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 $A \to B$.

Definition: Countable

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

Theorem

The countable union of countable sets is countable.

Proof

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

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

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

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

Proof

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

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

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

Set $A = \{x \subset X : x \notin \phi(x)\}$, 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

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

Topology of the Real Line

Completeness (as a metric space)

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

1. $x_i \to x$ if $\forall \varepsilon > 0$, $\exists n \in \mathbb{N}$ such that $|x_i - x| < \varepsilon$, $\forall i \ge n$.

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

Definition: Open Inteval

(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.
  $\varnothing$ 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, $(U \setminus \{x\}) \cap A = \emptyset$ 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 $x_{i_k} \to x \in A$.

- 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.
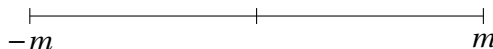   Assume that A is not bounded from abvove.
    Then there exists a sequence $\{x_i\}$, $x_i \in A$ where $x_{i+1} > x_i + 1$ and $\{x_i\}$ has no convergent subsequences.
    Then compactness implies closedness.
    A closed and bounded $\implies$ A (sequentially) compact.
    Let any $\{x_i\}$, $x_i \in A$.
    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.

$$\vdash\!\!\!\!\!-\!\!\!-\!\!\!-\!\!\!-\!\!\!-\!\!\!-\!\!\!-\!\!\!+\!\!\!-\!\!\!-\!\!\!-\!\!\!-\!\!\!-\!\!\!-\!\!\!-\!\!\!\dashv$$
$$-m \qquad\qquad\qquad\qquad m$$

    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

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

Definition: Perfectly Symmetric Sets

Let $\{\xi_n\}$ where $\xi_n \in \left(0, \frac{1}{2}\right)$.
$E_0 = [0,1]$, $E_1 = [0, \xi_1] \cup [1 - \xi_1, 1]$, $E_2 = [0, \xi_1\xi_2] \cup [\xi_1 - \xi_1\xi_2, \xi_1] \cup [1 - \xi_1, 1 - \xi_1 + \xi_1\xi_2] \cup [1 - \xi_1\xi_2, 1]$.
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 $|E| = \lim_{n\to\infty} |E_n| = \lim_{n\to\infty} \left(2^n \xi_1 \xi_2 \cdots \xi_n\right) = \lambda$ where $\lambda \in [0,1)$.
Let

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

, then

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

Proof

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

$C_0 = [0,1]$
$C_1 = [0,1/3] \cup [2/3,1]$
$C_2 = [0,1/9] \cup [2/9,3/9] \cup [6/9,7/9] \cup [8/9,1]$
$C_n = \bigcup_{n=1}^{2^n} C_n^k$
$|C_n^k| = \left(\frac{1}{3}\right)^n$
$C = \bigcap_{n=1}^{\infty} C_n$
$|C_n| = 2^n \frac{1}{3^n} = \left(\frac{2}{3}\right)^n \implies |C| = \lim_{n\to\infty} |C_n| = 0$
Closed, no interior points and uncountable.

- Perfect Symmetric Sets

$\{\xi_k\} \in \left(0, \frac{1}{2}\right)$
$E_0 = [0,1]$
$E_1 = [0,\xi_1] \cup [1-\xi_1, 1]$
$E_2 = [0,\xi_1\xi_2] \cup [\xi_1 - \xi_1\xi_2, \xi_1] \cup [1-\xi_1, 1-\xi_1+\xi_1\xi_2] \cup [1-\xi_1\xi_2, 1]$
$E_n = \bigcup_{n=1}^{2^n} E_n^k$
$|E_n^k| \xi_1 \xi_2 \cdots \xi_n$
$|E_n| = 2^n \xi_1 \xi_2 \cdots \xi_n$
$$2\xi_n = \frac{\left(1 + \frac{\log\left(\frac{1}{n}\right)}{n-1}\right)^{n-1}}{\left(1 + \frac{\log\left(\frac{1}{n}\right)}{n}\right)^n} < 1$$
$$|E_n| = \frac{1}{\left(1 + \frac{\log\left(\frac{1}{n}\right)}{n}\right)^n}$$
$|E| = \lim_{n\to\infty} |E_n| = \frac{1}{e^{\log\left(\frac{1}{n}\right)}} = \lambda, \quad \lambda \in (0,1)$

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)

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

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

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 $m^*(A) = \inf\{\sum_{n=1}^{\infty} I_n : A \subseteq \bigcup_{n=1}^{\infty}\}$
Question: $m^*(A \cup B) \overset{?}{=} m^*(A) + m^*(B)$ for $A \cap B \neq \varnothing$?

Properties

1. $A \subseteq B \implies m^*(A) \leq m^*(B)$.

2. $m^*(\varnothing) = 0$.

3. If I is an interval, then $m^*(I) = |I|$.

4. If $\{A_i\}$ is countable, $m^*\left(\bigcup A_i\right) \leq \sum m^*(A_i)$.

- 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 $\sum_{n,i} |I_n^i| = \sum_i \left(\sum_n |I_n^i|\right) \leq \sum_i \left(m^*(A_i) + \frac{\varepsilon}{2^i}\right)$.

  – 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

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

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

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

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

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

January 16, 2024

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

Lebesgue Outer Measure

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

Properties

1. $A \subset B \implies m^*(A) \leq m^*(B)$.

2. $m^*(\varnothing) = 0$.

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 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, $A_i \cap A_j = \varnothing \implies m^*\left(\bigcup_{i=1}^{\infty}(A_i)\right) = \sum_{i=1}^{\infty} m^* A_i$.

        (c) A, B measurable $\implies A \cup B,\ A \cap B,\ A \setminus B$ measurable.

        (d) $A \cap B = \varnothing \implies m^*(A \cup B) = m^*(A) + m^*(B)$.

        (e) $\{A_i\}_i^{\infty}$ with A_i measurable, then $\bigcup_{i=1}^{\infty} A_i$ is measurable and $A_i \cap A_j \varnothing \implies m^*\left(\bigcup_{i=1}^{\infty} A_i\right) = \sum_{i=1}^{\infty} m^*(A_i)$.

        - 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 $A_i \cap A_j = \varnothing$.

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

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

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

$$\implies \bigcup_{i=1}^{\infty} A_i \text{ measurable}$$

Proof of Claim:

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

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

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 $A_i' \cap A_j' = \varnothing$ and A_i' is measurable.

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

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. $\varnothing \in S$.

2. $A^c \in S$ if A^c.

