, f^{-1}(V) = (f^{-1}(V) \cap (\mathbb{R} \setminus D)) \cup (f^{-1}(V) \cap D)$.

By measure completeness, we are automatically safe on $f^{-1}(V) \cap D$.

Claim: $f^{-1}(V) \cap (\mathbb{R} \setminus D) = \bar{f}^{-1}(V)$.

Claim: \bar{f}^{-1} is measurable.

Claim: $\bar{f}^{-1}(V) = U \cap (\mathbb{R} \setminus D)$ where $U \subset \mathbb{R}$ open.

Since $U \cap (\mathbb{R} \setminus D)$ is open in the subspace topology, we are done.

Alternatively (similarly to Problem 8 below), for D such that $m(D) = 0$, $\forall n, \exists U^n$ such that $m(U^n) \leq 2^{-n}$, $U^n \supset D$ and $U^n = \bigcup_i (a_i, b_i)$ where $(a_j, b_j) \cap (a_k, b_k) = \emptyset$ and $a_i, b_i \in \mathbb{R} \setminus D$. So

$$f_n = \begin{cases} f(x), & x \in (U^n)^c \\ f(a_i) + \frac{f(b_i) - f(a_i)}{b_i - a_i}(x - a_i), & x \in (a_i, b_i) \subset U^n \end{cases}$$

Then $\{x : f_n(x) \neq f(x)\} \subset U^n$ and $m(\{x : f_n(x) \neq f(x)\}) \leq 2^{-n}$.

Homework 4 Problem 8

Assume $f(x)$ is decreasing.

1. Discontinuities are limited to jump discontinuities.
2. Discontinuities are countable.
3. $D = \{x_i\}_i$, $\forall n$ there exists an open cover $\{I_i^n = (a_i, b_i)\}$ where $\bigcup_i I_i^n = C^n \supset \{x_i\}_i$ and $m(C^n) \leq 2^{-n}$.

Then $\{x : f_n(x) \neq f(x)\} \subset C^n$ and $\mu(\{x : f_n(x) \neq f(x)\}) \leq 2^{-n}$.

Claim: $f_n(x) \rightarrow f(x)$ on $\mathbb{R} \setminus G$ where $G = \bigcap_n \bigcup_{k=n}^\infty \{x : f_k(x) \neq f(x)\}$.

By monotone convergence, $\mu(g) = \lim_{n \rightarrow +\infty} \mu(\bigcup_{k=n}^\infty \{x : f_k(x) \neq f(x)\}) = \lim_{n \rightarrow +\infty} \left(\sum_{k=n}^{+\infty} 2^{-k} \right) = 0$.

Consider the complement, $G^c = \bigcap_{n=1}^\infty \bigcap_{k=n}^{+\infty} \{x : f_k(x) = f(x)\}$.

Then $\forall x \in G^c, x \in \bigcap_{k=n_0}^{+\infty} \{x : f_k(x) = f(x)\}$, so $f_n(x) = f(x) \forall n \geq n_0$.

Riemann Integration

Given a function $f : [a, b] \rightarrow \mathbb{R}$ bounded and P a partition of $[a, b]$ where

$$a = x_0 < x_1 < \dots < x_n = b$$

The Cauchy sum

$$C(P, [a, b]) = \sum_{i=1}^n f(\xi_i)(x_i - x_{i-1}), \quad \xi_i \in [x_{i-1}, x_i)$$

alternatively

$$\phi(P, [a, b]) = \sum_i f(\xi_i) \chi_{[x_i, x_{i+1})}$$

Consider the upper Riemann sum

$$S(P, [a, b]) = \sum_i M_i(x_i, x_{i+1}), \quad M_i = \sup_{[x_i, x_{i+1}]} f(x)$$

and the lower Riemann sum

$$s(P, [a, b]) = \sum_i m_i(x_i, x_{i+1}), \quad m_i = \inf_{[x_i, x_{i+1}]} f(x)$$

then define

$$S = \inf_P S(P, [a, b]) = s = \sup_P s(P, [a, b]) \implies \int_a^b f(x) dx = \lim_{l(P) \rightarrow 0} C(P, [a, b])$$

Theorem:

f is Riemann integrable on $[a, b]$ if and only if f is continuous m -a.e. (w.r.t Lebesgue measure) on $[a, b]$.

Proof

(\implies) Let f be Riemann integrable on $[a, b]$.

Define the oscillation

$$\begin{aligned} \text{Osc}_I(f) &= \sup_I f(x) - \inf_I f(x) \\ \text{Osc}_x(f) &= \lim_{\delta \rightarrow 0} \text{Osc}_{(x-\delta, x+\delta)}(f) \end{aligned}$$

and observe that f is continuous at x if and only if $\text{Osc}_x(f) = 0$.

Let $D = \{x : \text{Osc}_x(f) > 0\}$ and $D_k = \left\{x : \text{Osc}_x(f) > \frac{1}{k}\right\}$ such that $D_k \subset D_{k+1}$ and $D = \bigcup_k D_k$.

Therefore $m(D_k) \rightarrow m(D)$.

To show that $m(D) = 0$, assume otherwise that $m(D) > 0$.

Therefore, $\exists k$ such that $m(D_k) > d_{k_0}$ for any $k \geq k_0$.

Then, for any partition P we may examine

$$S(P, [a, b]) - s(P, [a, b]) = \sum_{I_i} (M_i - m_i) |I_i|$$

We want to show that this is $\geq \delta > 0$ for any P .

February 13, 2024

Recall: Riemann Integration

$f(x) \geq 0$ on $[a, b]$ bounded.

Partition $P = \{a = x_0 < x_1 < \dots < x_n = b\}$, $[x_{i-1}, x_i]$.

IMAGE HERE - Riemann Integration

Upper Riemann Sum: $S_P = \sum_{i=1}^n M_i(x_i - x_{i-1})$ where $M_i = \sup\{f(x) : x \in [x_{i-1}, x_i]\}$.

Lower Riemann Sum: $s_P = \sum_{i=1}^n m_i(x_i - x_{i-1})$ where $m_i = \inf\{f(x) : x \in [x_{i-1}, x_i]\}$.

Step Functions: $\phi_{P,\alpha} = \sum_i \alpha_i \chi_{I_i}$ where $I_i = [x_{i-1}, x_i]$.

Set $S = \inf_P S_P = \inf\left\{\sum_i \alpha_i |I_i| : \phi_{P,\alpha}(x) \geq f(x)\right\}$

and $s = \sup_P s_P = \sup\left\{\sum_i \alpha_i |I_i| : \phi_{P,\alpha}(x) \leq f(x)\right\}$.

Definition: Riemann Integrable

The function f is Riemann integrable if $S = s$.

Remark:

$$S_P - s_P = \sum_{i=1}^n (M_i - m_i)(x_i - x_{i-1}) \rightarrow 0 \text{ as } \ell(P) \rightarrow 0$$

Remark:

If f is continuous, then it is Riemann integrable.

Theorem:

Given $f : [a, b] \rightarrow \mathbb{R}$ bounded, then f is Riemann integrable if and only if f is continuous m -a.e.
 $m(D) = 0$ if and only if f is Riemann integrable.

Proof

Recall that $\text{Osc}_I(f) = \sup_I f(x) - \inf_I f(x)$ and $\text{Osc}_{x_0}(f) = \lim_{\delta \rightarrow 0} \text{Osc}_{(x_0-\delta, x_0+\delta)}(f)$.

IMAGE HERE - 2 Oscillation

Write $D = \{x \in [a, b] : f \text{ is not continuous at } x\}$, and $D_k = \{x \in [a, b] : \text{Osc}_x(f) \geq 1/k\}$ closed (since D_k^C open). Then

$$D = \bigcup_k D_k = \{x \in [a, b] : \text{Osc}_x(f) > 0\}$$

We have $m(D_k) \xrightarrow[k \rightarrow \infty]{} m(D)$.

Then there exists an open cover of D_k , $\{I_i\}$ such that $m(D_k) + \varepsilon \geq \sum_i |I_i| \geq m(D_k) - \varepsilon$.

Since D_k is closed and bounded, it is compact and there exists finite subcover $\{I_{i_k}\}_{k=1}^\ell \subset \{I_i\}$.

(\Leftarrow) Assume that f is Riemann integrable and, for sake of contradiction, that $m(D) > 0$.

Then $m(D_k) \geq m > 0$, $\forall k \geq k_0$.

