

Measure Theory

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Part I

Chapter 1

Measures

1.1 Measures

1.1 (σ -algebras). Let Ω be a set. A σ -algebra of sets on Ω is a collection $\mathcal{M} \subset \mathcal{P}(\Omega)$ which is closed under countable unions and complements.

- (a) generated by a set.
- (b) countable and cocountable sets
- (c) Borel

1.2 (Measures). A *measurable space* is a pair (Ω, \mathcal{M}) of a set Ω and a σ -algebra \mathcal{M} on Ω . Each element of \mathcal{M} is called *measurable*. We often omit \mathcal{M} to just write Ω for (Ω, \mathcal{M}) if there is no confusion.

Let (Ω, \mathcal{M}) be a measurable space. A *measure* on (Ω, \mathcal{M}) is a set function $\mu : \mathcal{M} \rightarrow [0, \infty] : \emptyset \mapsto 0$ that is *countably additive*: we have

$$\mu\left(\bigsqcup_{i=1}^{\infty} E_i\right) = \sum_{i=1}^{\infty} \mu(E_i)$$

for $(E_i)_{i=1}^{\infty} \subset \mathcal{M}$. Here the squared cup notation reads the disjoint union. A *measure space* is a triple $(\Omega, \mathcal{M}, \mu)$, where μ is a measure on (Ω, \mathcal{M}) . Let μ be a measure on Ω .

- (a) μ is monotone: for $E, F \in \mathcal{M}$ if $E \subset F$ then $\mu(E) \leq \mu(F)$.
- (b) μ is countably subadditive: for
- (c) μ is continuous from below:
- (d) μ is continuous from above:

1.3 (Complete measures). Let $(\Omega, \mathcal{M}, \mu)$ be a measure space. A *null set* is a measurable set N satisfying $\mu(N) = 0$, and a *full set* is a measurable set whose complement is a null set.

A *complete measure* is a measure such that every subset of a null set is measurable.

For a predicate P of points $x \in \Omega$, we say P is true *almost everywhere* or *a.e.* on Ω if there is a full set $F \subset \Omega$ such that $P(x)$ is true for all $x \in F$.

1.2 Carathéodory extension

1.4 (Outer measures). Let Ω be a set. An *outer measure* on Ω is a set function $\mu^* : \mathcal{P}(\Omega) \rightarrow [0, \infty] : \emptyset \mapsto 0$ such that

(i) μ^* is *monotone*: we have

$$S_1 \subset S_2 \Rightarrow \mu^*(S_1) \leq \mu^*(S_2)$$

for $S_1, S_2 \in \mathcal{P}(\Omega)$,

(ii) μ^* is *countably subadditive*: we have

$$\mu^*\left(\bigcup_{i=1}^{\infty} S_i\right) \leq \sum_{i=1}^{\infty} \mu^*(S_i)$$

for $(S_i)_{i=1}^{\infty} \subset \mathcal{P}(\Omega)$.

Comparing the definition of measures, we can see the outer measures extend the domain to the power set, but loosen the countable additivity to monotone countable subadditivity.

(a) A set function $\mu^* : \mathcal{P}(\Omega) \rightarrow [0, \infty] : \emptyset \mapsto 0$ is an outer measure if and only if μ^* is *monotonically countably subadditive*:

$$S \subset \bigcup_{i=1}^{\infty} S_i \Rightarrow \mu^*(S) \leq \sum_{i=1}^{\infty} \mu^*(S_i)$$

for $S \in \mathcal{P}(\Omega)$ and $(S_i)_{i=1}^{\infty} \subset \mathcal{P}(\Omega)$.

(b) For $\emptyset \in \mathcal{B} \subset \mathcal{P}(\Omega)$, let $\rho : \mathcal{B} \rightarrow [0, \infty] : \emptyset \mapsto 0$ be a set function. We can associate an outer measure $\mu^* : \mathcal{P}(\Omega) \rightarrow [0, \infty]$ by defining as

$$\mu^*(S) := \inf \left\{ \sum_{i=1}^{\infty} \rho(B_i) : S \subset \bigcup_{i=1}^{\infty} B_i, B_i \in \mathcal{B} \right\},$$

where we use the convention $\inf \emptyset = \infty$.

Proof.

□

1.5 (Carathéodory measurable sets). Let μ^* be an outer measure on a set Ω . We want to construct a measure by restriction of μ^* on a properly defined σ -algebra. A subset $E \subset \Omega$ is called *Carathéodory measurable* relative to μ^* if

$$\mu^*(S) = \mu^*(S \cap E) + \mu^*(S \setminus E)$$

for every $S \in \mathcal{P}(\Omega)$. Let \mathcal{M} be the collection of all Carathéodory measurable subsets relative to μ^* .

(a) \mathcal{M} is an algebra and μ^* is finitely additive on \mathcal{M} .

(b) \mathcal{M} is a σ -algebra and μ^* is countably additive on \mathcal{M} . That is, $\mu := \mu^*|_{\mathcal{M}}$ is a measure.

(c) The measure μ is complete.

Proof.

□

1.6 (Carathéodory extension theorem). The Carathéodory extension is a construction method for a measure extending a given set function ρ on $\mathcal{B} \subset \mathcal{P}(\Omega)$ for a set Ω . The idea is to restrict the outer measure μ^* associated to ρ in order to obtain a measure μ . We want to find a sufficient condition for μ to be a measure on a σ -algebra containing \mathcal{B} .

For $\emptyset \in \mathcal{B} \subset \mathcal{P}(\Omega)$, let $\rho : \mathcal{B} \rightarrow [0, \infty] : \emptyset \mapsto 0$ be a set function. Let $\mu^* : \mathcal{P}(\Omega) \rightarrow [0, \infty]$ be the associated outer measure of ρ , and $\mu : \mathcal{M} \rightarrow [0, \infty]$ the measure defined by the restriction of μ^* on Carathéodory measurable subsets.

(a) μ^* extends ρ if ρ satisfies the monotone countable subadditivity: for $B \in \mathcal{B}$ and $\{B_i\}_{i=1}^{\infty} \subset \mathcal{B}$, we have

$$B \subset \bigcup_{i=1}^{\infty} B_i \Rightarrow \rho(B) \leq \sum_{i=1}^{\infty} \rho(B_i).$$

- (b) μ extends ρ if ρ satisfies the following property in addition: for $B, A \in \mathcal{B}$ and any $\varepsilon > 0$, there are $\{C_j\}_{j=1}^\infty, \{D_j\}_{j=1}^\infty \subset \mathcal{B}$ such that

$$B \cap A \subset \bigcup_{j=1}^\infty C_j, \quad B \setminus A \subset \bigcup_{j=1}^\infty D_j, \quad \sum_{j=1}^\infty \rho(C_j) + \sum_{j=1}^\infty \rho(D_j) < \rho(B) + \varepsilon.$$

Proof. (a) Clearly $\mu^*(A) \leq \rho(A)$ for $A \in \mathcal{B}$. For the opposite direction, we may assume $\mu^*(A) < \infty$. For any $\varepsilon > 0$ we have $\{B_i\}_{i=1}^\infty$ such that $A \subset \bigcup_{i=1}^\infty B_i$ and

$$\rho(A) \leq \sum_{i=1}^\infty \rho(B_i) < \mu^*(A) + \varepsilon.$$

Limiting $\varepsilon \rightarrow 0$, we get $\rho(A) \leq \mu^*(A)$.