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 smallet 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

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

Then $A\mathcal{C} = \mathcal{C}^\ell \cup \mathcal{C}^r \cup \mathcal{C}^m$.
$\forall I_k \in \mathcal{C}^m = \{I_k\}$, $I_k = (c_k, d_k)$ for some $c_k, d_k \in \mathbb{R}$, define

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

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

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

Observe that

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

Therefore

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

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

Therefore

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

$$= \sum_{I \in \mathcal{C}^r} |I| + \sum_{I \in \mathcal{C}^\ell} |I| + \sum_k \left(|I_k^\ell| + |I_k^r| \right)$$

$$\leq \sum_{I \in \mathcal{C}} |I| + \sum_{k=1}^{+\infty} \frac{\varepsilon}{2^{k+1}}$$

$$\leq m^*(E) + \frac{\varepsilon}{2} + \frac{\varepsilon}{2}$$

$$\leq m^*(E) + \varepsilon$$

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. $\forall A \in \mathbb{R}$, $\exists \bigcap_{n=1}^{\infty} U_n = F \in B$, 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 ech 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 $A = \{ x \in (0, 1) : x$ 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 $(A + r) \cap (A + s) = \varnothing$ 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. $\varnothing, X \in \tau$

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. $\varnothing \in \Lambda$

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 $\mu : \Lambda \to [0, +\infty]$ such that

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

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

Proposition: Monotonicity

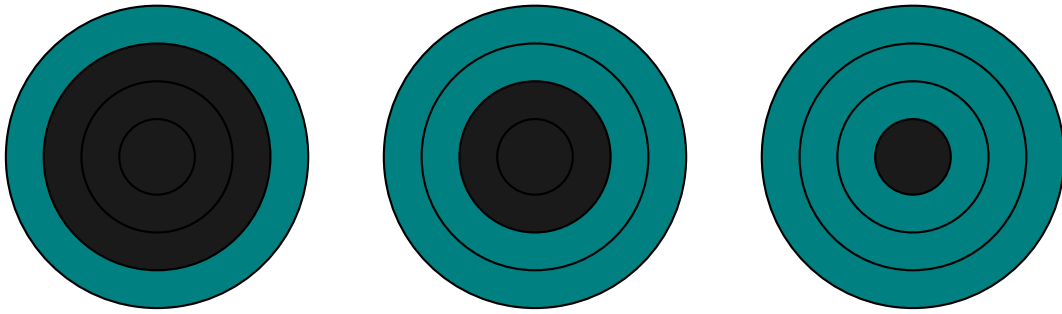$A, B \in \Lambda$, $A \subseteq B \implies \mu(A) \leq \mu(B)$.

Proposition: Countable Subadditivity

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

Proposition: Monotone Convergence

Given $A_i \subset \Lambda$ such that $A_i \subset A_{i+1}$ where $A = \bigcup_{i=1}^{\infty} A_i$, then $\mu(A_i) \to \mu(A)$.
Similarly, if $A_i \supset A_{i+1}$ such that $A = \bigcap_{i=1}^{\infty} A_i$, then $\mu(A_i) \to \mu(A)$ if $\mu(A_k) < +\infty$ for some $k = 1, 2, 3, \ldots$.

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

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

and

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

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

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

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 $(X, \overline{\Lambda}, \overline{\mu})$ such that

1. $\Lambda \subset \overline{\Lambda}$.

2. If $A \in \Lambda$, then $\overline{\mu}(A) = \mu(A)$.

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

Proof (Construction)

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

1. $\overline{\Lambda}$ is a σ-Algebra.

   (a) If $A \cup Z \in \overline{\Lambda}$, then $(A \cup Z)^c \in \overline{\Lambda}$.

   (b) If $A_i \cup Z_i \in \overline{\Lambda}$, then $\bigcup(A_i \cup Z_i) \in \overline{\Lambda}$.

2. $\overline{\mu}$ is a well-defined measure on $\overline{\Lambda}$.

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

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

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 $\bigcup Z_i \subset \bigcup D_i$,

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

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- 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 $\overline{\mu}$ is well defined.
  Given $\{A_i \cup Z_i\}$ with $(A_i \cup Z_i) \cap (A_j \cup Z_j) = \emptyset$ for all $i \neq j$,

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

  So $\overline{\mu}$ 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 $F = \{B \in \Lambda : \forall \varepsilon > 0, \exists C \subset B$ 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

$$\bigcap_{i=1}^{\infty} A_i \setminus \bigcap_{i=1}^{\infty} C_i \subset \bigcup_{i=1}^{\infty} (A_i \setminus C_i)$$

$$\nu \left(\bigcap_{i=1}^{\infty} A_i \setminus \bigcap_{i=1}^{\infty} C_i \right) \leq \sum_{i=1}^{\infty} \nu(A_i \setminus C_i) < \varepsilon$$

Therefore

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

so $\exists N \gg 1$ such that $\nu \left(\bigcup_{i=1}^{\infty} \setminus \bigcup_{i=1}^{N} C_i < \varepsilon \right)$ 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, $\mu : \Lambda \to [0, +\infty]$

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

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

Properties of a Measure

Monotonicity

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

Countable Subadditivity

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

Monotone Convergence

$A_i \subset A_{i+1},\; A_i \to \bigcup A_i \implies \mu(A) = \mu\left(\bigcup A_i\right).$
$A_i \supset A_{i+1},\; A_i \to \bigcap A_i \implies \mu(A_i) \to \mu\left(\bigcap A_i\right)$ if $\mu(A_1) < \infty$

- Example
  $A_n = (n, +\infty)$ gives $\bigcap A_n = \varnothing$

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 $v(B) = \mu(B \cap A)$ such that (X, Λ, v) is a new measure space.
Define $F = \{B \in \Lambda : \forall \varepsilon > 0, \exists C \text{ closed}, C \subset B, v(B \setminus C) < \varepsilon\}$, 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.
$U = \bigcup U_i$, $U_i = \left\{ x \in U : \text{dist}(x, U^c) \leq \frac{1}{i} \right\}$, therefore $\mathcal{B} \subset F$.
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, $\forall A \subset \Lambda$ 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

$$B \cap A^c = B \setminus A \subset D$$
$$(B \cap A^c)^c \supset D^c$$
$$B \cap (B^c \cup A) \supset D^c \cap B$$
$$A \supset B \setminus D$$

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

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

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, $\exists U \supset A^c$ ($\Longrightarrow U^c \subset A$), $\mu(U \setminus A^c) < \varepsilon$. 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
  ($\Longrightarrow$)
  Let $B(r, x_0) = \{x \in \mathbb{R}^n : |x - x_0| < r\}$ and $\overline{B(r, x_0)} = \{x \in \mathbb{R}^n : |x - x_0| \le r, \text{compact}\}$.
  Then $\mu(B(r, x_0)) \le \mu(\overline{B(r, x_0)}) < +\infty$. 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 $\mu(A) \le \mu(U_i) \le \mu(A) + \frac{1}{i} < +\infty$.
  Set $G = \bigcap U_i \in \mathcal{B}$, then $\mu(G) = \mu(A)$.
  ($\Longleftarrow$)

  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 $\{U_{\lambda_i}\}_{i=1}^{\lambda}$ where

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

  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 $\mu(C_i) \le \mu((V \cap B(i)) \setminus C_i) < \frac{1}{i}$ and $\mu(V \cap B(i)) \le \mu(C_i) + \frac{1}{i}$.
     Then $\mu(V) = \lim_{i \to \infty} \mu(V \cap B(i)) = \lim_{i \to \infty} \mu(C_i)$, 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 $\mu(A) \le \mu(U_i) \le \mu(A) + \frac{1}{i}$ 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. $\mu^*(\varnothing) = 0$.

2. $\mu^*(A) \le \mu^*(B)$ if $A \subseteq B$.

3. $\mu^*\left(\bigcup A_i\right) \le \sum \mu^*(A_i)$, $\forall A_i \in 2^X$ (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

$u^* : 2^X \to [0, +\infty]$.

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

2. Monotonicity: $\mu^*(A) \le \mu^*(B)$, $A \subseteq B$

3. Countable Subadditivity: $\mu^*\left(\bigcup_i A_i\right) \le \sum_i \mu^*(A_i)$.

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

$\forall A \subseteq \mathbb{R}^n$, $\forall s \ge 0$, $H_s^\delta(A) = \inf\left\{\sum_i (d(E_i))^s : \bigcup_i E_i \supset A, d(E_i) \le \delta\right\}$ where $d(E_i)$ is the diameter of E_i.
Notice that $H_s^{\delta_1}(A) \le H_s^{\delta_2}(A)$ if $\delta_2 \le \delta_1$.
Let $H_s^*(A) = \lim_{\delta \to 0} H_s^\delta(A)$, $\forall A \in 2^{\mathbb{R}^n}$.
Claim: H_s^* is an outer measure.