Now for any partition $P = \{x_0, x_1, \dots, x_n\}$,

$$\begin{aligned} S_P - s_P &= \sum_{i=1}^n (M_i - m_i)(x_i - x_{i-1}) \\ &\geq \sum_{(x_{i-1}, x_i) \cap D_k \neq \emptyset} (M_i - m_i)(x_i - x_{i-1}) \\ &\geq \frac{1}{k} \sum_{(x_{i-1}, x_i) \cap D_k \neq \emptyset} (x_i - x_{i-1}) \end{aligned}$$

Since $\bigcup_{(x_{i-1}, x_i) \cap D_k \neq \emptyset} [x_{i-1}, x_i] \supset D_k$,

$$\sum_{(x_{i-1}, x_i) \cap D_k \neq \emptyset} (x_i - x_{i-1}) = m\left(\bigcup_{(x_{i-1}, x_i) \cap D_k \neq \emptyset} [x_{i-1}, x_i]\right) \geq m(D_k)$$

we conclude that

$$S_P - s_P \geq \frac{m}{k_0} \geq 0$$

(\implies) Assume $m(D) = 0$.

Then, for any k satisfying $\frac{1}{k} < \frac{\varepsilon}{2(b-a)}$, $m(D_k) = 0$ and $\{I_{i_k}\}_{k=1}^\ell \subset \{I_i\}$ for open intervals I_i .

We have, also, $\bigcup_{k=1}^\ell I_{i_k} \supset D_k$ so

$$\sum_{k=1}^\ell |I_{i_k}| \leq \sum_i |I_i| \leq \frac{\varepsilon}{2M}$$

and

$$[a, b] \setminus \bigcup_{k=1}^\ell I_{i_k} \subset D_k^c$$

compact.

Claim: there exists some partition $P = \{x_i\}_{i=0}^n$ such that $S_P - s_P < \varepsilon = \frac{1}{k}$.

Given $\text{Osc}_x(f) \leq 2M$,

$$\begin{aligned} S_P - s_P &= \sum_i (M_i - m_i)(x_i - x_{i-1}) \\ &= \sum_{[x_{i-1}, x_i] \cap D_k = \emptyset} + \sum_{[x_{i-1}, x_i] \cap D_k \neq \emptyset} \\ &\leq \frac{\varepsilon}{2(b-a)}(b-a) + 2M \cdot \frac{\varepsilon}{4M} \end{aligned}$$

Definition: Lebesgue Integration

Given a measure space (X, Λ, μ) and simple function $s = \sum_i \alpha_i \chi_{A_i}$ for $\alpha_i \in \mathbb{R}$ and $A_i \in \Lambda$,

$$\int_E s \, d\mu = \sum_i \alpha_i \mu(A_i \cap E)$$

Then, for extended real-valued $f \geq 0$,

$$\int_E f \, d\mu = \sup \left\{ \sum_i \alpha_i \mu(A \cap E) : 0 \leq s(x) \leq f(x) \right\}$$

Properties

1. For $0 \leq f \leq g$ on E , $\int_E f \, d\mu \leq \int_E g \, d\mu$.
2. For $A \subset B$ where $A, B \in \Lambda$, $\int_A f \, d\mu \leq \int_B f \, d\mu$.
3. Since $f \geq 0$, $\forall c \in \mathbb{R}_{\geq 0}$ $\int_E c f \, d\mu = c \int_E f \, d\mu$.
4. $f = 0$ μ -a.e. if and only if $\int_X f \, d\mu = 0$.
5. $\int_E f \, d\mu = \int_X f \chi_E \, d\mu$.
6. For $f, g \geq 0$, $\int_E f + g \, d\mu = \int_E f \, d\mu + \int_E g \, d\mu$.

7. For $A, B \in \Lambda$ where $A \cap B = \emptyset$, $\int_{A \cup B} f d\mu = \int_A f d\mu + \int_B f d\mu$.

• Proof of 4

$$(\implies) \sum_i \alpha_i \chi_{A_i} = s(x) = f(x) \implies \alpha_i > 0 \implies \mu(A_i) = 0.$$

$$(\impliedby) f \geq \alpha > 0 \text{ and } \mu(A) > 0 \implies f(x) \geq \alpha \chi_A \implies \int_X f d\mu \geq \alpha \mu(A) > 0 \text{ a contradiction.}$$

• Proof of 5

$$s\chi_E = \sum_i \alpha_i \chi_{A_i \cap E}.$$

• Proof of 6

$$\text{If } 0 \leq s_1 \leq f \text{ and } 0 \leq s_2 \leq g, \text{ then } 0 \leq s_1 + s_2 \leq f + g.$$

Monotone Convergence of Lebesgue Integration

On a measure space (X, Λ, μ) , let $f_n \geq 0$ be a sequence of measurable functions which is monotone $f_i(x) \leq f_{i+1}(x)$ and converging $f_n(x) \rightarrow f(x)$ for any $x \in X$. Then

$$\lim_{n \rightarrow +\infty} \int_X f_n d\mu = \int_X f d\mu = \int_X \left(\lim_{n \rightarrow +\infty} f_n \right) d\mu$$

Proof

Observe that $f_n(x) \leq f(x)$, $\forall x \in X$, so

$$\int_X f_n d\mu \leq \int_X f_{n+1} d\mu \leq \int_X f d\mu$$

so

$$\lim_{n \rightarrow +\infty} \int_X f_n d\mu \leq \int_X f d\mu$$

We want to show that

$$\lim_{n \rightarrow +\infty} \int_X f_n d\mu \geq \int_X f d\mu$$

Let s be a simple function satisfying $0 \leq s(x) \leq f(x)$, and define

$$E_n = \{x \in X : f_n(x) \geq cs(x)\}$$

for some $c \in (0, 1)$.

Then $E_n \subset E_{n+1}$ and $\bigcup_n E_n = X$. Consider

$$\int_X f_n d\mu \geq \int_{E_n} f_n d\mu \geq c \int_{E_n} s(x) d\mu = c \sum_i \alpha_i \mu(A_i \cap E_n)$$

For any i , $A_i \cap E_n \rightarrow A_i$. Therefore $\mu(A_i \cap E_n) \xrightarrow{n \rightarrow +\infty} \mu(A_i)$. So

$$\lim_{n \rightarrow +\infty} \int_X f_n d\mu \geq c \sum_i \alpha_i \mu(A_i)$$

for $0 \leq s = \sum \alpha_i \chi_{A_i} \leq f(x)$. Since this hold for any c ,

$$\lim_{n \rightarrow +\infty} \int_X f_n d\mu \geq \int_X f d\mu$$

Corollary

Given a measurable sequence $f_n \geq 0$ with $f(x) = \sum_n f_n(x)$,

$$\int_X f \, d\mu = \sum_n \int_X f_n \, d\mu$$

and

$$\phi_n(x) = \sum_{k=1}^n f_k(x) \rightarrow f(x)$$

Definition: Fatou's Lemma

Given a sequence of measurable functions $f_n \geq 0$,

$$\int_X \left(\liminf_{n \rightarrow +\infty} f_n \right) d\mu \leq \liminf_{n \rightarrow +\infty} \int_X f_n \, d\mu$$

Proof

Observe that

$$\liminf_{n \rightarrow +\infty} f_n = \lim_{n \rightarrow +\infty} \overbrace{(\inf\{f_n(x), f_{n+1}(x), \dots\})}^{g_n(x)}$$

so, by monotone convergence,

$$\int_X \left(\lim_{n \rightarrow +\infty} g_n(x) \right) d\mu = \lim_{n \rightarrow +\infty} \int_X g_n(x) \, d\mu$$

and $g_n(x) \leq f_n(x)$ gives

$$\int_X g_n(x) \, d\mu \leq \int_X f_n(x) \, d\mu$$

and implies

$$\lim_{n \rightarrow +\infty} \int_X g_n(x) \, d\mu \leq \liminf_{n \rightarrow +\infty} \int_X f_n(x) \, d\mu$$

Space of Integrable Functions

Write

$$f(x) = f^+(x) - f^-(x)$$

where

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

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

Then for $\int_X f^+ \, d\mu$ and $\int_X f^- \, d\mu$, $\int_X f \, d\mu$ is defined when at least one is finite.

If both are finite, then

$$L_\mu^1(x) = \int_X |f| \, d\mu = \int_X f^+ \, d\mu + \int_X f^- \, d\mu \leq +\infty$$

Properties

1. For any $\alpha, \beta \in \mathbb{R}$,

$$\int_X (\alpha f + \beta g) d\mu = \alpha \int_X f d\mu + \beta \int_X g d\mu$$

if $f, g \in L^1_\mu(x)$.