(b) Let $A \in \mathcal{B}$. It is enough to check the inequality $\mu^*(S \cap A) + \mu^*(S \setminus A) \leq \mu^*(S)$ for $S \in \mathcal{P}(\Omega)$ with $\mu^*(S) < \infty$. By the finiteness of $\mu^*(S)$, we may assume there is $\{B_i\}_{i=1}^\infty \subset \mathcal{B}$ such that $S \subset \bigcup_{i=1}^\infty B_i$. From the condition, we have $B_i \cap A \subset \bigcup_{j=1}^\infty C_{i,j}$ and $B_i \setminus A \subset \bigcup_{j=1}^\infty D_{i,j}$ satisfying

$$\begin{aligned} \mu^*(S \cap A) + \mu^*(S \setminus A) &\leq \mu^*\left(\bigcup_{j=1}^\infty (B_i \cap A)\right) + \mu^*\left(\bigcup_{j=1}^\infty (B_i \setminus A)\right) \\ &\leq \sum_{i,j=1}^\infty \rho(C_{i,j}) + \sum_{i,j=1}^\infty \rho(D_{i,j}) \\ &\leq \sum_{i=1}^\infty (\rho(B_i) + 2^{-i} \varepsilon) \\ &< \mu^*(S) + \varepsilon. \end{aligned}$$

Therefore, A is Carathéodory measurable relative to μ^* , so the domain of μ contains the domain of ρ . The values coincide by the part (a). \square

1.7 (Uniqueness of extension of measures). The Carathéodory extension also provides a uniqueness result for measure extensions. Let $\rho : \mathcal{B} \rightarrow [0, \infty] : \emptyset \mapsto 0$ be a set function, where $\emptyset \in \mathcal{B} \subset \mathcal{P}(\Omega)$ for a set Ω . We say ρ is σ -finite if there is a cover $\{B_i\}_{i=1}^\infty \subset \mathcal{B}$ of Ω such that $\rho(B_i) < \infty$ for each i .

Let \mathcal{M} be a σ -algebra containing \mathcal{B} . Let μ be a measure on \mathcal{M} , which extends ρ , given by the restriction of the outer measure μ^* associated to ρ . Let ν be another measure on \mathcal{M} which extends ρ . Let $E \in \mathcal{M}$ and $\{E_i\}_{i=1}^\infty \subset \mathcal{M}$.

- (a) $\nu(E) \leq \mu(E)$.
- (b) $\nu(E_i) = \mu(E_i)$ implies $\nu\left(\bigcup_{i=1}^\infty E_i\right) = \mu\left(\bigcup_{i=1}^\infty E_i\right)$.
- (c) $\nu(E) = \mu(E)$ for $\mu(E) < \infty$.
- (d) $\nu(E) = \mu(E)$ for $\mu(E) = \infty$, if ρ is σ -finite

Proof. (a) We may assume $\mu(E) < \infty$. By the definition of the outer measure, there is $\{B_i\}_{i=1}^\infty \subset \mathcal{B}$ such that $E \subset \bigcup_{i=1}^\infty B_i$. Also, whenever $E \subset \bigcup_{i=1}^\infty B_i$ we have

$$\nu(E) \leq \nu\left(\bigcup_{i=1}^\infty B_i\right) \leq \sum_{i=1}^\infty \nu(B_i) = \sum_{i=1}^\infty \rho(B_i) = \sum_{i=1}^\infty \mu(B_i),$$

hence $\nu(E) \leq \mu(E)$.

(b) In the light of the inclusion-exclusion principle, we have

$$\mu(E_i \cup E_j) = \mu(E_i) + \mu(E_j) - \mu(E_i \cap E_j) \leq \nu(E_i) + \nu(E_j) - \nu(E_i \cap E_j) = \nu(E_i \cup E_j),$$

so that $\mu(E_i \cup E_j) = \nu(E_i \cap E_j)$. Applying it inductively, we have for every n that

$$\mu\left(\bigcup_{i=1}^n B_i\right) = \nu\left(\bigcup_{i=1}^n B_i\right),$$

and by limiting $n \rightarrow \infty$ the continuity from below gives

$$\mu\left(\bigcup_{i=1}^{\infty} B_i\right) = \nu\left(\bigcup_{i=1}^{\infty} B_i\right).$$

(c) Because $\mu(E) < \infty$, for any $\varepsilon > 0$ we have a sequence $(B_i)_{i=1}^{\infty} \subset \mathcal{B}$ such that $E \subset \bigcup_{i=1}^{\infty} B_i$ and

$$\sum_{i=1}^{\infty} \rho(B_i) < \mu(E) + \varepsilon.$$

Applying the part (b) Then, we have

$$\mu(E) \leq \mu\left(\bigcup_{i=1}^{\infty} B_i\right) = \nu\left(\bigcup_{i=1}^{\infty} B_i\right) = \nu\left(\bigcup_{i=1}^{\infty} B_i \setminus E\right) + \nu(E)$$

and

$$\nu\left(\bigcup_{i=1}^{\infty} B_i \setminus E\right) \leq \mu\left(\bigcup_{i=1}^{\infty} B_i \setminus E\right) = \mu\left(\bigcup_{i=1}^{\infty} B_i\right) - \mu(E) \leq \sum_{i=1}^{\infty} \mu(B_i) - \mu(E) = \sum_{i=1}^{\infty} \rho(B_i) - \mu(E) < \varepsilon,$$

we get $\mu(E) < \nu(E) + \varepsilon$ and $\mu(E) \leq \nu(E)$ by limiting $\varepsilon \rightarrow 0$.

(d) Let $\{B_i\}_{i=1}^{\infty} \subset \mathcal{B}$ be a cover of Ω such that $\rho(B_i) < \infty$. Define $E_1 := B_1$ and $E_n := B_n \setminus \bigcup_{i=1}^{n-1} B_i$ for $n \geq 2$ so that $\{E_i\}_{i=1}^{\infty}$ is a pairwise disjoint cover of Ω with

$$\mu(E \cap E_i) \leq \mu(E_i) \leq \mu(B_i) = \rho(B_i) < \infty$$

for each i , so we have by the part (c) that

$$\nu(E) = \sum_{i=1}^{\infty} \nu(E \cap E_i) = \sum_{i=1}^{\infty} \mu(E \cap E_i) = \mu(E).$$

□

1.3 Measures on the real line

1.8 (Borel σ -algebra).

1.9 (Distribution functions).

1.10 (Helly selection theorem).

1.11 (Vitali set).

Exercises

1.12 (Boolean algebras and rings).

1.13 (Cardinalities). infinite σ -algebra is $\geq \mathfrak{c}$.

1.14 (Semi-rings and semi-algebras). We will prove a simplified Carathéodory extension with respect to *semi-rings* and *semi-algebras*. Let $\mathcal{A} \subset \mathcal{P}(\Omega)$ such that $\emptyset \in \mathcal{A}$. We say that \mathcal{A} is a semi-ring if it is closed under finite intersections, and each relative complement is a finite union of elements of \mathcal{A} . We say that \mathcal{A} is a semi-algebra

Let \mathcal{A} be a semi-ring of sets over Ω . Suppose a set function $\rho : \mathcal{A} \rightarrow [0, \infty] : \emptyset \mapsto 0$ satisfies

(i) ρ is *disjointly countably subadditive*: we have

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

for $(A_i)_{i=1}^{\infty} \subset \mathcal{A}$,

(ii) ρ is *finitely additive*: we have

$$\rho(A_1 \sqcup A_2) = \rho(A_1) + \rho(A_2)$$

for $A_1, A_2 \in \mathcal{A}$.

A set function satisfying the above conditions are occasionally called a *pre-measure*.

(a)

(b)

1.15 (Monotone class lemma). A collection $\mathcal{C} \subset \mathcal{P}(\Omega)$ is called a *monotone class* if it is closed under countable increasing unions and countable decreasing intersections.

Let H be a vector space closed under bounded monotone convergence. If $\text{span}\{\mathbf{1}_A : A \in \mathcal{A}\} \subset H$ then $B^\infty(\sigma(\mathcal{A})) \subset H$.