- Verify

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

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

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

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

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

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

and

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

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

Definition: Hausdorff Measure

The Hausdroff Measure $H_s : \Lambda \to [0, +\infty)$ 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 $\delta > 0$,

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

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

- 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 $A, B \subset \mathbb{R}^n$, $\operatorname{dist}(A, B) > 0$, then $H_s^*(A \cup B) = H_s^*(A) + H_s^*(B)$.
Since $\{E_i\}$ covering $A \cup B$, $d(E_i) < \frac{1}{4}\operatorname{dist}(A, B)$ gives

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

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

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

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

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

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

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

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

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 $d(E_i^j) < \frac{1}{j}$,

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

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

$$H_s^{\frac{i}{j}}(B) \le H_s^{\frac{1}{j}}\left(\bigcup_i E_i^j\right)$$

$$\le \sum_i H_s^{\frac{1}{j}}\left(E_i^j\right)$$

$$\le \sum_i \left(d(E_i^j)\right)^s$$

$$\le H_s^{\frac{1}{j}}(A) + \frac{1}{j}$$

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

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

Fractional or Hausdorff Dimension

Theorem:

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

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

Proof

$$H_s^\delta(A) \sim \sum_i (d(E_i))^s$$

$$= \sum_i (d(E_i))^t (d(E_i))^{s-t}$$

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

In the other direction, when $s < t$

$$\sum_i (d(E_i))^t = \sum_i (d(E_i))^s (d(E_i))^{t-s}$$

$$\le \delta^{t-s} \sum_i (d(E_i))^s$$

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 $k \to \infty$.
Is $s > n$ 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 $H_s^\delta(C^n) \sim \frac{2^n}{(3^n)^s} = \left(\frac{2}{3^s}\right)^n$.

Example 3

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

January 30, 2024

Lemma:

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

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

Proof 2 Implies 3

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

Proof 3 Implies 4

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

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 $f : X \to [-\infty, +\infty]$ 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 measruable.

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

- 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

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

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

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

Propositon:

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

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

Proppsotion:

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

1. $g_n(x) = \sup\{f_1(x), f_2(x), \ldots, f_n(x)\}$ and $h_n(x) = \inf\{f_1(x), f_2(x), \ldots, f_n(x)\}$ measurable.

2. $g(x) = \sup\{f_n(x)\}$ and $h(x) = \inf\{f_n(x)\}$ measurable.

3. $\limsup_{n \to +\infty} f_n(x) = \inf_n \sup\{f_n(x), f_{n+1}(x), \ldots\}$ and $\liminf_{n \to +\infty} f_n(x) = \sup_n \inf\{f_n(x), f_{n+1}(x), \ldots\}$ measurable.

4. $f_n(x) \to f(x)$ pointwise $\implies f$ measurable.

Proof of A

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

Proof of B

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

Definition: Almost Everywhere Convergence

For $f_n(x)$ measurable, $f_n(x) \to f(x)$ μ-a.e. in X if $f_n(x) \to f(x)$ 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 $f_n(x) \to f(x)$ μ-a.e. in X, $f(x)$ is measurable.

Proof

$f_n(x) \to f(x)$ 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. $|\phi_n(x)| \le |\phi_{n+1}(x)|$.

2. $\phi_n(x) \to f(x)$ 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 $N_n = \{x \in X : f(x) \le -n\}$ and $P_n = \{x \in X : f(x) \ge n\}$.
Then $\bigcap_n (N_n \cup P_n) = \varnothing$.
Define

$$A_{n,k} = \left\{ x \in X : \frac{k-1}{2^n} < f(x) \le \frac{k}{2^n} \right\}_{k=-1,-2,\ldots,-n2^n+1}$$

$$A_{n,0} = \left\{ x \in X : \frac{-1}{2^n} < f(x) < 0 \right\}$$

$$A_{n,1} = \left\{ x \in X : 0 < f(x) < \frac{1}{2^n} \right\}$$

$$A_{n,k} = \left\{ x \in X : \frac{k-1}{2^n} \le f(x) < \frac{k}{2^n} \right\}_{k=2,3,\ldots,n2^n}$$

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. $\forall x \in X, \phi_n(x) \to f(x)$.

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 $f_n \to f$ μ-a.e. in X, then $\forall \delta > 0$, $\exists A \in \Lambda$ such that $\mu(X \setminus A) < \delta$ and $f_n(x) \rightrightarrows f(x)$ in A.

Recall: Pointwise Convergence

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

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

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

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

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

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

February 2, 2024

Review: Measurable Function

An extended, real-valued function $f : X \to [-\infty, +\infty]$ 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, $f^{-1}(U) = \{x : f(x) \in V\}$ 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) $\limsup_{n \to \infty} f_n$ and $\liminf_{n \to \infty} f_n$ are measurable.

(d) if $f_n \to f$ 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

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

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. $\phi_n \to f$ pointwise.

2. $\phi_n \rightrightarrows f$ for f bounded.

Proof

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

$$A_{n,0} = \left\{x : -\frac{1}{2^n} < f(x) < 0\right\}$$
$$A_{n,1} = \left\{x : 0 < f(x) < \frac{1}{2n}\right\}$$
$$A_{n,k} = \left\{x : \frac{k-1}{2^n} \le f(x) < \frac{k}{2^n}\right\}$$
$$P_n = \{x : f(x) \ge n\}$$

and

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

So

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

Egoroff Theorem

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

1. $f_n(x) \to f(x)$ 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 $D = \{x : f_n(x) \to f(x)\} = X$.
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

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

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

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

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 $A = \bigcup_i \left(A_{m_i,1/i}\right)$,

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

and

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

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

Example

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

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

Proof

($\Longrightarrow$)
$\forall \varepsilon > 0$, $\exists m \in \mathbb{N}$ 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 $M \geq \varepsilon/2$.
($\Longleftarrow$)

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. $A_1 \subset A_2 \subset \cdots$, then $\mu\left(\bigcup_i A_i\right) = \lim_{i\to\infty} \mu(A_i)$.

2. $A_1 \supset A_2 \supset \cdots$, then $\mu\left(\bigcap_i A_i\right) \lim_{i\to\infty} \mu(A_i)$ for $\mu(A_1) < +\infty$.

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

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

then $\mu(F) = \lim_{k\to\infty} \mu(A_k) = 0$ 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

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

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

   K is bounded, $k \subset (-M, M)$ 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 $\mu(K_n) \to \mu(U)$.

   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

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

   It follows that

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

   and

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

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

   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 $\lim_{m \to \infty} m(U^n) = m(A)$ and $m(B) = m(A)$.

Problem 4

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

That is, $\overline{f} : \mathbb{R} \setminus D \to \mathbb{R}$ 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: $f^{-1}(V) \cap (\mathbb{R} \setminus D) = \overline{f}^{-1}(V)$.

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

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

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

Alternatively (similary to Probelm 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 $(a_j, b_j) \cap (a_k, b_k) = \varnothing$ 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: $f_n(x) \to f(x)$ on $\mathbb{R} \setminus G$ where $G = \bigcap_n^\infty \bigcup_{k=n}^\infty \{x : f_k(x) \neq f(x)\}$.

By monotone convergence, $\mu(g) = \lim_{n \to +\infty} \mu(\bigcup_{k=n}^\infty \{x : f_n(x) \neq f(x)\}) = \lim_{n \to +\infty} (\sum_{k=n}^{+\infty} 2^{ik}) = 0$.