2. For $f \in L^1_\mu(x)$,

$$\left| \int_X f d\mu \right| \leq \int_X |f| d\mu$$

$$\left| \int_X f^+ d\mu - \int_X f^- d\mu \right| \leq \int_X f^+ d\mu + \int_X f^- d\mu$$

3. For $f \leq g$, $f, g \in L^1_\mu(x)$, $\int_X f d\mu \leq \int_X g d\mu$.

4. $\int_{A \cup B} f d\mu = \int_A f d\mu + \int_B f d\mu$.

5. $f = 0$ μ -a.e. if and only if $\int_X |f| d\mu = 0$.

February 15, 2024

Recall

Given (X, Λ, μ) a measure space and X topological.

$M_\mu(x) = \{f : X \rightarrow \mathbb{R} : \text{measurable}\}.$

$L^1_\mu(x) = \{f \in M_\mu(x) : \int_X |f| d\mu < +\infty\}.$

$\|f\|_1 = \|f\|_{L^1_\mu(x)} = \int_X |f| d\mu.$

$L^\infty_\mu(x) = \{f \in M_\mu(x) : \|f\|_{L^\infty_\mu(x)} < +\infty\}.$

$\|f\|_\infty = \|f\|_{L^\infty_\mu(x)} = \inf\{M = \mu(\{x \in X : |f(x)| > M\}) = 0\}.$

$C_c(x)$ the space of continuous functions with compact support.

Remark

In $L^1_\mu(x)$ and $L^\infty_\mu(x)$, $[f] = [g]$ if and only if $f = g$ μ -a.e.

Topologies

1. $f_n, f \in M_\mu(x)$, $f_n \rightarrow f$ μ -a.e. in X .
2. $f_n \rightarrow f$ in $L^\infty_\mu(x)$ if and only if $\exists A \in \Lambda$, $\mu(A) = 0$, $f_n \rightrightarrows +\infty$ in $X \setminus A$.
3. $f_n \rightarrow f$ in $L^1_\mu(x)$, $\lim_{n \rightarrow +\infty} \|f_n - f\| = \lim_{n \rightarrow +\infty} \int_X |f_n - f| d\mu.$
4. $f_n \rightarrow f$ in measure if $\forall \varepsilon > 0$, $\lim_{n \rightarrow +\infty} \mu(\{x \in X : |f_n(x) - f(x)| \geq \varepsilon\}) = 0.$

Theorem:

For (X, Λ, μ) with $\mu(x) < +\infty$, assume

1. $f_n \rightarrow f$ μ -a.e. in X .
2. $\|f_n\|_\infty \leq M \leq +\infty, \forall n$

Then, $f_n \rightarrow f$ in $L_\mu^1(x)$. Therefore

$$\lim_{n \rightarrow +\infty} \int_X f_n d\mu = \int_X \left(\lim_{n \rightarrow +\infty} f_n \right) d\mu$$

Proof

Step 1: $f \in L_\mu^\infty(x)$ and $\|f\|_\infty \leq M$.

Given $\varepsilon > 0$, $\{x \in X : |f(x)| > M + \varepsilon\} \subset \{x : |f_n(x)| > M + \varepsilon\}, \forall n \geq n_0$.

Then, $\mu(\{x : |f(x)| > M + \varepsilon\}) = 0$. Therefore $\|f\|_\infty \leq M$.

Step 2: consider $\int_X |f_n - f| d\mu$.

Since $\mu(X) < +\infty$, by Egoroff's theorem $\exists A \subset X$ with $\mu(X \setminus A) < \frac{\varepsilon}{4M}$ where $f_n(x) \rightarrow f(x)$ in A .

Then, $\forall \varepsilon > 0, \exists n_0 \in \mathbb{N}$ such that $|f_n(x) - f(x)| < \frac{\varepsilon}{2\mu(x)}, \forall x \in A, \forall n \geq n_0$.

$$\begin{aligned} \int_X |f_n - f| d\mu &= \int_A |f_n - f| d\mu + \int_{X \setminus A} |f_n - f| d\mu \\ &= \frac{\varepsilon}{2\mu(x)} \mu(A) + 2M\mu(X \setminus A) \frac{\varepsilon}{4M} \\ &= \frac{\varepsilon}{2} + \frac{\varepsilon}{2} \\ &= \varepsilon \end{aligned}$$

So $f_n \rightarrow f$ in $L_\mu^1(x)$.

Step 3: observe

$$\left| \int_X f_n d\mu - \int_X f d\mu \right| = \left| \int_X (f_n - f) d\mu \right| \leq \int_X |f_n - f| d\mu \xrightarrow{n \rightarrow +\infty} 0$$

Remark

For $\mu(X) < +\infty$,

1. $L_\mu^\infty(x) \subset L_\mu^1(x)$.
2. $f_n \rightarrow f$ in $L_\mu^\infty(x) \implies f_n \rightarrow f$ in $L_\mu^1(x)$.

Theorem: Dominated Convergence

Let (X, Λ, μ) and $f_n \in M_\mu(x)$. If $\exists g \in L_\mu^1(x)$ such that $|f_n(x)| \leq g(x), \forall n$ and $f_n \rightarrow f$ μ -a.e. in X , then $f_n \rightarrow f$ in $L_\mu^1(x)$.

In particular,

$$\lim_{n \rightarrow +\infty} \int_X f_n d\mu = \int_X f d\mu$$

Proof

Note that $|f_n(x)| \leq g(x)$, $\forall n$ means $|f(x)| \leq g(x)$ and, consequently, that $f_n, f \in L^1_\mu(x)$. Define $\phi_n(x) := 2g(x) - |f_n(x) - f(x)|$. Since

$$|f_n(x) - f(x)| \leq |f_n(x)| + |f(x)| \leq 2g(x)$$

$\phi_n \geq 0$.

By Fatou's lemma,

$$\begin{aligned} \int_X \left(\liminf_{n \rightarrow +\infty} \phi_n \right) d\mu &\leq \liminf_{n \rightarrow +\infty} \int_X \phi_n d\mu \\ &\leq \liminf_{n \rightarrow +\infty} \left(2 \int_X g d\mu - \int_X |f_n - f| d\mu \right) \\ &= 2 \int_X g d\mu - \limsup_{n \rightarrow +\infty} \int_X |f_n - f| d\mu \end{aligned}$$

Therefore

$$\limsup_{n \rightarrow +\infty} \int_X |f_n - f| d\mu \leq 0 \implies \lim_{n \rightarrow +\infty} \int_X |f_n - f| d\mu = 0$$

and $f_n \rightarrow f$ in $L^1_\mu(x)$.

Definition: Vitality Continuity

On a measure space (X, Λ, μ) , $\nu : \Lambda \rightarrow \mathbb{R}$ is said to be Vitali continuous if for any $\varepsilon > 0$, there exists $\delta > 0$ such that

$$\nu(A) < \varepsilon, \forall A \in \Lambda, \mu(A) < \delta$$

Write $\forall f \in L^1_\mu(x)$, $\nu_f(A) = \int_A |f| d\mu$.

Lemma

If $f \in L^1_\mu$, then ν_f is Vitali continuous.

• Proof

$$\text{Set } f_n(x) = \begin{cases} f(x) & |f(x)| \leq n \\ n & |f(x)| > n \end{cases}$$

Then $f_n \rightarrow f$ in X and $|f_n(x)| \leq |f(x)|$. Therefore,

$$\int_A |f| d\mu \leq \int_A ||f| - |f_n|| d\mu + \int_A |f_n| d\mu$$

By dominated convergence, for $\varepsilon > 0$, $\exists n_0$ such that $\int_X |f_n - f| d\mu < \frac{\varepsilon}{2}$ for all $n \geq n_0$. Then

$$\int_A ||f| - |f_n|| d\mu \leq \int_X ||f| - |f_n|| d\mu \leq \frac{\varepsilon}{2}, \quad \forall n \geq n_0$$

In particular

$$\int_A |f_{n_0}| d\mu \leq n_0 \mu(A)$$

Letting $\delta = \frac{\varepsilon}{2n_0}$ gives

$$\int_A |f| d\mu \leq \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon$$

if $\mu(A) < \delta$.

Lemma

If (X, Λ, μ) , $\mu(X) < +\infty$, and $f_n \rightarrow f$ μ -a.e. in X , then $f_n \rightarrow f$ in measure μ .

Remark

Proof can be done through Egoroff's Theorem.

Proof

Set $A_{n,\varepsilon} = \{x : |f_n(x) - f(x)| \geq \varepsilon\}$ and $A_\varepsilon = \bigcap_{n=1}^{\infty} \bigcup_{j \geq n} A_{j,\varepsilon}$, and $N = \bigcup_{\varepsilon > 0} A_\varepsilon$.