1.16 (Steinhaus theorem). Let λ denote the Lebesgue measure on \mathbb{R} and let $E \subset \mathbb{R}$ be a Lebesgue measurable set with $\lambda(E) > 0$.

(a) For any $0 < \alpha < 1$, there is an interval $I = (a, b)$ such that $\lambda(E \cap I) > \alpha\lambda(I)$.

(b) $E - E = \{x - y : x, y \in E\}$ contains an open interval containing zero.

Proof. (a) We may assume $\lambda(E) < \infty$. Since λ is outer measure and $\lambda(E) \neq 0$, we have an open subset U of \mathbb{R} such that $\lambda(U) < \alpha^{-1}\lambda(E)$. Because U is a countable disjoint union of open intervals $U = \bigsqcup_{i=1}^{\infty} (a_i, b_i)$, we have

$$\sum_{i=1}^{\infty} \lambda((a_i, b_i)) = \lambda(U) < \alpha^{-1}\lambda(E) = \alpha^{-1} \sum_{i=1}^{\infty} \lambda(E \cap (a_i, b_i)).$$

Therefore, there is i such that $\alpha\lambda((a_i, b_i)) < \lambda(E \cap (a_i, b_i))$. □

Problems

- *1. Every Lebesgue measurable set in \mathbb{R} of positive measure contains an arbitrarily long arithmetic progression.

Chapter 2

Measurable functions

2.1 Simple functions

2.1 (Measurability of pointwise limits). Conversely, every measurable extended real-valued function is a pointwise limit of simple functions.

Proof. Let $f(x) = \lim_{n \rightarrow \infty} s_n(x)$.

□

2.2 Almost everywhere convergence

2.2 (Almost everywhere convergence). Let (Ω, μ) be a measure space and let $f_n : \Omega \rightarrow \overline{\mathbb{R}}$ and $f : \Omega \rightarrow \overline{\mathbb{R}}$ be measurable functions. The set of convergence of the sequence f_n is defined as the set

$$\{x \in \Omega : \lim_{n \rightarrow \infty} f_n(x) = f(x)\},$$

and the set of divergence is defined as its complement. We say f_n converges to f *almost everywhere* with respect to μ if the set of divergence is a null set in μ . We simply write

$$f_n \rightarrow f \text{ a.e.}$$

if f_n converges to f almost everywhere, and we frequently omit the measure μ if it has no confusion.

(a) If μ is complete and, if $f_n \rightarrow f$ a.e., then f is measurable.

2.3 (Borel-Cantelli lemma). Let (Ω, μ) be a measure space and let $f_n : \Omega \rightarrow \overline{\mathbb{R}}$ and $f : \Omega \rightarrow \overline{\mathbb{R}}$ be a sequence of measurable functions. Note that the set of divergence is given by

$$\bigcup_{\varepsilon > 0} \bigcap_{n=1}^{\infty} \bigcup_{i=n}^{\infty} \{x : |f_n(x) - f(x)| \geq \varepsilon\}.$$

Each measurable set of the form

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

is sometimes called the *tail event*, coined in probability theory.

(a) $f_n \rightarrow f$ a.e. if and only if for each $\varepsilon > 0$ we have

$$\mu(\{x : \limsup_{n \rightarrow \infty} |f_n(x) - f(x)| \geq \varepsilon\}) = 0.$$

(b) $f_n \rightarrow f$ a.e. if and only if for each $\varepsilon > 0$ we have

$$\mu(\limsup_{n \rightarrow \infty} \{x : |f_n(x) - f(x)| \geq \varepsilon\}) = 0.$$

(c) $f_n \rightarrow f$ a.e. if for each $\varepsilon > 0$ we have

$$\sum_{n=1}^{\infty} \mu(\{x : |f_n(x) - f(x)| \geq \varepsilon\}) < \infty.$$

Proof. (b) The set of divergence of the sequence f_n is given by

$$\bigcup_{m=1}^{\infty} \bigcap_{n=1}^{\infty} \bigcup_{i=n}^{\infty} \{x : |f_i(x) - f(x)| \geq \frac{1}{m}\} = \bigcup_{m=1}^{\infty} \bigcap_{n=1}^{\infty} (\Omega \setminus E_n^m).$$

(c) Since

$$\mu\left(\bigcup_{i=1}^{\infty} \{x : |f_i(x) - f(x)| \geq \varepsilon\}\right) \leq \sum_{i=1}^{\infty} \mu(\{x : |f_i(x) - f(x)| \geq \varepsilon\}) < \infty,$$

we have by the continuity from above that

$$\begin{aligned} \mu(\limsup_{n \rightarrow \infty} \{x : |f_n(x) - f(x)| \geq \varepsilon\}) &= \mu\left(\bigcap_{n=1}^{\infty} \bigcup_{i=n}^{\infty} \{x : |f_i(x) - f(x)| \geq \varepsilon\}\right) \\ &= \lim_{n \rightarrow \infty} \mu\left(\bigcup_{i=n}^{\infty} \{x : |f_i(x) - f(x)| \geq \varepsilon\}\right) \\ &\leq \lim_{n \rightarrow \infty} \sum_{i=n}^{\infty} \mu(\{x : |f_i(x) - f(x)| \geq \varepsilon\}) = 0. \end{aligned} \quad \square$$

2.4 (Convergence in measure). Let (Ω, μ) be a measure space and let $f_n : \Omega \rightarrow \overline{\mathbb{R}}$ be a sequence of measurable functions. We say f_n converges to a measurable function $f : \Omega \rightarrow \overline{\mathbb{R}}$ in measure if for each $\varepsilon > 0$ we have

$$\lim_{n \rightarrow \infty} \mu(\{x : |f_n(x) - f(x)| \geq \varepsilon\}) = 0.$$

(a) If $f_n \rightarrow f$ in measure, then there is a subsequence f_{n_k} such that $f_{n_k} \rightarrow f$ a.e.

(b) If every subsequence f_{n_k} of f_n has a further subsequence $f_{n_{k_j}}$ such that $f_{n_{k_j}} \rightarrow f$ a.e., then $f_n \rightarrow f$ in measure.

Proof. (a) Since for each positive integer k we have $\mu(\{x : |f_n(x) - f(x)| \geq \frac{1}{k}\}) \rightarrow 0$ as $n \rightarrow \infty$, there exists n_k such that

$$\mu(\{x : |f_{n_k}(x) - f(x)| \geq \frac{1}{k}\}) < \frac{1}{2^k}.$$

By the Borel-Cantelli lemma, we get

$$\mu(\limsup_{k \rightarrow \infty} \{x : |f_{n_k}(x) - f(x)| \geq \frac{1}{k}\}) = 0.$$

Then, for each $\varepsilon > 0$,

$$\begin{aligned} \limsup_{k \rightarrow \infty} \{x : |f_{n_k}(x) - f(x)| \geq \varepsilon\} &= \bigcap_{k=\lceil \varepsilon^{-1} \rceil}^{\infty} \bigcup_{j=k}^{\infty} \{x : |f_{n_j}(x) - f(x)| \geq \varepsilon\} \\ &\subset \bigcap_{k=\lceil \varepsilon^{-1} \rceil}^{\infty} \bigcup_{j=k}^{\infty} \{x : |f_{n_j}(x) - f(x)| \geq \frac{1}{k}\} \\ &= \limsup_{k \rightarrow \infty} \{x : |f_{n_k}(x) - f(x)| \geq \frac{1}{k}\} \end{aligned}$$

implies the limit superior of the tail events is a null set, hence $f_{n_k} \rightarrow f$ a.e.