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

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 $f : [a, b] \to \mathbb{R}$ bounded and P a partiation of $[a, b]$ where

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

The Cauchy sum

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

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

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

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

$$\mathrm{Osc}_I(f) = \sup_I f(x) - \inf_I f(x)$$

$$\mathrm{Osc}_x(f) = \lim_{\delta\to 0} \mathrm{Osc}_{(x-\delta, x+\delta)}(f)$$

and observe that f is continuous at x if and only if $\mathrm{Osc}_x(f) = 0$.
Let $D = \{x : \mathrm{Osc}_x(f) > 0\}$ and $D_k = \left\{x : \mathrm{Osc}_x(f) > \frac{1}{k}\right\}$ such that $D_k \subset D_{k+1}$ and $D = \bigcup_k D_k$.
Therefore $m(D_k) \to m(D)$.
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 $P = \{a = x_0 < x_1 < \cdots < x_n = b\}$, $[x_{i-1}, x_i]$.
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 $S = \inf_P S_P = \inf\{\sum_i \alpha_i |I_i| : \phi_{P,\alpha}(x) \geq f(x)\}$
and $s = \sup_P s_P = \sup\{\sum_i \alpha_i |I_i| : \phi_{P,\alpha}(x) \leq f(x)\}$.

Definition: Riemann Integrable

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

Remark:

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

Remark:

If f is continuous, then it is Riemann integrable.

Theorem:

Given $f : [a, b] \to \mathbb{R}$ 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 $\text{Osc}_{x_0}(f) = \lim_{\delta \to 0} \text{Osc}_{(x_0 - \delta, x_0 + \delta)}(f)$.
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 $m(D_k) \xrightarrow[k \to \infty]{} m(D)$.
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 $\{I_{i_k}\}_{k=1}^{\ell} \subset \{I_i\}$.
($\Longleftarrow$) 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 $P = \{x_0, x_1, \ldots, x_n\}$,

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

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

$$\sum_{(x_i, x_{i-1}) \cap D_k \neq \emptyset} (x_i - x_{i-1}) = m\left(\bigcup_{(x_{i-1}, x_i) \cap D_k \neq 0} [x_{i-1}, x_i] \right) \geq m(D_k)$$

we conclude that

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

($\Longrightarrow$) 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 $\mathrm{Osc}_x(f) \leq 2M$,

$$S_P - s_P = \sum_i (M_i - m_i)(x_i - x_{i-1})$$

$$= \sum_{[x_{i-1}, x_i] \cap D_k = \varnothing} + \sum_{[x_{i-1}, x_i] \cap D_k \neq \varnothing}$$

$$\leq \frac{\varepsilon}{2(b-a)}(b-a) + 2M \cdot \frac{\varepsilon}{4M}$$

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 $f \geq 0$, $\forall c \in \mathbb{R}_{\geq 0}$ $\int_E cf \, d\mu = c \int_E f \, d\mu$.

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
  ($\Longrightarrow$) $\sum_i \alpha_i \chi_{A_i} = s(x) = f(x) \Longrightarrow \alpha_i > 0 \Longrightarrow \mu(A_i) = 0$.
  ($\Longleftarrow$) $f \geq \alpha > 0$ and $\mu(A) > 0 \Longrightarrow f(x) \geq \alpha \chi_A \Longrightarrow \int_X f \, d\mu \geq \alpha_{\mu(A)} > 0$ a contradiction.

- Proof of 5
  $s\chi_E = \sum_i \alpha_i \chi_{A_i \cap E}$.

- Proof of 6
  If $0 \leq s_1 \leq f$ and $0 \leq s_2 \leq g$, 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 $f_n(x) \to f(x)$ for any $x \in X$. Then

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

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

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

We want to show that

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

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, $A_i \cap E_n \to A_i$. Therefore $\mu(A_i \cap E_n) \xrightarrow{n \to +\infty} \mu(A_i)$. So

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

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

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

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 $f_n \geq 0$,

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

Proof

Observe that

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

so, by monotone convergence,

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

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

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

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

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

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

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

$$\left| \int_X f^+ \, d\mu - \int_x f^{-1} \, d\mu \right| \leq \int_X f^+ \, d\mu + \int_X f^- \, d\mu$$

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.
$M_\mu(x) = \{ f : X \to \mathbb{R} : \text{ measurable} \}$.
$L^1_\mu(x) = \{ f \in M_\mu(x) : \int_X |f| \, d\mu < +\infty \}$.
$||f||_1 = ||f||_{L^1_\mu(x)} = \int_X |f| \, d\mu$.
$L^\infty_\mu(x) = \{ f \in M_\mu(x) : ||f||_{L^\infty_\mu(x)} < +\infty \}$.
$||f||_\infty = ||f||_{L^\infty_\mu(x)} = \inf\{ M = \mu(\{ x \in X : |f(x)| > M \}) = 0 \}$.
$C_c(x)$ 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. $f_n, f \in M_\mu(x)$, $f_n \to f$ μ-a.e. in X.

2. $f_n \to f$ 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. $f_n \to f$ in $L^1_\mu(x)$, $\lim_{n \to +\infty} ||f_n - f|| = \lim_{n \to +\infty} \int_X |f_n - f| \, d\mu$.

4. $f_n \to f$ in measure if $\forall \varepsilon > 0$, $\lim_{n \to +\infty} \mu(\{ x \in X : |f_n(x) - f(x)| \geq \varepsilon \}) = 0$.

Theorem:

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

1. $f_n \to f$ μ-a.e. in X.

2. $||f_n||_\infty \le M \le +\infty$, $\forall n$

Then, $f_n \to f$ in $L^1_\mu(x)$. Therefore

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

Proof

Step 1: $f \in L^\infty_\mu(x)$ and $||f||_\infty \le M$.
Given $\varepsilon > 0$, $\{x \in X : |f(x)| > M + \varepsilon\} \subset \{x : |f_n(x)| > M + \varepsilon\}$, $\forall n \ge n_0$.
Then, $\mu(\{x : |f(x)| > M + \varepsilon\}) = 0$. Therefore $||f||_\infty \le M$.
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 $f_n(x) \rightrightarrows f(x)$ in A.
Then, $\forall \varepsilon > 0$, $\exists n_0 \in \mathbb{N}$ such that $|f_n(x) - f(x)| < \frac{\varepsilon}{2\mu(x)}$, $\forall x \in A$, $\forall n \ge n_0$.

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

So $f_n \to f$ in $L^1_\mu(x)$.
Step 3: observe

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

Remark

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

1. $L^\infty_\mu(x) \subset L^1_\mu(x)$.

2. $f_n \to f$ in $L^\infty_\mu(x) \implies f_n \to f$ in $L^1_\mu(x)$.