Then $N^c = \bigcap_{\varepsilon > 0} A_\varepsilon^c$, $A_\varepsilon^c = \bigcup_{n=1}^{j \geq n} A_{j,\varepsilon}^c$, and $A_{j,\varepsilon}^c = \{x : |f_j(x) - f(x)| < \varepsilon\}$.

Therefore, $\forall x \in N^c$, $f_n(x) \rightarrow f(x)$ and $\forall x \in N$, $f_n \not\rightarrow f(x)$.

So $\mu(N) = 0$ implies $\mu(A_\varepsilon) = 0$ for any $\varepsilon > 0$. Therefore

$$\mu\left(\bigcup_{j \geq n} A_{j,\varepsilon}\right) \rightarrow \mu(A_\varepsilon) = 0$$

since $\mu(X) < +\infty$. Then

$$\bigcup_{j \geq n} A_{j,\varepsilon} \supset \bigcup_{j \geq n+1} A_{j,\varepsilon}$$

and

$$A_{n,\varepsilon} \subset \bigcup_{j \geq n} A_{j,\varepsilon}$$

which implies $\mu(A_{n,\varepsilon}) \rightarrow 0$ as $n \rightarrow +\infty$.

Lemma (Chebyshev's Inequality)

~ Very Trivial ♥ ~

If $f \in L_\mu^1(X)$ and $f \geq 0$, then $\mu(\{x : f > \alpha\}) \leq \frac{1}{\alpha} \int_X f d\mu$.

Proof

$$\int_X f d\mu \geq \int_{\{x : f(x) > \alpha\}} f d\mu \geq \int_{\{x : f(x) \geq \alpha\}} f d\mu = \alpha \mu(\{x : f(x) > \alpha\})$$

Corollary

$f_n \rightarrow f$ in $L^1_\mu(x)$ implies $f_n \rightarrow f$ in measure.
Since $\forall \varepsilon > 0$,

$$\mu(\{x : |f_n(x) - f(x)| \geq \varepsilon\}) \leq \frac{1}{\varepsilon} \int_X |f_n - f| d\mu \rightarrow 0$$

Definition: Vitali Equicontinuity

A sequence $\{f_n\}$ of Vitali continuous functions is Vitali equicontinuous if $\forall \varepsilon > 0$, $\exists \delta > 0$ such that $\nu_n(A) < \varepsilon$, $\forall n$, $\forall A \in \Lambda$, $\mu(A) < \delta$.

Theorem

On (X, Λ, μ) with $\mu(X) < +\infty$, $f_n \rightarrow f$ in $L^1_\mu(x)$ if and only if ν_{f_n} is Vitali equicontinuous and $f_n \rightarrow f$ in measure μ .

Proof

(\implies) By assumption, $\int_X |f_n - f| d\mu \rightarrow 0$ as $n \rightarrow +\infty$.

Therefore, $\exists n_0 \in \mathbb{N}$ such that $\int_X |f_n - f| d\mu < \frac{\varepsilon}{2}$, $\forall n \geq n_0$. See that for all $n \geq n_0$,

$$\begin{aligned} \left| \int_A |f_n| d\mu - \int_A |f| d\mu \right| &= \int_A ||f_n| - |f|| d\mu \\ &\leq \int_X |f_n - f| d\mu \\ &< \frac{\varepsilon}{2} \end{aligned}$$

and therefore $\int_A |f_n| d\mu \leq \int_A |f| d\mu + \frac{\varepsilon}{2}$.

So there exists $\delta_0 > 0$ such that $\int_A |f_n| d\mu \leq \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon$ for any $n \geq n_0$ and $\mu(A) < \delta_0$.

Then $\exists \delta_n > 0$ such that $\int_A |f_n| d\mu < \varepsilon$, $\forall A \in \Lambda$ and $\mu(A) < \delta_n$.

Set $\delta = \min\{\delta_0, \dots, \delta_{n_0-1}\} > 0$. Then $\int_A |f_n| d\mu < \varepsilon$, $\forall n$, $\forall A \in \Lambda$, $\mu(A) < \delta$.

(\impliedby)

By Vitali equicontinuity, $\exists \delta > 0$ giving $\int_A (|f_n| + |f|) d\mu < \frac{\varepsilon}{2}$, $\forall A \in \Lambda$, $\mu(A) < \delta$. Then

$$\begin{aligned} \int_X |f_n - f| d\mu &= \int_{\{x : |f_n(x) - f(x)| < \frac{\varepsilon}{2\mu(x)}\}} |f_n - f| d\mu + \int_{\{x : |f_n(x) - f(x)| \geq \frac{\varepsilon}{2\mu(x)}\}} |f_n - f| d\mu \\ &\leq \frac{\varepsilon}{2\mu(x)} \mu(x) + \int_{A_{n,\varepsilon}} (|f_n| + |f|) d\mu \end{aligned}$$

for $\varepsilon > 0$, $\mu(A_{n,\varepsilon}) \rightarrow 0$ as $n \rightarrow +\infty$.

So $\exists n_0 \in \mathbb{N}$ where $\mu(A_{n,\varepsilon}) < \delta$ for $n \geq n_0$ such that

$$\int_X |f_n - f| d\mu < \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon$$

Theorem: Riesz Theorem

On (X, Λ, μ) , $\mu(X) < +\infty$, if $f_n, f \in M_\mu(x)$ and $f_n \rightarrow f$ in measure then there exists a subsequence $\{f_{n_k}\} \subset \{f_n\}$ such that $f_{n_k} \rightarrow f$ μ -a.e.

Proof

Take

$$A_{n,\varepsilon} = \{x : |f_n(x) - f(x)| \geq \varepsilon\}$$

and $f_n \rightarrow f$ in measure.

Then $\forall \varepsilon > 0$, $\mu(A_{n,\varepsilon}) \rightarrow 0$ as $n \rightarrow +\infty$.

Let $\varepsilon = \frac{1}{i}$. There exists n_i such that $\mu(A_{n_i, \frac{1}{i}}) < 2^{-i}$. Set

$$A = \bigcap_n \bigcup_{j \geq n} A_{n_j, \frac{1}{i}}$$

Claim

1. $\mu(A) = 0$.
2. $f_{n_k} \rightarrow f$ in $X \setminus A$.

Since $\mu(X) < +\infty$,

$$\mu(A) = \lim_{n \rightarrow +\infty} \mu\left(\bigcup_{j \geq n} A_{n_j, \frac{1}{i}}\right)$$

where

$$\begin{aligned} \mu\left(\bigcup_{j \geq n} A_{n_j, \frac{1}{i}}\right) &\leq \sum_{j \geq n} \mu(A_{n_j, \frac{1}{i}}) \\ &\leq \sum_{j \geq n} 2^{-i} \\ &\xrightarrow{n \rightarrow +\infty} 0 \end{aligned}$$

Then

$$X \setminus A = \bigcup_{n=1}^{+\infty} \bigcap_{j \geq n} A_{n_j, \frac{1}{i}}^c$$

where $A_{n_j, \frac{1}{i}}^c = \left\{x : |f_{n_j}(x) - f(x)| < \frac{1}{j}\right\}$, $\forall \varepsilon > \frac{1}{j_0}$.

So for some n_0 , $x \in X \setminus A$ implies that $x \in \bigcap_{j \geq n_0} A_{n_j, \frac{1}{j}}^c$ where $j = \max\{n_0, j_0\}$.

February 20, 2024

Riesz Representation Theorem

Linear Functionals

On a vector space V , a map $T : V \rightarrow \mathbb{R}$ such that $T(\alpha x + \beta y) = \alpha T(x) + \beta T(y)$, $\forall \alpha, \beta \in \mathbb{R}$, $\forall x, y \in V$ is called a linear functional.

A linear functional is positive if $Tf \geq 0$ when $f \geq 0$.

Example

On (X, Λ, μ) , $L^1_\mu(X) = V$, take $Tf = \int_X f d\mu$. Then

$$T(\alpha x + \beta g) = \int_X \alpha x + \beta g d\mu = \alpha \int_X x d\mu + \beta \int_X g d\mu = \alpha Tf + \beta Tg$$

Example

On (X, Λ, μ) , X locally compact Hausdorff, μ Radon.

$C_c(X)$, the space of continuous functions with compact support.

Recall: $\text{supp}(f) = \{x : f(x) \neq 0\}$ and $\text{supp}(f)^c = \{x : \exists \text{ open neighborhood } U \text{ of } x, f = 0 \text{ in } U\}$.

Then, $Tf = \int_X f d\mu$ on $C_c(X) \subset L^1_\mu(X)$ is a linear functional.