(b) □

2.5 (Egorov theorem). Egorov's theorem informally states that an almost everywhere convergent functional sequence is “almost” uniformly convergent. Through this famous theorem, we introduce a convenient “ $\varepsilon/2^m$ ” argument”, occasionally used throughout measure theory to construct a measurable set having a special property.

Let (Ω, μ) be a finite measure space and let $f_n : \Omega \rightarrow \overline{\mathbb{R}}$ be a sequence of measurable functions such that $f_n \rightarrow f$ a.e. For each positive integer m , which indexes the tolerance $1/m$, consider an increasing sequence of measurable subsets

$$E_n^m := \bigcap_{i=n}^{\infty} \{x : |f_i(x) - f(x)| < \frac{1}{m}\}.$$

- (a) E_n^m converges to a full set for each m .
- (b) For every $\varepsilon > 0$ there is a measurable $K \subset \Omega$ such that $\mu(\Omega \setminus K) < \varepsilon$ and for each m there is finite n satisfying $K \subset E_n^m$.
- (c) For every $\varepsilon > 0$ there is a measurable $K \subset \Omega$ such that $\mu(\Omega \setminus K) < \varepsilon$ and $f_n \rightarrow f$ uniformly on K .

Proof. (a) Recall that the a.e. convergence $f_n \rightarrow f$ means that for every fixed m the intersection

$$\bigcap_{n=1}^{\infty} (\Omega \setminus E_n^m) = \limsup_n \{x : |f_n(x) - f(x)| \geq \frac{1}{m}\}$$

is a null set. Since $\mu(\Omega) < \infty$, it is equivalent to E_n^m converges to a full set for each m by the continuity from above.

(b) For each m , we can find n_m such that

$$\mu(\Omega \setminus E_{n_m}^m) < \frac{\varepsilon}{2^m}.$$

If we define

$$K := \bigcap_{m=1}^{\infty} E_{n_m}^m,$$

then it satisfies the second conclusion, and also have

$$\mu(\Omega \setminus K) = \mu\left(\bigcup_{m=1}^{\infty} (\Omega \setminus E_{n_m}^m)\right) \leq \sum_{m=1}^{\infty} \mu(\Omega \setminus E_{n_m}^m) < \sum_{m=1}^{\infty} \frac{\varepsilon}{2^m} = \varepsilon.$$

(c) Fix $m > 0$. Since $n \geq n_m$ implies $K \subset E_{n_m}^m \subset E_n^m$, we have

$$n \geq n_m \Rightarrow \sup_{x \in K} |f_n(x) - f(x)| < \frac{1}{m}. \quad \square$$

Exercises

2.6 (Cauchy's functional equation). Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be a function. Cauchy's functional equation refers to the equation $f(x + y) = f(x) + f(y)$, satisfied for all $x, y \in \mathbb{R}$. Suppose f satisfies the Cauchy functional equation. We ask if f is linear, that is $f(x) = ax$ for all $x \in \mathbb{R}$, where $a := f(1)$.

- (a) $f(x) = ax$ for all $x \in \mathbb{Q}$, but there is a nonlinear solution of Cauchy's functional equation.
- (b) If f is continuous at a point, then f is linear.
- (c) If f is Lebesgue measurable, then f is linear.

2.7 (Pointwise approximation by simple functions). Let (Ω, μ) be a measure space and X a metric space with Borel measurable structure. By a *simple function* we mean a measurable function $s : \Omega \rightarrow X$ of finite image.

- (a) For each open set $U \subset X$ there is a sequence of open sets U_i such that $U = \bigcup_i U_i$ and $\overline{U_i} \subset U$. Let $f : \Omega \rightarrow X$ be any function.
- (b) If f is the pointwise limit of a sequence of measurable functions, then f is measurable.
- (c) If f is measurable, then f is the pointwise limit of a sequence of simple functions, if X is separable.
- *(d) The pointwise limit of a net of simple functions may not be measurable.

Proof. (b) Suppose a sequence $(f_n)_n$ of measurable functions converges pointwisely to a function f . For fixed open $U \subset X$ we claim

$$f^{-1}(U) = \bigcup_{i=1}^{\infty} \liminf_{n \rightarrow \infty} f_n^{-1}(U_i).$$

If it is true, then $f^{-1}(U)$ is the countable set operation of measurable sets $f_n^{-1}(U_i)$. Let U_i be the sequence associated to U taken by the part (a).

(\subset) If $\omega \in f^{-1}(U)$, then for some i we have $f(\omega) \in U_i$, so $f_n(\omega)$ is eventually in U_i , thus we have $\omega \in \liminf_{n \rightarrow \infty} f_n^{-1}(U_i)$.

(\supset) If $\omega \in \liminf_{n \rightarrow \infty} f_n^{-1}(U_i)$ for some i , then $f_n(\omega)$ is eventually in U_i , so $f(\omega) \in \overline{U_i} \subset U$, thus we have $\omega \in f^{-1}(U)$.

(c) Suppose there is a increasing sequence of finite tagged partitions $\mathcal{P}_n \subset \mathcal{B}$ satisfying the following property: for each open-neighborhood pair (x, U) there is n and i such that $P_{n,i} \in \mathcal{P}_n$ and $x \in P_{n,i} \subset U$. We denote the tags by $t_{n,i} \in P_{n,i}$ for each $P_{n,i} \in \mathcal{P}_n$. Define

$$s_n(\omega) := t_{n,i} \quad \text{for } f(\omega) \in P_{n,i}.$$

To show $s_n(\omega) \rightarrow f(\omega)$, fix an open $f(\omega) \in U \subset X$. Then, there is n_0 such that there is a sequence $(P_{n,i_n})_{n=n_0}^{\infty}$ satisfying $P_{n,i_n} \in \mathcal{P}_n$ and $f(\omega) \in P_{n,i_n} \subset U$. Then, for all $n \geq n_0$, we have for $f(\omega) \in P_{n,i_n}$ that $s_n(\omega) = t_{n,i_n} \in P_{n,i_n} \subset U$.

The existence of such sequence of partitions...

Another approach: mimicking Pettis measurability theorem. □

Chapter 3

Lebesgue integral

3.1 Monotone convergence theorem

3.1 (Lebesgue integral of non-negative functions). Let (Ω, μ) be a measure space. Let $f : \Omega \rightarrow \mathbb{R}_{\geq 0}$ be a measurable function. The *Lebesgue integral* of f is defined by

$$\int f \, d\mu := \sup \left\{ \int s \, d\mu : 0 \leq s \leq f, s \text{ simple} \right\}$$

3.2 (Monotone convergence theorem). Let (Ω, μ) be a measure space. Let f_n and f be measurable functions $\Omega \rightarrow \mathbb{R}_{\geq 0}$.

- (a) $E \mapsto \int_E f \, d\mu$ is a measure if f is simple.
- (b) $E \mapsto \int_E f \, d\mu$ is a measure even if f is not simple.
- (c) If $f_n \uparrow f$ a.e., then $\int f_n \rightarrow \int f$.

Proof. (a) Clear from the linearity of the integral for simple functions.

(b) For $E_n \uparrow E$, we want to show the continuity from below, $\int_{E_n} f \rightarrow \int_E f$. Take $\varepsilon > 0$. We introduce a continuous bijection $\beta : [0, \infty] \rightarrow [0, 1] : t \mapsto t/(1+t)$ to avoid dividing the cases for infinity. By the definition of the Lebesgue integral, we have a simple function s such that $0 \leq s \leq f$ and

$$\beta\left(\int_E f\right) - \beta\left(\int_E s\right) < \varepsilon,$$

whether or not $\int_E f$ diverges. Then,

$$\begin{aligned} \beta\left(\int_E f\right) - \beta\left(\int_{E_n} f\right) &= [\beta\left(\int_E f\right) - \beta\left(\int_E s\right)] + [\beta\left(\int_E s\right) - \beta\left(\int_{E_n} s\right)] + [\beta\left(\int_{E_n} s\right) - \beta\left(\int_{E_n} f\right)] \\ &< \varepsilon + [\beta\left(\int_E s\right) - \beta\left(\int_{E_n} s\right)] + 0 \\ &\xrightarrow{n \rightarrow \infty} \varepsilon \end{aligned}$$

by the part (a). We are done by letting $\varepsilon \rightarrow 0$.