Theorem: Dominated Convergence

Let (X, Λ, μ) and $f_n \in M_\mu(x)$. If $\exists g \in L^1_\mu(x)$ such that $|f_n(x)| \le g(x)$, $\forall n$ and $f_n \to f$ μ-a.e. in X, then $f_n \to f$ in $L^1_\mu(x)$.
In particular,

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

Proof

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

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

$\phi_n \ge 0$.
By Fatou's lemma,

$$\int_X \left(\liminf_{n \to +\infty} \phi_n \right) d\mu \le \liminf_{n \to +\infty} \int_X \phi_n \, d\mu$$
$$\le \liminf_{n \to +\infty} \left(2 \int_X g \, d\mu - \int_X |f_n - f| \, d\mu \right)$$
$$= 2 \int_X g \, d\mu - \limsup_{n \to +\infty} \int_X |f_n - f| \, d\mu$$

Therefore

$$\limsup_{n \to +\infty} \int_X |f_n - f| \, d\mu \le 0 \implies \lim_{n \to +\infty} \int_X |f_n - f| \, d\mu = 0$$

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

Definition: Vitality Continuity

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

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

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

Lemma

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

- Proof
  Set $f_n(x) = \begin{cases} f(x) & |f(x)| \le n \\ n & |f(x)| > n \end{cases}$.
  Then $f_n \to f$ in X and $|f_n(x)| \le |f(x)|$. Therefore,

$$\int_A |f| \, d\mu \le \int_A ||f| - |f_n|| \, d\mu + \int_A |f_n| \, d\mu$$

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

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

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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 $f_n \to f$ μ-a.e. in X, then $f_n \to f$ 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, $\forall x \in N^c$, $f_n(x) \to f(x)$ and $\forall x \in N$, $f_n \nrightarrow f(x)$.
So $\mu(N) = 0$ implies $\mu(A_\varepsilon) = 0$ for any $\varepsilon > 0$. Therefore

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

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

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

and

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

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

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

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

$$\mu(\{x : |f_n(x) - f(x)| \ge \varepsilon\}) \le \frac{1}{\varepsilon} \int_X |f_n - f| \, d\mu \to 0$$

Definition: Vitali Equicontinuity

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

Theorem

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

Proof

($\Longrightarrow$) By assumption, $\int_X |f_n - f| \, d\mu \to 0$ as $n \to +\infty$.
Therefore, $\exists n_0 \in \mathbb{N}$ such that $\int_X |f_n - f| \, d\mu < \frac{\varepsilon}{2}$, $\forall n \ge n_0$. See that for all $n \ge n_0$,

$$\left| \int_A |f_n| \, d\mu - \int_A |f| \, d\mu \right| = \int_A \big||f_n| - |f|big\big| \, d\mu$$

$$\le \int_X |f_n - f| \, d\mu$$

$$< \frac{\varepsilon}{2}$$

and therefore $\int_A |f_n| \, d\mu \le \int_A |f| \, d\mu + \frac{\varepsilon}{2}$.
So there exists $\delta_0 > 0$ such that $\int_A |f_n| \, d\mu \le \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon$ for any $n \ge n_0$ 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 $\delta = \min\{\delta_0, \ldots, \delta_{n_0 - 1}\} > 0$. Then $\int_A |f_n| \, d\mu < \varepsilon$, $\forall n$, $\forall A \in \Lambda$, $\mu(A) < \delta$.
($\Longleftarrow$)
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

$$\int_X |f_n - f| \, d\mu = \int_{\left\{x : |f_n(x) - f(x)| < \frac{\varepsilon}{2\mu(x)}\right\}} |f_n - f| \, d\mu + \int_{\left\{x : |f_n(x) - f(x)| \ge \frac{\varepsilon}{2\mu(x)}\right\}} |f_n - f| \, d\mu$$

$$\le \frac{\varepsilon}{2\mu(x)} \mu(x) + \int_{A_{n,\varepsilon}} (|f_n| + |f|) \, d\mu$$

for $\varepsilon > 0$, $\mu(A_{n,\varepsilon}) \to 0$ as $n \to +\infty$.
So $\exists n_0 \in \mathbb{N}$ where $\mu(A_{n,\varepsilon}) < \delta$ for $n \ge n_0$ 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 $f_n \to f$ in measure then there exists a subsequence $\{f_{n_k}\} \subset \{f_n\}$ such that $f_{n_k} \to f$ μ-a.e.

Proof

Take

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

and $f_n \to f$ in measure.

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

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

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

Claim

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

2. $f_{n_k} \to f$ in $X \setminus A$.

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

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

where

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

Then

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

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

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

February 20, 2024

Riesz Representation Theorem

Linear Functionals

On a vector space V, a map $T : V \to \mathbb{R}$ 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

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

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 comapct, 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 continous 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 $K \prec f \prec U$.

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, $K \prec f \prec V$. 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 $\mu^*(U) = \sup\{Tf \ : \ f \prec U\}$.
  Then for any $A \subset X$, $\mu^*(A) = \inf\{\mu^*(U) \ : \ A \subset U, \ U \text{ open}\}$.

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

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

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

  - Lemma: Partition of Unity
    For X LCH, $U_1, U_2, \ldots, U_n$ open, K compact and $K \subset \bigcup_{i=1}^n U_i$.
    Then there exists a partition of unity $h_i \prec U_i$ 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, $\exists \overline{A}_i \prec g_i \prec U_i$.
    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. $h_i \prec U_i$, since we have not modified the support.

    2. $K \prec \sum_i h_i$, since $\forall x \in K \subset \bigcup_i A_i \subset \bigcup_i \overline{A}_i \subset \bigcup_i U$.

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

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

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

  - Proof of 3
    Take $\bigcup_i U_i$, U_i open and consider $\mu^*\left(\bigcup_i U_i\right)$.
    Then $\forall f \prec \bigcup_i U_i$, there exists a finite subcover $f \prec \bigcup_{j=1}^n U_{i_j}$, $\{U_{i_j}\} \subset \{U_i\}$.

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

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

and

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

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

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

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

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 $\mu(K) \le \mu(V)$.
    By Urysohn's lemma, $K \subset \bigcup_i H_i \subset \bigcup \overline{H}_i \prec f \prec V$ and

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

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

  - Proof of 3
    $\forall K \subset V$, K compact, V open, $\mu(K) \le \mu(V)$, by the definition of the outer measure $\exists f \prec V$ such that

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

    We have supp$(f) = K \subset V$, so there exists U open $U \supset K$ such that $\mu^*(U) \le \mu^*(K) + \frac{\varepsilon}{2}$.
    By Urysohn's lemma, $\exists K \prec g \prec U$ and

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

    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 $U \cap V = \varnothing$.
  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 $W_1 \cap W_2 = \varnothing$.
  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 $\exists K$ comapct 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 $\mathcal{B} \subset \Lambda$.

Proof: Step 3 (Verify)

For any $f \in C_c(X)$, write $f(x) \in [a, b]$.
Take $P = \{a = y_0 < y_1 < \cdots < y_{n-1} < y_n = b\}$ with $\ell(P) = \max\{y_i - y_{i-1} : i = 1, \ldots, n\}$.
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 linrity will make the reverse true by taking $-f$.

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

$$T(h_i f) \leq (y_i + \varepsilon)Th_i$$
$$\leq (|a| + y_i + \varepsilon)Th_i - |a|Th_i$$
$$\leq (|a| + y_i + \varepsilon)\mu(V_i) - |a|Th_i$$
$$\leq y_{i-1}\mu(A_i)$$
$$\leq \int_{A_i} f \, d\mu + c\varepsilon$$
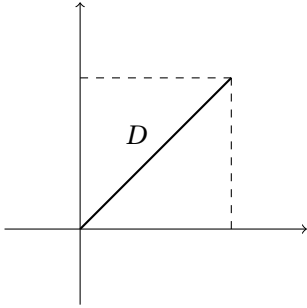
By summing each term, we get

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

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

$$0 = \alpha_1 < \alpha_2 < \cdots \to 1$$

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.

$$\forall x \in [0,1], \quad \int_{[0,1]} f(x,y) \, dm(y)$$

$$\forall x \in [\alpha_n, \alpha_{n+1}], n > 1, \quad \int_{[0,1]} -g_n(x)g_{n-1}(y) + g_n(x)g_n(y) \, dm(y) = 0$$

$$\forall x \in [\alpha_1, \alpha_2], n = 1, \quad \int_{[0,1]} g_1(x)g_1(y) \, dm(y)$$

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

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

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, v), $(x \times y, \Lambda \times \Gamma, \mu \times v)$?