Theorem: Riesz Representation

Let X be a locally compact Hausdorff space and T be a positive linear functional on $C_c(X)$.

Then there exists a unique, complete Radon measure μ such that $Tf = \int_X f d\mu$.

Lemma 0

If X is locally compact Hausdorff, if $K \subset U \subset X$ with K compact, U open, then there exists some V open with \overline{V} compact such that $K \subset V \subset \overline{V} \subset U$.

Lemma 1 (Urysohn's)

If X is locally compact Hausdorff, if $K \subset U \subset X$ with K compact, U open, then there exists some continuous function f with compact support such that

1. $\text{supp}(f) \subset U$
2. $0 \leq f \leq 1$
3. $f \equiv 1$ in K

Write $K \subset f \subset U$.

Radon Measure

For (X, Λ, μ) , μ is a Radon measure if

1. μ is Borel
2. $\mu(K) < +\infty$ for K compact
3. $\mu(V) = \sup\{\mu(K) : K \subset V, K \text{ compact}\}$ for every V open.
4. $\mu(A) = \inf\{\mu(V) : A \subset V, V \text{ open}\}$ for every V open.

Proof: Step 1 (Uniqueness)

Suppose μ_1 and μ_2 such that $Tf = \int_X f d\mu_1 = \int_X f d\mu_2, \forall f \in C_c(X)$.

We want to show that $\mu_1(K) = \mu_2(K), \forall K$ compact so that $\mu_1 = \mu_2$.

So, for any K compact, there is some V open with $V \supset K$ such that $\mu_2(V) < \mu_2(K) + \varepsilon$.

By Urysohn's lemma, $K < f < V$. So

$$\mu_1(K) = \int_K d\mu_1 = \int_X \chi_K d\mu \leq \int_X f d\mu_1 = \int_X f d\mu_2 \leq \mu_2(V) < \mu_2(K) + \varepsilon$$

Assuming $\mu_1(V) < \mu_1(V) + \varepsilon$ and repeating the proof mutatis mutandis shows $\mu_1 = \mu_2$.

Proof: Step 2 (Construction)

Let T be a positive linear function on $C_c(X)$.

We want to construct a complete Radon measure μ such that $Tf = \int_X f d\mu, \forall f \in C_c(X)$.

- Outer Measure

For any U open, let $\mu^*(U) = \sup\{Tf : f < U\}$.

Then for any $A \subset X, \mu^*(A) = \inf\{\mu^*(U) : A \subset U, U \text{ open}\}$.

1. $\mu^*(\emptyset) = 0$.

2. $\mu^*(A) \leq \mu^*(B)$ if $A \subset B$.

3. $\mu^*(\bigcup_i A_i) \leq \sum_i \mu^*(A_i), \forall A_i \subset X$.

- Lemma: Partition of Unity

For X LCH, U_1, U_2, \dots, U_n open, K compact and $K \subset \bigcup_{i=1}^n U_i$.

Then there exists a partition of unity $h_i < U_i$ and $\sum_{i=1}^n h_i = 1$ on K .

Since, $\forall x \in K, \exists V_x$ open, $\overline{V_x} \subset U_i$ for some i .

Then there exists a subcover $\{U_{x_i}\}_{i=1}^m$ and $H_i = \bigcup_i V_{x_i}$ while $\overline{V_{x_i}} \subset U_i$.

Thus $\overline{H_i}$ is compact and $H_i \subset \overline{H_i} \subset U_i$.

By Urysohn's lemma, $\exists \bar{A}_i < g_i < U_i$.

Write $h_1 = g_1, h_2(1 - g_1)g_2, h_k = (1 - g_1)(1 - g_2) \cdots g_k, h_n = (1 - g_1)(1 - g_2) \cdots (1 - g_m)g_n$. Then

1. $h_i < U_i$, since we have not modified the support.

2. $K < \sum_i h_i$, since $\forall x \in K \subset \bigcup_i A_i \subset \bigcup_i \bar{A}_i \subset \bigcup_i U_i$.

Then $x \in \bar{H}_{i_0}$ for some i_0 implies that $g_{i_0}(x) = 1$.

$$\sum_i h_i(x) = \sum_{i \leq i_0} h_i(x) = g_1(x) + (1 - g_1(x))g_2(x) + \cdots + (1 - g_1(x)) \cdots (1 - g_{i_0-1}(x)) = g_1(x) + (1 - g_1(x)) = 1$$

Therefore, $K \subset \bigcup_i \bar{A}_i < \sum_{i=1}^n h_i$.

- Proof of 3

Take $\bigcup_i U_i, U_i$ open and consider $\mu^*(\bigcup_i U_i)$.

Then $\forall f < \bigcup_i U_i$, there exists a finite subcover $f < \bigcup_{j=1}^n U_{i_j}, \{U_{i_j}\} \subset \{U_i\}$.

By the partition of unity, $\exists h_j < U_{i_j}$ where $\sum h_j = 1$ on $\text{supp}(f)$. So

$$f = \left(\sum_j h_j \right) f = \sum_j (h_j f)$$

and

$$Tf = \sum_j T(h_j f) \leq \sum_j \mu^*(U_{i_j}) \quad \text{and} \quad h_j f < U_{i_j}$$

It follows that $\mu^*\left(\bigcup_i U_i\right) \leq \sum_i \mu^*(U_i)$.

For $\bigcup_i A_i$, $A_i \subset X$, by definition there exists U_i open with $U_i \supset A_i$ and $\mu^*(U_i) \leq \mu^*(A_i) + \frac{\varepsilon}{2^i}$. Thus

$$\mu^*\left(\bigcup_i A_i\right) \leq \mu^*\left(\bigcup_i U_i\right) \leq \sum_i \mu^*(U_i) \leq \sum_i \left(\mu^*(A_i) + \frac{\varepsilon}{2^i}\right) \leq \sum_i \mu^*(A_i) + \varepsilon$$

Therefore μ^* is an outer measure and, by the Caratheodory construction, (X, Λ, μ) complete.

- Radon Measure

1. Borel.
2. $\mu(K) < +\infty$ for K compact.
3. $\mu(V) = \sup\{\mu(K) : K \subset V, K \text{ compact}\}$.
4. $\mu(A) = \inf\{\mu(V) : A \subset V, V \text{ open}\}$.

- Proof of 2

By definition of μ^* , for any K compact there is some V open such that $K \subset V$ and $\mu(K) \leq \mu(V)$.

By Urysohn's lemma, $K \subset \bigcup_i H_i \subset \bigcup_i \overline{H_i} < f < V$ and

$$\mu(K) \leq \mu\left(\bigcup_i H_i\right) \leq Tf < +\infty, \quad f \in C_c(X)$$

since $\mu^*\left(\bigcup_i H_i\right) = \sup\{Tg : g < \bigcup_i H_i\}$ for $g \leq f$.

- Proof of 3

$\forall K \subset V$, K compact, V open, $\mu(K) \leq \mu(V)$, by the definition of the outer measure $\exists f < V$ such that

$$\mu^*(V) \leq Tf + \frac{\varepsilon}{2}$$

We have $\text{supp}(f) = K \subset V$, so there exists U open $U \supset K$ such that $\mu^*(U) \leq \mu^*(K) + \frac{\varepsilon}{2}$.

By Urysohn's lemma, $\exists K < g < U$ and

$$\mu^*(V) < Tf + \frac{\varepsilon}{2} \leq Tg + \frac{\varepsilon}{2} \leq \mu^*(U) + \frac{\varepsilon}{2} \leq \mu^*(K) + \varepsilon$$

Therefore, $\mu^*(V) = \sup\{\mu^*(K) : K \subset V, K \text{ compact}\}$.

– Lemma

If $A, B \subset X$, $\exists U \supset A$ U open, $\exists V \supset B$ V open, such that $U \cap V = \emptyset$.

Then $\mu^*(A \cup B) = \mu^*(A) + \mu^*(B)$.

* Proof

For $\forall W$ open, $W \supset A \cup B$, take

$$\begin{cases} W_1 = W \cap A \\ W_2 = W \cap B \end{cases}$$

such that $W_1 \cap W_2 = \emptyset$.

Fact: $f \prec W$ if and only if $f = f_1 + f_2$ where $f_1 \prec W_1$ and $f_2 \prec W_2$.

Since $Tf = Tf_1 + Tf_2$ gives $\mu^*(W) = \mu^*(W_1) + \mu^*(W_2) \geq \mu^*(A) + \mu^*(B)$, we have

$$\mu^*(A) + \mu^*(B) \geq \mu^*(A \cup B) \geq \mu^*(A) + \mu^*(B)$$

– Lemma (Proof of 1)

If for any A open, $\mu^*(E \cap A) + \mu^*(E \cap A^c) \leq \mu^*(E)$, then μ is Borel.