(c) Define $E_n := \{x : f(x) < (1+\varepsilon)f_n(x)\}$, which converges to a full set because $f_n \rightarrow f$ a.e. Since f is a measure, we can choose N such that

$$\beta\left(\int_E f\right) - \beta\left(\int_{E_N} f\right) < \varepsilon.$$

With this N , we have

$$\beta\left(\int_{E_N} f\right) - \beta\left(\int_{E_N} f_n\right) \leq \frac{\int_{E_N} f - \int_{E_N} f_n}{(1 + \int_{E_N} f)(1 + \int_{E_N} f_n)} < \varepsilon, \quad n \geq N.$$

Then, we have for $n \geq N$ that

$$\begin{aligned}\beta(\int_E f) - \beta(\int_E f_n) &= [\beta(\int_E f) - \beta(\int_{E_N} f)] + [\beta(\int_{E_N} f) - \beta(\int_{E_N} f_n)] + [\beta(\int_{E_N} f_n) - \beta(\int_E f_n)] \\ &< 0 + \varepsilon + \varepsilon,\end{aligned}$$

so we are done by letting $n \rightarrow \infty$ and $\varepsilon \rightarrow 0$. □

3.3 (Corollaries of monotone convergence theorem). Fatou's lemma, linearity of the integral, $f \geq 0$ and $\int f = 0$ imply $f = 0$ a.e.

3.2 Dominated convergence theorem

3.4 (Lebesgue integral of complex-valued functions).

3.5 (Bounded convergence theorem). Semifinite measures

(a)

$$\sup_{g \leq f} \int g \, d\mu = \int f \, d\mu$$

where g runs through bounded measurable functions.

(b)

3.3 Product measures

3.6 (Fubini-Tonelli theorem). Lebesgue measure on Euclidean spaces

Exercises

3.7 (Convergence of one-parameter family).

Part II

Chapter 4

Signed measures

4.1 Radon-Nikodym theorem

An integrable function as a measure σ -finite measures

Chapter 5

Borel measures

5.1 Continuous functions on metric spaces

Urysohn and Tietze.

5.1 (Regular Borel measures on metric spaces). Let μ be a Borel measure on a metric space Ω . We say μ is *outer regular* if

$$\mu(E) = \inf\{\mu(U) : E \subset U, U \text{ open}\},$$

and say μ is *inner regular* if

$$\mu(E) = \sup\{\mu(F) : F \subset E, F \text{ closed}\},$$

for every Borel subset $E \subset \Omega$. If μ is both outer and inner regular, we say μ is *regular*.

- (a) Let E be σ -finite. Then, E is μ -regular if and only if for any $\varepsilon > 0$ there are open U and closed F such that $F \subset E \subset U$ and $\mu(U \setminus F) < \varepsilon$.
- (b) If μ is σ -finite, then the set of μ -regular subsets is a σ -algebra. (may be extended?)
- (c) Every closed set is G_δ .
- (d) Every finite Borel measure on Ω is regular.

Proof.

□

5.2 (Luzin's theorem). Let μ be a regular Borel measure on a metric space Ω . Let $f : \Omega \rightarrow \mathbb{R}$ be a Borel measurable function. Two proofs: direct and Egoroff.

- (a) If $E \subset \Omega$ is σ -finite, then there is a continuous g blabla
- (b) If f vanishes outside a σ -finite set, then for any $\varepsilon > 0$ there is a closed set $F \subset \Omega$ such that $f|_F : F \rightarrow \mathbb{R}$ is continuous and $\mu(\Omega \setminus F) < \varepsilon$.
- (c) If f vanishes outside a σ -finite set, then for any $\varepsilon > 0$ there is a closed set $F \subset \Omega$ and continuous $g : \Omega \rightarrow \mathbb{R}$ such that $f|_F = g|_F$ and $\mu(\Omega \setminus F) < \varepsilon$.
- (d) If f is further bounded, then g also can be taken to be bounded.

Proof. (a) Let $\varepsilon > 0$ and suppose $E \subset \Omega$ is measurable with $\mu(E) < \infty$. Since E is σ -finite, we have open U and closed F such that $F \subset E \subset U$ and $\mu(U \setminus F) < \varepsilon/2$. By the Urysohn lemma, there is a continuous function $g : \Omega \rightarrow [0, 1]$ such that $g|_{U^c} = 0$ and $g|_F = 1$. Then,

$$\int |\mathbf{1}_E - g| d\mu = \int_{U \setminus F} |\mathbf{1}_E - g| d\mu \leq 2\mu(U \setminus F) < \varepsilon.$$

(b) Since \mathbb{R} is second countable, we have a base $(V_n)_{n=1}^\infty$ of \mathbb{R} . Since μ is σ -finite, for each n we can take open U_n and closed F_n such that

$$F_n \subset f^{-1}(V_n) \subset U_n$$

and $\mu(U_n \setminus F_n) < \varepsilon/2^n$. Define $F := (\bigcup_{n=1}^\infty (U_n \setminus F_n))^c$ so that $\mu(\Omega \setminus F) < \varepsilon$ and F is closed. Then,

$$\begin{aligned} U_n \cap F &= U_n \cap ((U_n^c \cup F_n) \cap F) \\ &= (U_n \cap (U_n^c \cup F_n)) \cap F \\ &= (\emptyset \cup (U_n \cap F_n)) \cap F \\ &\subset F_n \cap F \end{aligned}$$

proves $f^{-1}(V_n)$ is open in F for every n , hence the continuity of $f|_F$. (In fact, we require that X to be just a topological space.)

(b') We can alternatively use the part (a) and the Egoroff theorem. By the part (a), we can construct a sequence (f_n) of continuous functions $X \rightarrow \mathbb{R}$ such that $f_n \rightarrow f$ in L^1 . By taking a subsequence, we may assume $f_n \rightarrow f$ pointwise. Assuming μ is finite, by the Egorov theorem, there is a measurable $A \subset X$ such that $f_n \rightarrow f$ uniformly on A and $\mu(X \setminus A) < \varepsilon/2$. Since μ is inner regular, we have closed $F \subset A$ such that $\mu(A \setminus F) < \varepsilon/2$, so that we have $\mu(X \setminus F) < \varepsilon$. Then, f is continuous on A , and of course on F .

□

5.2 Locally compact spaces

compact closed set not containing infy

open open not containing infy

closed closed set containing infy

for a measure that “vanishes at infy” = tight
two definitions of inner regularity is equivalent.

inner regular on compact sets \rightarrow inner regular on closed sets
inner regular on compact sets + sigma finite \rightarrow tight

5.3 (One-point compactification).

5.4 (Regular Borel measures on locally compact metric spaces). sss

(a) $C_c(\Omega)$ is dense in $L^p(\mu)$ for $1 \leq p < \infty$.

(b) If μ is σ -finite, then for any $\varepsilon > 0$ there is compact $K \subset \Omega$ and continuous $g : \Omega \rightarrow \mathbb{R}$ such that $f|_K = g|_K$ and $\mu(\Omega \setminus K) < \varepsilon$.