We want

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

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 $(\mu \times v)(R) = \mu(A)v(B)$.
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 i $P \in \Omega(Q)$.

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 $(A_i)^Y \in \Lambda$, $\left(\bigcup_i A_i\right)_X \in \Gamma$ and $\left(\bigcup_i a_i\right)^Y \in \Lambda$.

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

$$\int_{X \times Y} \chi_{A \times B}(x, y) \, d(\mu \times v) = (\mu \times v)(A \times B) = \mu(A)v(B)$$

Define

$$\phi(x) = \int_Y \chi_{A \times B}(x, y) \, dv(y) = v(B)\chi_A$$

$$\psi(y) = \int_X \chi_{A \times B}(x, y) \, d\mu(x) = \mu(A)\chi_B$$

so

$$\int_X \phi \, d\mu = \int_X \int_Y \chi_{A \times B} \, dv d\mu = \mu(A)v(B) = \int_Y \int_X \chi_{A \times B} \, d\mu dv = \int_Y \psi(y) \, dv$$

Now $\forall P \in \Lambda \times \Gamma$,

$$\phi(x) = \int_Y \chi_P(x, y) \, dv(y) = \int_Y \chi_{P_x} \, dv$$

$$\psi(y) = \int_X \chi_P(x, y) \, d\mu(x) = \int_X \chi_{P^y} \, d\mu$$

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 $P_i \subset P_{i+1}$, $\chi_{P_i} \le \chi_{P_{i+1}}$, $\phi_i \le \phi_{i+1}$, $\psi_i \le \psi_{i+1}$, $\phi_i \to \phi$ and $\psi_i \to \psi$.
   Apply monotone convergence theorem for integration.

3. $P_i \in \Lambda \times \Gamma = M$, $P_i \supset P_{i+1}$, $\int \phi_1 \, d\mu < +\infty$, and $\int \psi_1 \, d\nu < +\infty$.

   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, $M_k \to M$ 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. $\phi_n(x, y) \to f(x, y)$ pointwise on $X \times Y$, then $(\phi_n)_x(y) \to f_x(y)$ in Y and $(\phi_n)_y(x) \to f_y(x)$ in X for fixed $x \in X$, $y \in Y$ respectively.

Therefore,

$$\phi_n = \sum_{j=1}^{k} \alpha_j \chi_{P_j} \quad \text{and} \quad \forall x \in X, \ (\phi_n)_x(y) = \sum_{j=1}^{k} \alpha_j \chi_{(P_j)_x}$$

$$\forall y \in Y, \ (\phi_n)_y(x) = \sum_{j=1}^{k} \alpha_j \chi_{(P_j)^y}$$

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 $f \geq 0$.

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

Proof

There exist ϕ_n simple such that $\phi_n \to f$ 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

$$\int_{X \times Y} |f(x, y)| \, d(\mu \times \nu) < +\infty$$

February 27, 2024

Definition: Lp Space

For (X, Λ, μ) a complete measure space,

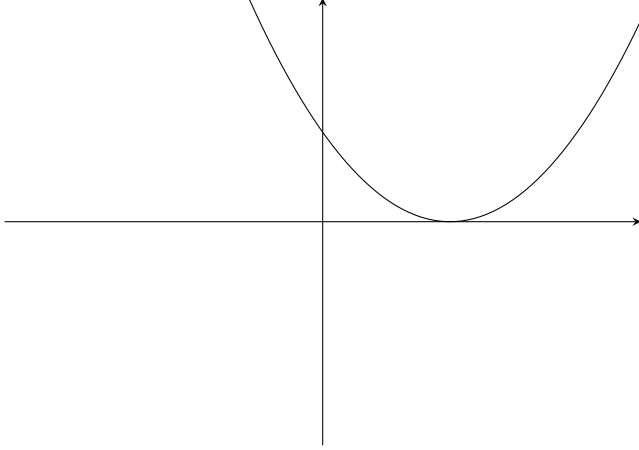$$L_\mu^p(x) = \left\{ f : \int_X |f|^p \, d\mu < +\infty \right\}$$

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: Convec Funxtions

A function ϕ is convex if $((1-\lambda)+\lambda)\phi((1-\lambda)x+\lambda y) \leq (1-\lambda)\phi(x)+\lambda\phi(y)$,

Equivalently,

$$\frac{[\phi((1-\lambda)x+\lambda y)-\phi(x)]}{\lambda(y-x)} \leq \frac{[\phi(y)-\phi((1-\lambda)x+\lambda y)]}{(1-\lambda)(y-x)}$$

$$\frac{\phi(z)-\phi(x)}{z-x} \leq \frac{\phi(y)-\phi(z)}{y-z}$$

$$\phi'(a) \leq \phi'(b)$$

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

$$\frac{\phi(t) - \phi(a)}{t - a} \leq \beta$$
$$\phi(t) \leq \beta(t - a) + \phi(a)$$

$$\frac{\phi(b) - \phi(t)}{b - t} \geq \beta$$
$$\phi(b) - \phi(t) \geq \beta(b - t)$$
$$\phi(t) \leq \phi(b) + \beta(t - b)$$

Therefore

$$\phi(t) \leq \phi(s) + \beta(t - s), \quad \forall s$$
$$\phi(t) \leq \phi \circ f + \beta(t - s), \quad \forall x \in X$$
$$\phi(t) \leq \int_X \phi \circ f \, d\mu + \beta \overbrace{\left(t - \int_x f \, d\mu \right)}^{=0}$$
$$\phi \left(\int_X f \, d\mu \right) \leq \int_X \phi \circ f \, d\mu$$

Compare: $e^{\int_X f \, d\mu} \leq \int_X e^{f(x)} \, d\mu$.

Theorem: Holder Inequality

On (X, Λ, μ) with $1 \leq p \leq +\infty$,

$$\left| \int_X fg \, d\mu \right| \leq \left(\int_X |f|^p \right)^{\frac{1}{p}} \left(\int_X |g|^q \right)^{\frac{1}{q}}$$

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

$$\left| \int_X fg \, d\mu \right| \leq \int |f||g| \, d\mu \leq ||g||_\infty \int_X |f| \, d\mu = ||f||_1 ||g||_\infty$$

We have $\frac{1}{p} + \frac{1}{q} = 1$ and $1 - \lambda = \frac{1}{p}$ while $\lambda = \frac{1}{q}$, so

$$\frac{|f|}{||f||_p} \cdot \frac{|g|}{||g||_q} = \left(\frac{|f|^p}{||f||_p}\right)^{\frac{1}{p}}\left(\frac{|g|^q}{||g||_q}\right)^{\frac{1}{q}}$$

$$= \left(\frac{|f|^p}{||f||_p}\right)^{\frac{1}{p}}\left(\frac{|g|^q}{||g||_q}\right)^{\frac{1}{q}}$$