* Proof

For any open set $V \supset E$, $\mu^*(V) \leq \mu^*(E) + \frac{\varepsilon}{2}$.

By 3, $V \cap A$ is open and $\exists K$ compact with $K \subset V \cap A$ such that $\mu^*(V \cap A) \leq \mu^*(K) + \frac{\varepsilon}{2}$. So

$$\mu^*(E \cap A) + \mu^*(E \cap A^c) \leq \mu^*(V \cap A) + \mu^*(E \cap A^c) \leq \frac{\varepsilon}{2} + \mu^*(K) + \mu^*(E \cap A^c)$$

Since $K \subset V \cap A \subset A$ and A open, we may find $K \subset W \subset \overline{W} \subset A$ where $K \subset W$ and $A^c \subset \overline{W}^c$. Therefore

$$\frac{\varepsilon}{2} + \mu^*(K \cup (E \cap A^c)) \leq \frac{\varepsilon}{2} + \mu^*((V \cap A) \cup (V \cap A^c)) \leq \frac{\varepsilon}{2} + \mu^*(V) \leq \varepsilon + \mu^*(E)$$

Therefore $A \in \Lambda$, and $B \subset \Lambda$.

Proof: Step 3 (Verify)

For any $f \in C_c(X)$, write $f(x) \in [a, b]$.

Take $P = \{a = y_0 < y_1 < \dots < y_{n-1} < y_n = b\}$ with $\ell(P) = \max\{y_i - y_{i-1} : i = 1, \dots, n\}$.

Then, take $A_i = \{x \in X : y_{i-1} < f(x) \leq y_i\} \cap \text{supp}(f)$.

We have $\bigcup_i A_i = \text{supp}(f)$.

So for each A_i there is some V_i open where $V_i \supset A_i$, $f(x) < y_i + \varepsilon$, $\forall x \in V_i$, and

$$\text{supp}(f) = \bigcup_i A_i \subset \bigcup_i V_i$$

By partition of unity, $\exists h_i \prec V_i$ such that $\sum_i h_i = 1$ in $\text{supp}(f)$.

Therefore $f = \sum_i (h_i f)$ and $Tf = \sum_i T(h_i f)$.

We want to show that $Tf \leq \int_X f d\mu$ since linearity will make the reverse true by taking $-f$.

Since $f h_i \leq (y_i + \varepsilon) h_i$,

$$\begin{aligned}
 T(h_i f) &\leq (y_i + \varepsilon) T h_i \\
 &\leq (|a| + y_i + \varepsilon) T h_i - |a| T h_i \\
 &\leq (|a| + y_i + \varepsilon) \mu(V_i) - |a| T h_i \\
 &\leq y_{i-1} \mu(A_i) \\
 &\leq \int_{A_i} f d\mu + c\varepsilon
 \end{aligned}$$

By summing each term, we get

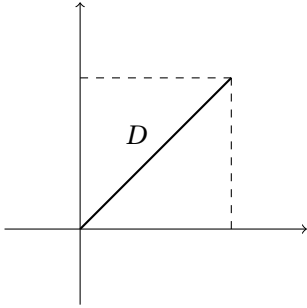
$$\sum_i T(h_i f) \leq \int_X f d\mu + c\varepsilon$$

February 22, 2024

Fubini's Theorem

Product of measure spaces.

Example 1



Given m a Lebesgue measure, m_c a counting measure, $\chi_D(x, y)$, $\forall x \in [0, 1]$,

$$\int \chi_D(x, y) dm_c(y) = \int_{[0,1]} \chi_{\{x=y\}}(y) dm_c(y) = \chi_{[0,1]}(x)$$

$$\int_{[0,1]} \int_{[0,1]} \chi_D(x, y) dm(y) dm(x) = \int_{[0,1]} \chi_{[0,1]} dm(x) = 1$$

And $\forall y \in [0, 1]$,

$$\int_{[0,1]} \chi_D(x, y) dm(x) = \int \chi_{\{x=y\}} dm(x) = 0$$

$$\int_{[0,1]} \int_{[0,1]} \chi_D(x, y) dm(x) dm(y) = 0$$

Example 2

For

$$0 = \alpha_1 < \alpha_2 < \dots \rightarrow 1$$

and $g_n(x) = \frac{1}{\alpha_{n+1} - \alpha_n} \chi_{[\alpha_n, \alpha_{n+1}]}$, $x \in [0, 1]$.

$$1. \int_{[0,1]} g_n(x) dm(x) = 1$$

$$2. f(x, y) = \sum_{n=1}^{+\infty} (g_n(x) - g_{n+1}(x)) g_n(y)$$

3.

$$\begin{aligned} \forall x \in [0, 1], \quad \int_{[0,1]} f(x, y) dm(y) \\ \forall x \in [\alpha_n, \alpha_{n+1}], n > 1, \quad \int_{[0,1]} -g_n(x) g_{n-1}(y) + g_n(x) g_n(y) dm(y) = 0 \\ \forall x \in [\alpha_1, \alpha_2], n = 1, \quad \int_{[0,1]} g_1(x) g_1(y) dm(y) \end{aligned}$$

$$\int_{x,y} f(x, y) dm(y) = g_1(x)$$

$$\int_{[0,1]} \left(\int_{[0,1]} f(x, y) dm(y) \right) dm(x) = \int_{[0,1]} g(x) dm(x) = 1$$

For $\forall n \in [0, 1], y \in [\alpha_n, \alpha_m]$

$$\int_{[0,1]} f(x, y) dm(x) = \left(\int (g_n(x) - g_{n+1}(x)) dm(x) \right) g_n(y) = 0$$

$$\int_{[0,1]} \left(\int_{[0,1]} f(x, y) dm(x) \right) dm(y) = 0$$

Therefore, with (X, Λ, μ) and (Y, Γ, ν) , $(x \times y, \Lambda \times \Gamma, \mu \times \nu)$?

We want

$$\int_X \int_Y f(x, y) d\nu(y) d\mu(x) = \int_{X \times Y} f(x, y) dm(\mu \times \nu) = \int_Y \int_X f(x, y) d\mu(x) d\nu(y)$$

Definition: Elementary Set

Take $A \in \Lambda$, $B \in \Gamma$ and construct $R = A \times B \subset X \times Y$ a measurable rectangle.

Define $Q = \bigcup_{i=1}^k R_i$ where $\{R_i\}$ are finitely many disjoint, measurable rectangles.

Then $(\mu \times \nu)(R) = \mu(A)\nu(B)$.

Take $\Lambda \times \Gamma$ the σ -algebra generated by all measurable rectangles.

Definition: Monotone Class

A collection M of subsets is a monotone class if

$$1. A_i \in M, A_i \subset A_{i+1} \implies \bigcup_i A_i \in M.$$

$$2. A_i \in M, A_i \supset A_{i+1} \implies \bigcap_i A_i \in M.$$

Proposition:

Let M be the monotone class generated by the set E of all elementary sets, then $M = \Lambda \times \Gamma$.

Proof

$$M \subset \Lambda \times \Gamma.$$

Then, $\forall P \subset X \times Y$, define $\Omega(P) = \{Q : P \setminus Q, Q \setminus P, P \cup Q \in M\}$ with

1. $Q \in \Omega(P)$ if and only if $P \in \Omega(Q)$.
2. $\Omega(P)$ is a monotone class.
3. If $P \in E$, then $E \subset \Omega(P)$. Therefore $M \subset \Omega(P)$.
4. So $\forall P \in M$, $M \subset \Omega(P)$ and $\forall P, Q \in M$, $P \setminus Q, Q \setminus P, P \cup Q \in M$.
5. $X \times Y \in E \in M$, so $\forall P \in M$, $P^c = X \times Y \setminus P \in M$.

Proposition:

If $E \in \Lambda \times \Gamma$, then $E_X = \{y : (x, y) \in E\} \in \Gamma$ and $E^Y = \{x : (x, y) \in E\} \in \Lambda$.

Proof

1. For any measurable rectangle $R = A \times B$, $R_X = B \in \Gamma$ and $R^Y = A \in \Lambda$.
2. For $(A_i)_X \in \Gamma$ and $(A_i)^Y \in \Lambda$, $(\bigcup_i A_i)_X \in \Gamma$ and $(\bigcup_i A_i)^Y \in \Lambda$.
3. For A with $A_X \in \Gamma$ and $A^Y \in \Lambda$, $(A^c)_X \in \Gamma$ and $(A^c)^Y \in \Lambda$.