5.5 (Tightness and inner regularity). We have a similar but confusing concept called tightness; we say a Borel measure μ on a topological space X is *tight* if for any $\varepsilon > 0$ there is a compact $K \subset X$ such that $\mu(X \setminus K) < \varepsilon$.

History of Bourbaki's text.

(a)

5.3 Riesz-Markov-Kakutani representation theorem

5.6 (Riesz-Markov-Kakutani representation theorem for C_0). Let Ω be a locally compact metric space. We want to establish the following one-to-one correspondence:

$$\begin{array}{ccc} \{\text{finite Borel measures on } \Omega\} & \xrightarrow{\sim} & \{\text{positive linear functionals on } C_0(\Omega)\} \\ \mu & \mapsto & (f \mapsto \int f d\mu). \end{array}$$

Let I a positive linear functional on $C_0(\Omega)$. Let \mathcal{T} be the set of all open subsets of Ω and $\rho : \mathcal{T} \rightarrow [0, \infty]$ a set function such that

$$\rho(U) := \sup \{I(f) : f \in C_c(U, [0, 1])\}$$

for open U . Let $\mu^* : \mathcal{P}(X) \rightarrow [0, \infty]$ be the associated outer measure defined from ρ , and $\mu := \mu^*|_{\mathcal{M}}$ the Carathéodory measure, where \mathcal{M} is the σ -algebra of Carathéodory measurable subsets relative to μ^* , and \mathcal{B} is the Borel σ -algebra of Ω .

- (a) $\mu^*|_{\mathcal{T}} = \rho$.
- (b) $\mathcal{B} \subset \mathcal{M}$.
- (c) $I(f) = \int f d\mu$ for $f \in C(\Omega)$, i.e. the map given above is surjective.
- (d) The map given above is injective.

Proof. (a) It suffices to show that ρ satisfies monotonically countably subadditive. Take an open set U and a countable open cover $\{U_i\}_{i=1}^{\infty}$ of U . Take any $f \in C_c(U, [0, 1])$ and let $K := \text{supp } f$. Since K is compact, there is a finite subcover $\{U_j\}_{j=1}^n$ of K , and since K is paracompact Hausdorff, there is a partition of unity $\{\chi_j\}_j$ on K subordinate to the open cover $\{U_j \cap K\}_j$. Note that $\text{supp } \chi_j \subset U_j \cap K$ for each j .

The set $\text{supp}(f \chi_j)$ is closed in K so the compactness, and we also have the inclusion $\text{supp}(f \chi_j) \subset \text{supp } \chi_j \subset U_j$. For every $0 < a \leq 1$, since $(f \chi_j)^{-1}((a, 1])$ is open in the interior of K and $(f \chi_j)^{-1}([a, 1])$ is closed in K , $f \chi_j$ is continuous on U_j . Now we have checked $f \chi_j \in C_c(U_j, [0, 1])$.

Then, because I is linear so that it preserves finite sum, we have

$$I(f) = I\left(\sum_{j=1}^n f \chi_j\right) = \sum_{j=1}^n I(f \chi_j) \leq \sum_{j=1}^n \rho(U_j) \leq \sum_{i=1}^{\infty} \rho(U_i).$$

Since f is arbitrary, we get $\rho(U) \leq \sum_{i=1}^{\infty} \rho(U_i)$.

(b) It suffices to show $\mathcal{T} \subset \mathcal{M}$. Clearly $\mu^*(E) \leq \mu^*(E \cap U) + \mu^*(E \setminus U)$ for any measurable E and open U . For the opposite direction, take $\varepsilon > 0$. Note that we may assume $\mu^*(E) < \infty$. There are open U_i such that $E \subset \bigcup_{i=1}^{\infty} U_i$ and

$$\mu^*(E) + \frac{\varepsilon}{3} > \sum_{i=1}^{\infty} \rho(U_i).$$

Take $f_i \in C_c(U_i \cap U, [0, 1])$ such that

$$\rho(U_i \cap U) - \frac{1}{3} \cdot \frac{\varepsilon}{2^i} < I(f_i),$$

and take $g_i \in C_c(U_i \setminus \text{supp } f_i, [0, 1])$ such that

$$\rho(U_i \setminus \text{supp } f_i) - \frac{1}{3} \cdot \frac{\varepsilon}{2^i} < I(g_i).$$

Then, since $f_i + g_i \in C_c(U_i, [0, 1])$, we have

$$\begin{aligned} \rho(U_i) &\geq I(f_i + g_i) > \rho(U_i \cap U) + \rho(U_i \setminus \text{supp } f_i) - \frac{2}{3} \cdot \frac{\varepsilon}{2^i} \\ &\geq \rho(U_i \cap U) + \rho(U_i \setminus U) - \frac{2}{3} \cdot \frac{\varepsilon}{2^i}. \end{aligned}$$

It implies

$$\mu^*(E) + \varepsilon > \sum_{i=1}^{\infty} \rho(U_i \cap U) + \sum_{i=1}^{\infty} \rho(U_i \setminus U) \geq \mu^*(E \cap U) + \mu^*(E \setminus U)$$

because $E \cap U \subset \bigcup_{i=1}^{\infty} U_i \cap U$ and $E \setminus U \subset \bigcup_{i=1}^{\infty} U_i \setminus U$.

(c) Note that we have

$$\rho(U) = \sup_{f \in C_c(U, [0, 1])} I(f), \quad \mu(E) = \inf_{\substack{E \subset U \\ U \text{ open}}} \rho(U).$$

We first claim that for $g \in C_c(\Omega, [0, 1])$, if K and K' are compact sets such that $g|_K = 1$ and $g|_{K'^c} = 0$ respectively, then we have

$$\mu(K) \leq I(g) \leq \mu(K').$$

The one inequality directly follows from

$$I(g) \leq \inf_{K' \subset U} \rho(U) = \mu(K').$$

For the other, take sufficiently small $\varepsilon > 0$ such that $U := g^{-1}((1 - \varepsilon, 1])$ satisfies $K \subset U \subset \text{supp } g$. For any $h \in C_c(U, [0, 1])$, the inequality $(1 - \varepsilon)h \leq g$ implies $I(h) \leq (1 - \varepsilon)^{-1}I(g)$, so

$$\mu(K) \leq \rho(U) \leq I(h) \leq (1 - \varepsilon)^{-1}I(g).$$

By limiting $\varepsilon \rightarrow 0$, we get $\mu(K) \leq I(g)$, the claim proved.

Since $C_c(\Omega)$ is the linear span of $C_c(\Omega, [0, 1])$, it is enough to show $I(f) = \int f d\mu$ for $f \in C_c(X, [0, 1])$. For a fixed positive integer n and for each index $1 \leq i \leq n$, let $K_i := f^{-1}([i/n, 1])$ and define

$$f_i(x) := \begin{cases} 0 & \text{if } x \in K_{i-1}^c, \\ f(x) - \frac{i-1}{n} & \text{if } x \in K_{i-1} \setminus K_i, \\ \frac{1}{n} & \text{if } x \in K_i, \end{cases}$$

where $K_0 := \text{supp } f$. Note that $nf_i \in C_c(X, [0, 1])$ and $f = \sum_{i=1}^n f_i$. For $1 \leq i \leq n$ we have $\mu(K_i) < \infty$ because K_i is compact subsets contained in a locally compact Hausdorff space $U := f^{-1}((0, 1])$, but $\mu(K_0)$ is possibly infinite. By the previous claim and the property of integral, we have

$$\frac{\mu(K_i)}{n} \leq I(f_i), \quad \frac{\mu(K_i)}{n} \leq \int f_i d\mu$$

for $1 \leq i \leq n$ and

$$I(f_i) \leq \frac{\mu(K_{i-1})}{n}, \quad \int f_i d\mu \leq \frac{\mu(K_{i-1})}{n}$$

for $2 \leq i \leq n$. Then, using the above inequalities and $\mu(K_n) \geq 0$, we have

$$I(f) \leq I(f_1) + \int f d\mu \quad \text{and} \quad \int f d\mu \leq \int f_1 d\mu + I(f).$$

Note that $f_1 = \min\{f, 1/n\}$ is a sequence of functions indexed by n . By the monotone convergence theorem, $\int f_1 d\mu \rightarrow 0$ as $n \rightarrow \infty$. We now show $I(f_1)$ converges to zero.