For

$$\left|\int_X fg\, d\mu\right| \le \int_X (|f||g|)\, d\mu$$

$$\int_X \frac{|f|}{||f||_p} \cdot \frac{|g|}{||g||_q} \le \int_X \frac{1}{p}\frac{|f|^p}{||f||_p^p} + \frac{1}{q}\frac{|g|^q}{||g||_q^q}$$

$$\frac{\int_X |fg|\, d\mu}{||f||_p||g||_q} \le \frac{1}{p}\frac{\int_X |f|^p\, d\mu}{\int_X |f|^p\, d\mu} + \frac{1}{q}\frac{\int_X |g|^q\, d\mu}{\int_X |g|^q\, d\mu}$$

$$\le \frac{1}{p} + \frac{1}{q}$$

Theorem: Minkowsky Inequality

On (X, Λ, μ) with $1 \le p \le +\infty$,

$$\left(\int_X |f+g|^p\, d\mu\right)^{\frac{1}{p}} \le \left(\int_X |f|^p\, d\mu\right)^{\frac{1}{p}} + \le \left(\int_X |g|^p\, d\mu\right)^{\frac{1}{p}}$$

Proof

If $p = 1$,

$$\int_X |f+g|\, d\mu \le \int_X |f|\, d\mu + \int_X |g|\, d\mu$$

$$||f+g||_{L^\infty} \le ||f||_\infty + ||g||_\infty$$

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

$$||f+g||_p^p = \int_X |f+g|^p\, d\mu = \int_X |f+g|^{p-1}|f+g|\, d\mu$$

$$\le \int_X |f+g|^{p-1}|f|\, d\mu + \int_X |f+g|^{p-1}|g|\, d\mu$$

$$\le \left(\int_X |f+g|^{p-1\frac{p}{p-1}}\, d\mu\right)^{\frac{p-1}{p}}\left(\int_X |f|^p\, d\mu\right)^{\frac{1}{p}} + \left(\int_X |f+g|^{p-1\frac{p}{p-1}}\, d\mu\right)^{\frac{p-1}{p}}\left(\int_X |g|^p\, d\mu\right)^{\frac{1}{p}}$$

$$= ||f+g||_p^{p-1}(||f||_p + ||g||_p)$$

Theorem:

$L_\mu^p(x)$ is a Banach space with $1 \le p \le +\infty$.

Proof

It suffices to verify $L_\mu^p(x)$ is complete, but the $p = +\infty$ case must be considered separately.

For $1 \le p < +\infty$, 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 $||f_n - f||_p \to 0$ as $n \to +\infty$.

Recall: a sequence is cauchy if $\forall \varepsilon > 0$, $\exists k \in \mathbb{N}$ such that $||f_n - f_m||_p < \varepsilon$, $\forall n, m \ge k$.

Pick f_{n_k} such that $||f_{n_{i+1}} - f_{n_i}||_p \le 2^{-i}$.

Take $g_k = \sum_{i=1}^k |f_{n_{i+1}}(x) - f_{n_i}(x)|$ and define $g(x) = \sum_{i=1}^\infty |f_{n_{i+1}}(x) - f_n(x)|$.

By the Minkowski inequality,

$$||g_k||_p \le \sum_{i=1}^k ||f_{n_{i+1}} f_{n_i}||_p \le 1$$

Therefore $\int_X |g_k|^p \, d\mu \le 1$, $\forall k$.

Then, by Fatou's Lemma

$$\int_X |g|^p \, d\mu \le 1$$

so g is μ-a.e. finite. So

$$s_k(x) = \sum_{i=1}^k \left(f_{n_{i+1}}(x) - f_{n_i}(x)\right) \to s(x) = \sum_{i=1}^\infty \left(f_{n_{i+1}}(x) - f_{n_i}(x)\right)$$

Therefore, by dominated convergence,

$$s_k \to s \text{ in } L_\mu^p(x) \quad \text{and} \quad f_{n_k} \to s + f_{n_i}(x) = f(x) \text{ in } L_\mu^p(x)$$

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 $B = \left(\bigcup_k B_k\right) \cup \left(\bigcup_{m,n} B_{m,n}\right)$ 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 $C_c(X) \subset L_\mu^p(x)$, $1 \le p < +\infty$.

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: $s_n(x) \to f$, where $s_n = \sum_{i=1}^{k} \alpha_i \chi_{A_i} \in L_\mu^p(x)$.

Step 2: If f is bounded, and $\mu(\text{supp}(f)) < +\infty$, we may use Vitali-Lusin.

February 29, 2024

Recall: Lp Space is Banach

Given (X, Λ, μ), $L_\mu^p(x)$ is a Banach space given $||f||_p = \left(\int_X |f|^p \, d\mu \right)^{1/p}$, $1 \le p \le +\infty$ and $||f||_\infty = \inf\{\mu : \mu(\{x : |f| > \mu\}) = 0$

Definition: Linear Operator

Given vector spaces $V \to W$, $\alpha, \beta \in \mathbb{R}$, and $u, v \in V$, the map (or operator) $T : V \to W$ is linear if

$$T(\alpha u + \beta v) = \alpha T(u) + \beta T(v)$$

Definition: Linear Functional

If $L : V \to \mathbb{R}$ for linear operator L, then L is called a linear functional.

Definition: Operator Norm

For normed vector spaces, we have $||T|| = \sup\{||Tx|| : ||x|| \le 1\}$.

Definition: Bounded Linear Functional

A linear functional $L : V \to \mathbb{R}$ which sastisfies $|L(v)| \le ||L|| ||v||$.

Definition: Dual Space

If V is a normed vector space, then the dual space V^* is the collection of all bounded linear functionals $L : V \to \mathbb{R}$.

Theorem:

$(L^p)^* = L^q$, $\frac{1}{p} + \frac{1}{q} = 1$, $1 < p, q < +\infty$.

Proof

The general proof will require Radon-Nikodym.

In this case, $\forall g \in L^q \implies L_g : L^p \to \mathbb{R}$.

Take $\phi(g) = L_g : L^q \to (L^p)^*$ so $L_g = \int_X f \cdot g \, d\mu$, $\forall f \in L^p$. Then

$$|L_g(f)| = \left| \int_X f \cdot g \, d\mu \right| \le \int_X |f||g| \, d\mu \le ||g||_q ||f||_p$$

So $||L_g|| \le ||g||_q$. We claim that $||L_g|| = ||g||_q$. Take

$$f = \frac{\text{sign}(g)|g|^{q-1}}{||g||_q^{q-1}}$$

and, since, $||g||_q^q = \int_X |g|^q \, d\mu$ and $q = p(q-1)$,

$$\int_X |f|^p \, d\mu = \int_X \frac{|g|^{p(q-1)}}{||g||_q^{p(q-1)}} \, d\mu = \frac{\int_X |g|^q \, d\mu}{\int_X |g|^q \, d\mu} = 1$$

Therefore,

$$L_g(f) = \int_X f \cdot g \, d\mu = \frac{\int_X |g|^q \, d\mu}{||g||_q^{q-1}} = ||g||_q$$

Since L_g is a linear operator, $L_g f_1 - L_g f_2 = L_g(f_1 - f_2)$ and $L_{g_1}(f) + L_{g_2}(f) = L_{g_1+g_2}(f)$.
That is, $||L_g|| = ||g||_q$ and L_g is injective. We claim that $L_G : L^q \to (L^p)^*$ is an isometric isomorphism.
Step 1 of proving isometry is that $\forall L \in (L^p)^*$, $\exists \nu$ such that $L(f) = \int_X f \, d\nu$, $\forall f \in L^p$.
Step 2, Radon-Nikodym, $\exists g \in L^q$ where $d\nu = g d\mu$. That is $\frac{d\nu}{d\mu} = g$.