Product Measure on Elementary Sets

Given $\mu \times \nu$, $(\mu \times \nu)(R) = \mu \times \nu(A \times B) = \mu(A)\nu(B)$.

$$\int_{X \times Y} \chi_{A \times B}(x, y) d(\mu \times \nu) = (\mu \times \nu)(A \times B) = \mu(A)\nu(B)$$

Define

$$\begin{aligned}\phi(x) &= \int_Y \chi_{A \times B}(x, y) d\nu(y) = \nu(B)\chi_A \\ \psi(y) &= \int_X \chi_{A \times B}(x, y) d\mu(x) = \mu(A)\chi_B\end{aligned}$$

so

$$\int_X \phi d\mu = \int_X \int_Y \chi_{A \times B} d\nu d\mu = \mu(A)\nu(B) = \int_Y \int_X \chi_{A \times B} d\mu d\nu = \int_Y \psi(y) d\nu$$

Now $\forall P \in \Lambda \times \Gamma$,

$$\begin{aligned}\phi(x) &= \int_Y \chi_P(x, y) d\nu(y) = \int_Y \chi_{P_x} d\nu \\ \psi(y) &= \int_X \chi_P(x, y) d\mu(x) = \int_X \chi_{P^y} d\mu\end{aligned}$$

so

$$(*) \quad (\mu \times \nu)(P) = \int_X \int_Y \chi_P \, d\nu d\mu = \int_X \phi \, d\mu = \int_Y \int_X \chi_P \, d\mu d\nu = \int_Y \psi \, d\nu$$

Theorem:

On (X, Λ, μ) and (Y, Γ, ν) σ -finite, the equality $*$ holds.

Recall that a space is σ -finite if $X = \bigcup_i X_i$, $X_i \in \Lambda$, $\mu(X_i) < +\infty$.

One may assume $X_i \subset X_{i+1}$.

Proof

1. E ok!

2. $P_i \in \Lambda \times \Gamma$, $P_i \subset P_{i+1}$, and the equality of the product measure holds for any i .

If $P_i \subset P_{i+1}$, $\chi_{P_i} \leq \chi_{P_{i+1}}$, $\phi_i \leq \phi_{i+1}$, $\psi_i \leq \psi_{i+1}$, $\phi_i \rightarrow \phi$ and $\psi_i \rightarrow \psi$.

Apply monotone convergence theorem for integration.

3. $P_i \in \Lambda \times \Gamma = M$, $P_i \supset P_{i+1}$, $\int \phi_i \, d\mu < +\infty$, and $\int \psi_i \, d\nu < +\infty$.

If 1, 2 and 3 hold, then $M = \Lambda \times \Gamma$.

4. $X = \bigcup_k X_k$, $Y = \bigcup_k Y_k$, $\Lambda_k = \{A \cap X_k : A \in \Lambda\}$, $\Gamma_k = \{B \cap Y_k : B \in \Gamma\}$.

Then take $\Lambda_k \times \Gamma_k = M_k$. By 2, $M_k \rightarrow M$ and 4 implies 3 holds.

Definition: Product Measure

Define

$$(\mu \times \nu)(P) = \int_X \phi \, d\mu + \int_Y \psi \, d\nu = \int_X \int_Y \chi_P \, d\nu d\mu = \int_Y \int_X \chi_P \, d\mu d\nu$$

Then

$$\int_{X \times Y} \chi_P \, d(\mu \times \nu)$$

On $(X \times Y, \Lambda \times \Gamma, \mu \times \nu)$.

Proposition:

If $f(x, y)$ is measurable, then $\forall y \in Y$, $f_y(x)$ is measurable and $\forall x \in X$, $f_x(y)$ is measurable.

Proof

1. χ_P measurable gives $P \in \Lambda \times \Gamma$ which implies $P_x \in \Gamma$ for all $x \in X$ and $P^y \in \Lambda$ for any $y \in Y$.

2. $\phi_n(x, y) \rightarrow f(x, y)$ pointwise on $X \times Y$, then $(\phi_n)_x(y) \rightarrow f_x(y)$ in Y and $(\phi_n)_y(x) \rightarrow f_y(x)$ in X for fixed $x \in X$, $y \in Y$ respectively.

Therefore,

$$\phi_n = \sum_{j=1}^k \alpha_j \chi_{P_j} \quad \text{and} \quad \forall x \in X, (\phi_n)_x(y) = \sum_{j=1}^k \alpha_j \chi_{(P_j)_x}(y)$$

$$\forall y \in Y, (\phi_n)_y(x) = \sum_{j=1}^k \alpha_j \chi_{(P_j)_y}(x)$$

Theorem: Fubini Theorem

Let (X, Λ, μ) and (Y, Γ, ν) be σ -finite measure spaces, and take $f(x, y)$ measurable on $(X \times Y, \Lambda \times \Gamma, \mu \times \nu)$. Assume also that $f \geq 0$.

$$\int_X \left(\int_Y f(x, y) d\nu(y) \right) d\mu(x) = \int_{X \times Y} f(x, y) d(\mu \times \nu) = \int_Y \left(\int_X f(x, y) d\mu(x) \right) d\nu(y)$$

Proof

There exist ϕ_n simple such that $\phi_n \rightarrow f$ monotonically.

Corollary

When f assumes negative values, if

$$\int_X \int_Y |f(x, y)| d\nu(y) d\mu(x) < +\infty$$

then Fubini holds for f . Likewise when

$$\int_{X \times Y} |f(x, y)| d(\mu \times \nu) < +\infty$$

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Definition: Lp Space

For (X, Λ, μ) a complete measure space,

$$L_\mu^p(x) = \left\{ f : \int_X |f|^p d\mu < +\infty \right\}$$

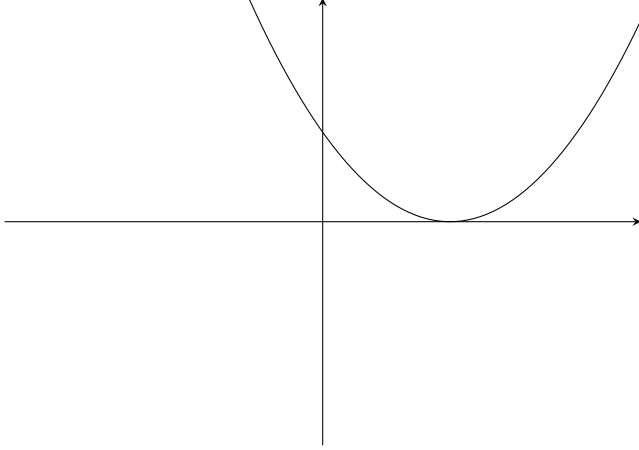
where $1 \leq p \leq +\infty$ and we identify $[f] = [g]$ if $f = g$ μ -a.e.

Definition: Banach Space

A normed, complete vector space.

Definition: Convex Functions

A function ϕ is convex if $((1-\lambda) + \lambda)\phi((1-\lambda)x + \lambda y) \leq (1-\lambda)\phi(x) + \lambda\phi(y)$,



Equivalently,

$$\begin{aligned}\frac{[\phi((1-\lambda)x + \lambda y) - \phi(x)]}{\lambda(y-x)} &\leq \frac{[\phi(y) - \phi((1-\lambda)x + \lambda y)]}{(1-\lambda)(y-x)} \\ \frac{\phi(z) - \phi(x)}{z-x} &\leq \frac{\phi(y) - \phi(z)}{y-z} \\ \phi'(a) &\leq \phi'(b)\end{aligned}$$

Theorem:

If ϕ is differentiable, then ϕ is convex if and only if ϕ' is non decreasing.
And if ϕ is twice differentiable, ϕ is convex if and only if $\phi'' \geq 0$.

Corollary

e^x is convex, since

$$e^{(1-\lambda)x + \lambda y} \leq (1-\lambda)e^x + e^y$$

Then if $e^x = a$ and $e^y = b$

$$a^{1-\lambda} b^\lambda \leq (1-\lambda)a + \lambda b$$

for $\lambda \in (0, 1)$.

If $\lambda = \frac{1}{2}$, then $\sqrt{ab} \leq \frac{a+b}{2}$.

Theorem: Jensen's Inequality

For ϕ convex and (X, Λ, μ) with $\mu(X) = 1$,

$$\phi\left(\int_X f d\mu\right) \leq \int_X \phi \circ f d\mu$$

where the range of f is in the domain of ϕ .

Compare: $\phi\left(\frac{a+b}{2}\right) \leq \frac{1}{2}(\phi(a) + \phi(b))$.