(d) Let μ and ν be finite Borel measures on Ω such that

$$\int g d\mu = \int g d\nu$$

for all $g \in C(\Omega)$. Let E be any measurable set. Since $\mu + \nu$ is a finite Borel measure, it is regular, and by the Luzin theorem, we have a closed set F and $g \in C(\Omega)$ with $0 \leq g \leq 1$ such that $\mathbf{1}_E|_F = g|_F$ and $(\mu + \nu)(\Omega \setminus F) < \varepsilon/2$. Then,

$$\begin{aligned} |\mu(E) - \nu(E)| &= \left| \int \mathbf{1}_E d\mu - \int \mathbf{1}_E d\nu \right| \\ &\leq \int_{\Omega \setminus F} |\mathbf{1}_E - g| d\mu + \int_{\Omega \setminus F} |g - \mathbf{1}_E| d\nu \\ &\leq 2\mu(\Omega \setminus F) + 2\nu(\Omega \setminus F) < \varepsilon. \end{aligned}$$

By limiting $\varepsilon \rightarrow 0$, we have $\mu(E) = \nu(E)$. □

5.7 (Dual of continuous function spaces).

5.4 Hausdorff measures

Exercises

Chapter 6

Lebesgue spaces

6.1 L^p spaces

6.1 (Hölder inequality).

Proof.

$$\int f g \leq C^p \int \frac{|f|^p}{p} + \frac{1}{C^q} \int \frac{|g|^q}{q}$$

Take C such that

$$C^p \int \frac{|f|^p}{p} = \frac{1}{C^q} \int \frac{|g|^q}{q}.$$

Then,

$$C^p \int \frac{|f|^p}{p} + \frac{1}{C^q} \int \frac{|g|^q}{q} = 2p^{-\frac{1}{p}} q^{-\frac{1}{q}} \left(\int |f|^p \right)^{\frac{1}{p}} \left(\int |g|^q \right)^{\frac{1}{q}}.$$

Note that we can show that $1 \leq 2p^{-\frac{1}{p}} q^{-\frac{1}{q}} \leq 2$ and the minimum is attained only if $p = q = 2$, so this method does not provide the sharpest constant. \square

6.2 L^1 spaces

6.2 (Convolution?).

6.3 (Approximate identity?).

6.4 (Continuity of translation?).

6.3 L^2 spaces

6.4 L^∞ spaces

Part III

Distribution theory

Chapter 7

Test functions

Chapter 8

Distributions

Chapter 9

Linear operators

9.1 Boundedness

Translation and multiplication operators

9.1 (Bitranspose extension).

9.2 Kernels

9.2 (Schur test).

9.3 (Young's inequality of integral operators).

9.3 Convolution

9.4 (Approximation of identity). Fejér, Poisson, box?

9.5 (Summability methods).

Part IV

Fundamental theorem of calculus

Chapter 10

Absolute continuity

The space of weakly differentiable functions with respect to all variables $= W_{\text{loc}}^{1,1}$.

10.1 (Product rule for weakly differentiable functions). We want to show that if u , v , and uv are weakly differentiable with respect to x_i , then $\partial_{x_i}(uv) = \partial_{x_i}u v + u \partial_{x_i}v$.

(a) If u is weakly differentiable with respect to x_i and $v \in C^1$, then $\partial_{x_i}(uv) = \partial_{x_i}u v + u \partial_{x_i}v$.

10.2 (Interchange of differentiation and integration). Let $f : \Omega_x \times \Omega_y \rightarrow \mathbb{R}$ be such that $\partial_{x_i}f$ is well-defined. Suppose f and $\partial_{x_i}f$ are locally integrable in x and integrable y .

Then,

$$\partial_{x_i} \int f(x, y) dy = \int \partial_{x_i} f(x, y) dy.$$

Do not think the Schwarz theorem as the condition for partial differentiation to commute. We should understand like this: if F is C^2 then the *classical* partial differentiation commute, and if F is not C^2 then the *classical* partial derivatives of order two or more are *meaningless* because it is not compatible with the generalized concept of differentiation.

10.1 Absolutely continuity

(a) f is Lip_{loc} iff f' is L_{loc}^∞

(b) f is AC_{loc} iff f' is L_{loc}^1

(a) f is Lip iff f' is L^∞

(b) f is AC iff f' is L^1

(c) f is BV iff f' is a finite regular Borel measure

10.3 (Absolute continuous measures).

10.4 (Absolute continuous functions).

10.5 (Functions of bounded variation).

10.2 Interpolations

weak L_p , marcinkiewicz

Definition 10.2.1. Let f be a measurable function on a measure space (X, μ) . The *distribution function* $\lambda_f : [0, \infty) \rightarrow [0, \infty)$ is defined as:

$$\lambda_f(\alpha) := \mu(\{x : |f(x)| > \alpha\}) = \mu(|f| > \alpha).$$

Do not use $\mu(\{x : |f(x)| \geq \alpha\})$. The strict inequality implies the *lower semi-continuity* of λ_f .

For $p > 0$,

$$\begin{aligned} \|f\|_{L^p}^p &= \int |f(x)|^p d\mu(x) \\ &= \int \int_0^{|f(x)|} p\alpha^{p-1} d\alpha d\mu(x) \\ &= \int_0^\infty \int_{|f(x)| > \alpha} p\alpha^{p-1} d\mu(x) d\alpha \\ &= p \int_0^\infty \left[\alpha \cdot \mu(|f| > \alpha)^{\frac{1}{p}} \right]^p \frac{d\alpha}{\alpha}. \end{aligned}$$

Definition 10.2.2.

$$\|f\|_{L^{p,q}}^q := p \int_0^\infty \left[\alpha \cdot \mu(|f| > \alpha)^{\frac{1}{p}} \right]^q \frac{d\alpha}{\alpha}.$$

Also,

$$\|f\|_{L^{p,\infty}} := \sup_{0 < \alpha < \infty} \left[\alpha \cdot \mu(|f| > \alpha)^{\frac{1}{p}} \right].$$

Theorem 10.2.3. For $p \geq 1$ we have $\|f\|_{p,\infty} \leq \|f\|_p$.