Useful Inequalities

Chebyshev's Inequality

Suppose $f \in L^p$, then

$$\mu(\{x : |f| > \alpha\}) \le \frac{||f||_p^p}{\alpha^p}$$

- Proof

$$||f||_p^p = \int_X |f|^p \, d\mu \ge \int_{\{x : |f| > \alpha\}} |f|^p \, d\mu \ge \int_{\{x : |f| > \alpha\}} \alpha^p \, d\mu$$

Minkowski's Inequality

$$\left|\left|\int_Y f(x, y) \, d\nu(y)\right|\right|_p \le \int_Y ||f(x, y)||_p \, d\nu(y)$$

Equivalently

$$\left(\int_X \left|\int_Y f(x, y) \, d\nu(y)\right|^p \, d\mu(x)\right)^{\frac{1}{p}} \le \int_Y \left(\int_X |f(x, y)|^p \, d\mu(x)\right)^{\frac{1}{p}} \, d\nu(y)$$

Recall

$$\int_X |fg| \, d\mu \le ||f||_p ||g||_q$$

for $\frac{1}{p} + \frac{1}{q} = 1$.
Then

$$||f||_p \le ||f||_r^\theta ||f||_s^{1-\theta}$$

if $\frac{1}{p} = \frac{\theta}{r} + \frac{1-\theta}{s}$ for $r < p < s$. Since $p\left(\frac{\theta}{r} + \frac{1-\theta}{s}\right) = 1$,

$$\frac{1}{\frac{r}{p\theta}} + \frac{1}{\frac{s}{p(1-\theta)}} = 1$$

and

$$\int_X |f|^p \, d\mu = \left(\int_X |f|^{p\theta} |f|^{p(1-\theta)}\right)^{\frac{1}{p}} \leq \left(\int_X |f|^r\right)^{\frac{\theta}{r}} \left(\int_X |f|^s\right)^{\frac{1-\theta}{s}} = ||f||_r^\theta ||f||_s^{1-\theta}$$

For $r < p < \infty$,

$$\left(\int_X |f|^p\right)^{\frac{1}{p}} = \left(\int_X |f|^r |f|^{p-r}\right)^{\frac{1}{p}} \leq ||f||_\infty^{1-\frac{r}{p}} \left(\left(\int_X |f|^r\right)^{\frac{1}{r}}\right)^{\frac{r}{p}} = ||f||_\infty^{\frac{r}{p}} ||f||_\infty^{1-\frac{r}{p}}$$

Homework 6 Problem 5

$$\int_X f \, d\mu = \sup\left\{\int_X s \, d\mu \; : \; 0 \leq s \leq f\right\}$$

so

$$\int_X f \, d\mu - \frac{1}{n} \leq \int_X s_n \, d\mu \leq \int_X f \, d\mu$$

Alternatively, $\forall f \geq 0$, $\exists s_n$ simple $0 \leq s_n \leq f$, $0 \leq s_n \leq s_{n+1}$. So

$$s_n = \sum \frac{k}{2^i} \chi_{A_{n,k}}$$

gives

$$\int_X s_n \, d\mu \rightarrow \int_X f \, d\mu$$

by monotone convergence theorem.

Homework 6 Problem 6

$$F(x) = \int_{-\infty}^x f(t) \, dt$$

was shown to be Vitali continuous, so

$$F(x) - F(y) = \left|\int_{(x,y)} f(t) \, dt\right| < \varepsilon$$

when $\mu((x,y)) = y - x < \delta$.

Homework 6 Problem 7

Given

$$\int_{\mathbb{R}} f_n \, dm \to \int_{\mathbb{R}} f \, dm$$

and $A \subset \mathbb{R}$, Fatou's Lemma gives

$$\int_A f \, dm \leq \liminf_{n \to +\infty} \int_A f_n \, dm$$

$$\int_{A^c} f \, dm \leq \liminf_{n \to +\infty} \left(\int_{\mathbb{R}} f_n \, dm - \int_A f_n \, dm \right)$$

Therefore

$$\int_{\mathbb{R}} f \, dm - \int_A f \, dm \leq \int_R f \, dm - \limsup_{n \to +\infty} \int_A f_n \, dm$$

Homework 6 Problem 8

Given

$$\int_{\mathbb{R}} g(x)(f(x+t) - f(x)) \, dx \to 0$$

with f, g integrable and $|g| \leq M$.
Part 1
If $f(x)$ is continuous with compact support, we would have
$\forall \varepsilon > 0, \exists \delta > 0$ such that $|f(x+t) - f(x)| < \frac{\varepsilon}{2kM}$, $\forall |f| < \delta$ where $\text{supp}(f)[-k, k]$.
Then, $\forall \varepsilon > 0, \exists \delta > 0$,

$$\left| \int_{\mathbb{R}} g(x)(f(x+t) - f(x)) \, dx \right| \leq \int_{\mathbb{R}} |g(x)||f(x+t) - f(x)| \, dx$$

$$\leq M \int_{-k}^{k} |f(x+t) - f(x)| \, dx$$

$$\leq M(2k)\frac{\varepsilon}{2kM}$$

$$= \varepsilon$$

when $|f| < \delta$.
Part 2
$||f - g||_{L^1} \leq \frac{\varepsilon}{2M}$, we have

$$\left| \int_{\mathbb{R}} g(x)(f(x+t) - f(x)) \, dx - \int_{\mathbb{R}} g(x)(f(x+t) - f(x)) \, dx \right| = \left| \int_{\mathbb{R}} g(x)\left((f(x+t) - f(x)) - (f(x) - g(x))\right) \, dx \right|$$

$$\leq M \int_{\mathbb{R}} (|f(x+t) - g(x+t)| + |f(x) - g(x)|)$$

$$\leq 2M||f - g||_{L^1(\mathbb{R})}$$

$$< \frac{\varepsilon}{2}$$

Part 3
We need $C_c(\mathbb{R}) \subset L^1(\mathbb{R})$ to be dense.
We may patch our functions with Urysohn's Lemma or, more explicitly,
Since $f_n = f\chi_{[-n,n]} \xrightarrow{n\to\infty} f$, $f_n \to f$ in L^1 by dominated convergence theorem. Then

$$\phi_n = \begin{cases} f & |f| \le n \\ n & f \ge n \\ -n & f \le -n \end{cases} \to f$$

Homework 7

1: Calculate.
2: Fatou's Lemma to $g \pm f_n$.
3: Part 3 of Homework 6 Problem 8.
5: Use monotone class and monotone convergence.
7: Do the rectangles.

Problem 4

Part 1
With Riemann integration, take

$$\int_a^b f(x)\sin(nx)\,dx = \int_a^b f(x)\frac{1}{n}d(-\cos(nx))$$

$$= \frac{1}{n}f(x)(-\cos(nx))|_a^b \overset{0}{+} \frac{1}{n}\int_a^b f'(x)\cos(nx)\,dx$$

and $\int_a^b |f'(x)|\,dx < +\infty$.
Part 2

$$\left| \int f(x)\sin(nx)\,dx - \int g(x)\sin(nx) \right| \le \int |f - g|\,dx$$

Part 3
Density. We need smooth

$$h(x) = \int g_n(x-y)f(x)\,dy$$

Problem 6

Write

$$\int_0^\infty \frac{\sin(x)}{x}\,dx = \int_0^\infty \int_0^\infty e^{-tx}\sin(x)\,dt\,dx = \int_0^\infty \int_0^\infty e^{-tx}\sin(x)\,dx\,dt$$

By integration by parts,

$$\int_0^\infty \left(\int_0^\infty e^{-tx}\sin(x)\,dx \right)dt = \int_0^\infty \frac{1}{1+t^2}\,dt$$