Proof

Write $t = \int_X f d\mu$. Then $\forall a < t < b$,

$$\frac{\phi(t) - \phi(a)}{t - a} \leq \frac{\phi(b) - \phi(t)}{b - t}$$

Set $\beta = \sup_a \frac{\phi(t) - \phi(a)}{t - a}$, then

$$\begin{aligned} \frac{\phi(t) - \phi(a)}{t - a} &\leq \beta \\ \phi(t) &\leq \beta(t - a) + \phi(a) \end{aligned}$$

$$\begin{aligned} \frac{\phi(b) - \phi(t)}{b - t} &\geq \beta \\ \phi(b) - \phi(t) &\geq \beta(b - t) \\ \phi(t) &\leq \phi(b) + \beta(t - b) \end{aligned}$$

Therefore

$$\begin{aligned} \phi(t) &\leq \phi(s) + \beta(t - s), \quad \forall s \\ \phi(t) &\leq \phi \circ f + \beta(t - s), \quad \forall x \in X \\ \phi(t) &\leq \int_X \phi \circ f d\mu + \beta \overbrace{\left(t - \int_X f d\mu\right)}^{=0} \\ \phi\left(\int_X f d\mu\right) &\leq \int_X \phi \circ f d\mu \end{aligned}$$

Compare: $e^{\int_X f d\mu} \leq \int_X e^{f(x)} d\mu$.

Theorem: Holder Inequality

On (X, Λ, μ) with $1 \leq p \leq +\infty$,

$$\left| \int_X f g d\mu \right| \leq \left(\int_X |f|^p d\mu \right)^{\frac{1}{p}} \left(\int_X |g|^q d\mu \right)^{\frac{1}{q}}$$

where $\frac{1}{p} + \frac{1}{q} = 1$, $p = 1 \implies q = \infty$ and $p = \infty \implies q = 1$.

Proof

Take $\|f\|_p = \left(\int_X |f|^p d\mu \right)^{\frac{1}{p}}$.

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

$$\left| \int_X f g d\mu \right| \leq \int_X |f| |g| d\mu \leq \|g\|_\infty \int_X |f| d\mu = \|f\|_1 \|g\|_\infty$$

We have $\frac{1}{p} + \frac{1}{q} = 1$ and $1 - \lambda = \frac{1}{p}$ while $\lambda = \frac{1}{q}$, so

$$\begin{aligned} \frac{|f|}{||f||_p} \cdot \frac{|g|}{||g||_q} &= \left(\frac{|f|^p}{||f||_p^p} \right)^{\frac{1}{p}} \left(\frac{|g|^q}{||g||_q^q} \right)^{\frac{1}{q}} \\ &= \left(\frac{|f|^p}{||f||_p^p} \right)^{\frac{1}{p}} \left(\frac{|g|^q}{||g||_q^q} \right)^{\frac{1}{q}} \end{aligned}$$

For

$$\begin{aligned} \left| \int_X fg \, d\mu \right| &\leq \int_X (|f||g|) \, d\mu \\ \int_X \frac{|f|}{||f||_p} \cdot \frac{|g|}{||g||_q} &\leq \int_X \frac{1}{p} \frac{|f|^p}{||f||_p^p} + \frac{1}{q} \frac{|g|^q}{||g||_q^q} \\ \frac{\int_X |fg| \, d\mu}{||f||_p ||g||_q} &\leq \frac{1}{p} \frac{\int_X |f|^p \, d\mu}{\int_X |f|^p \, d\mu} + \frac{1}{q} \frac{\int_X |g|^q \, d\mu}{\int_X |g|^q \, d\mu} \\ &\leq \frac{1}{p} + \frac{1}{q} \end{aligned}$$

Theorem: Minkowsky Inequality

On (X, Λ, μ) with $1 \leq p \leq +\infty$,

$$\left(\int_X |f+g|^p \, d\mu \right)^{\frac{1}{p}} \leq \left(\int_X |f|^p \, d\mu \right)^{\frac{1}{p}} + \left(\int_X |g|^p \, d\mu \right)^{\frac{1}{p}}$$

Proof

If $p = 1$,

$$\begin{aligned} \int_X |f+g| \, d\mu &\leq \int_X |f| \, d\mu + \int_X |g| \, d\mu \\ ||f+g||_{L^\infty} &\leq ||f||_\infty + ||g||_\infty \end{aligned}$$

For $1 < p < +\infty$, $1 < q < +\infty$, $\frac{1}{p} + \frac{1}{q} = 1$,

$$\frac{1}{q} = 1 - \frac{1}{p} = \frac{p-1}{p} \quad \text{and} \quad \frac{p}{p+1} = q$$

therefore

$$\begin{aligned} ||f+g||_p^p &= \int_X |f+g|^p \, d\mu = \int_X |f+g|^{p-1} |f+g| \, d\mu \\ &\leq \int_X |f+g|^{p-1} |f| \, d\mu + \int_X |f+g|^{p-1} |g| \, d\mu \\ &\leq \left(\int_X |f+g|^{p-1 \frac{p}{p-1}} \, d\mu \right)^{\frac{p-1}{p}} \left(\int_X |f|^p \, d\mu \right)^{\frac{1}{p}} + \left(\int_X |f+g|^{p-1 \frac{p}{p-1}} \, d\mu \right)^{\frac{p-1}{p}} \left(\int_X |g|^p \, d\mu \right)^{\frac{1}{p}} \\ &= ||f+g||_p^{p-1} (||f||_p + ||g||_p) \end{aligned}$$

Theorem:

$L_\mu^p(x)$ is a Banach space with $1 \leq p \leq +\infty$.

Proof

It suffices to verify $L_\mu^p(x)$ is complete, but the $p = +\infty$ case must be considered separately.

For $1 \leq p < +\infty$, let $\{f_n\}$ with $f_n \in L_\mu^p(x)$ be Cauchy.

We want to show that $\exists f \in L_\mu^p(x)$ such that $\|f_n - f\|_p \rightarrow 0$ as $n \rightarrow +\infty$.

Recall: a sequence is Cauchy if $\forall \varepsilon > 0, \exists k \in \mathbb{N}$ such that $\|f_n - f_m\|_p < \varepsilon, \forall n, m \geq k$.

Pick f_{n_k} such that $\|f_{n_{i+1}} - f_{n_i}\|_p \leq 2^{-i}$.

Take $g_k = \sum_{i=1}^k |f_{n_{i+1}}(x) - f_{n_i}(x)|$ and define $g(x) = \sum_{i=1}^{\infty} |f_{n_{i+1}}(x) - f_{n_i}(x)|$.

By the Minkowski inequality,

$$\|g_k\|_p \leq \sum_{i=1}^k \|f_{n_{i+1}} - f_{n_i}\|_p \leq 1$$

Therefore $\int_X |g_k|^p d\mu \leq 1, \forall k$.

Then, by Fatou's Lemma

$$\int_X |g|^p d\mu \leq 1$$

so g is μ -a.e. finite. So

$$s_k(x) = \sum_{i=1}^k (f_{n_{i+1}}(x) - f_{n_i}(x)) \rightarrow s(x) = \sum_{i=1}^{\infty} (f_{n_{i+1}}(x) - f_{n_i}(x))$$

Therefore, by dominated convergence,

$$s_k \rightarrow s \text{ in } L_\mu^p(x) \quad \text{and} \quad f_{n_k} \rightarrow s + f_{n_1}(x) = f(x) \text{ in } L_\mu^p(x)$$

For $p = +\infty$, let

$$B_k = \{x : |f_k(x)| > \|f_k\|_\infty\}$$

$$B_{m,n} = \{x : |f_m(x) - f_n(x)| > \|f_m - f_n\|_\infty\}$$

Then $B = (\bigcup_k B_k) \cup (\bigcup_{m,n} B_{m,n})$ and $\mu(B) = 0$. Examining the convergence on $X \setminus B$ completes the proof.

Theorem:

Let (X, Λ, μ) be a complete measure space with X Locally Compact Hausdorff and μ Radon.

Then $C_c(X) \subset L_\mu^p(x), 1 \leq p < +\infty$.

Remark

Write $\|f\|_C = \sup_X |f(x)|$, and take $C_0(X)$ the collection of continuous functions vanishing at infinity to be the completion.

Proof

Step 1: $s_n(x) \rightarrow f$, where $s_n = \sum_{i=1}^n \alpha_i \chi_{A_i} \in L_\mu^p(x)$.

Step 2: If f is bounded, and $\mu(\text{supp}(f)) < +\infty$, we may use Vitali-Lusin.