Proof. By the Chebyshev inequality,

$$\sup_{0 < \alpha < \infty} [\alpha^p \cdot \mu(|f| > \alpha)] \leq \int_0^\infty p\alpha^{p-1} \cdot \mu(|f| > \alpha) d\alpha = \|f\|_{L^p}^p.$$

□

10.6 (Marcinkiewicz interpolation). Let X be a σ -finite measure space and Y be a measure space. Let

$$1 < p_0 < p < p_1 < \infty.$$

If a sublinear operator $T : L^{p_0}(X) + L^{p_1}(X) \rightarrow M(Y)$ has two weak-type estimates

$$\|T\|_{L^{p_0}(X) \rightarrow L^{p_0,\infty}(Y)} < \infty \quad \text{and} \quad \|T\|_{L^{p_1}(X) \rightarrow L^{p_1,\infty}(Y)} < \infty,$$

then it has a strong-type estimate

$$\|T\|_{L^p(X) \rightarrow L^p(Y)} < \infty.$$

Proof. Let $f \in L^p(X)$ and denote $f_h = \chi_{|f| > \alpha} f$ and $f_l = \chi_{|f| \leq \alpha} f$. It is easy to show $f_h \in L^{p_0}$ and $f_l \in L^{p_1}$. Then,

$$\begin{aligned} \|Tf\|_{L^p(Y)}^p &\sim \int \alpha^p \cdot \mu(|Tf| > \alpha) \frac{d\alpha}{\alpha} \\ &\lesssim \int \alpha^p \cdot \mu(|Tf_h| > \alpha) \frac{d\alpha}{\alpha} + \int \alpha^p \cdot \mu(|Tf_l| > \alpha) \frac{d\alpha}{\alpha} \\ &\leq \int \alpha^p \cdot \frac{1}{\alpha^{p_0}} \|Tf_h\|_{L^{p_0,\infty}}^{p_0} \frac{d\alpha}{\alpha} + \int \alpha^p \cdot \frac{1}{\alpha^{p_1}} \|Tf_l\|_{L^{p_1,\infty}}^{p_1} \frac{d\alpha}{\alpha} \\ &\lesssim \int \alpha^{p-p_0} \|f_h\|_{p_0}^{p_0} \frac{d\alpha}{\alpha} + \int \alpha^{p-p_1} \|f_l\|_{p_1}^{p_1} \frac{d\alpha}{\alpha} \\ &\sim \|f\|_p^p. \end{aligned}$$

by (1) Fubini, (2) Sublinearity, (3) Chebyshev, (4) Boundedness, (5) Fubini.

□

10.7 (Hadamard's three line lemma). Let f be a bounded holomorphic function on vertical unit strip $\{z : 0 < \operatorname{Re} z < 1\}$ which is continuously extended to the boundary. Then, for $0 < \theta < 1$ we have

$$\|f\|_{L^\infty(\operatorname{Re}=\theta)} \leq \|f\|_{L^\infty(\operatorname{Re}=0)}^{1-\theta} \|f\|_{L^\infty(\operatorname{Re}=1)}^\theta.$$

Proof. Fix n and define

$$g_n(z) := \frac{f(z)}{\|f\|_{L^\infty(\operatorname{Re}=0)}^{1-z} \|f\|_{L^\infty(\operatorname{Re}=1)}^z} e^{-\frac{z(1-z)}{n}}.$$

Then,

$$|g_n(z)| \leq e^{-\frac{(\operatorname{Im} z)^2}{n}}$$

for z in the strip. By the maximum principle,

$$|f(z)| \leq \|f\|_{L^\infty(\operatorname{Re}=0)}^{1-\theta} \|f\|_{L^\infty(\operatorname{Re}=1)}^\theta e^{\frac{y^2}{n}}.$$

Letting $n \rightarrow \infty$, we are done. □

10.8 (Riesz-Thorin interpolation). Let X, Y be σ -finite measure spaces. Let

$$\frac{1}{p_\theta} = (1-\theta) \frac{1}{p_0} + \theta \frac{1}{p_1}, \quad \frac{1}{q_\theta} = (1-\theta) \frac{1}{q_0} + \theta \frac{1}{q_1}.$$

Then,

$$\|T\|_{p_\theta \rightarrow q_\theta} \leq \|T\|_{p_0 \rightarrow q_0}^{1-\theta} \|T\|_{p_1 \rightarrow q_1}^\theta.$$

Proof. Note that

$$\|T\|_{p_\theta \rightarrow q_\theta} = \sup_f \frac{\|Tf\|_{q_\theta}}{\|f\|_{p_\theta}} = \sup_{f, g} \frac{|\langle Tf, g \rangle|}{\|f\|_{p_\theta} \|g\|_{q'_\theta}}.$$

Consider a holomorphic function

$$z \mapsto \langle Tf_z, g_z \rangle = \int \overline{g_z(y)} Tf_z(y) dy,$$

where f_z and g_z are defined as

$$f_z = |f|^{\frac{p_\theta}{p_0}(1-z) + \frac{p_\theta}{p_1}z} \frac{f}{|f|}$$

so that we have $f_\theta = f$ and

$$\|f\|_{p_\theta}^{p_\theta} = \|f_z\|_{p_x}^{p_x}$$

for $\operatorname{Re} z = x$.

Then,

$$|\langle Tf_z, g_z \rangle| \leq \|T\|_{p_0 \rightarrow q_0} \|f_z\|_{p_0} \|g_z\|_{q'_0} = \|T\|_{p_0 \rightarrow q_0} \|f\|_{p_\theta}^{p_\theta/p_0} \|g\|_{q'_\theta}^{q'_\theta/q'_0}$$

for $\operatorname{Re} z = 0$, and

$$|\langle Tf_z, g_z \rangle| \leq \|T\|_{p_1 \rightarrow q_1} \|f_z\|_{p_1} \|g_z\|_{q'_1} = \|T\|_{p_1 \rightarrow q_1} \|f\|_{p_\theta}^{p_\theta/p_1} \|g\|_{q'_\theta}^{q'_\theta/q'_1}$$

for $\operatorname{Re} z = 1$. By Hadamard's three line lemma, we have

$$|\langle Tf_z, g_z \rangle| \leq \|T\|_{p_0 \rightarrow q_0}^{1-\theta} \|T\|_{p_1 \rightarrow q_1}^\theta \|f\|_{p_\theta} \|g\|_{q'_\theta}$$

for $\operatorname{Re} z = \theta$. Putting $z = \theta$ in the last inequality, we get the desired result. □

Chapter 11

Lebesgue differentiation theorem

11.1 Hardy-Littlewood maximal function

Let T_m be a net of linear operators. It seems to have two possible definitions of maximal functions:

$$T^*f := \sup_m |T_m f|$$

and

$$T^*f := \sup_{m, \varepsilon: |\varepsilon(x)|=1} |T_m(\varepsilon f)|.$$

11.1 (Hardy-Littlewood maximal function). The Hardy-Littlewood maximal function is just the maximal function defined with the approximate identity by the box kernel.

11.2 (Weak type estimate).

$$\|Mf\|_{1,\infty} \leq 3^d \|f\|_{L^1(\Omega)}.$$

(a) Proof by covering lemma.

Proof. (a) By the inner regularity of μ , there is a compact subset K of $\{|Mf| > \lambda\}$ such that

$$\mu(K) > \mu(\{|Mf| > \lambda\}) - \varepsilon.$$

For every $x \in K$, since $|Mf(x)| > \lambda$, we can choose an open ball B_x such that

$$\frac{1}{\mu(B_x)} \int_{B_x} |f| > \lambda$$

if and only if

$$\mu(B_x) < \frac{1}{\lambda} \int_{B_x} |f|.$$

With these balls, extract a finite open cover $\{B_i\}_i$ of K . Since the diameter of elements in this cover is clearly bounded, so the Vitali covering lemma can be applied to obtain a disjoint subcollection $\{B_k\}_k$ such that

$$K \subset \bigcup_i B_i \subset \bigcup_k 3B_k.$$

Therefore,

$$\mu(K) \leq \sum_k 3^d \mu(B_k) \leq \frac{3^d}{\lambda} \sum_k \int_{B_k} |f| \leq \frac{3^d}{\lambda} \|f\|_1.$$

The disjointness is important in the last inequality which shows the constant does not depend on the number of B_k 's. □

11.3 (Radially bounded approximate identity). If an approximate identity K_n is radially bounded, then its maximal function is dominated by the Hardy-Littlewood maximal function:

$$\sup_n |K_n * f(x)| \lesssim Mf(x)$$

for every n and x , hence has a weak type estimate.

11.4 (Almost everywhere convergence of operators). Suppose T_m is a sequence of linear operators such that the maximal function T^*f is dominated by Mf . If $f \in L^1(\Omega)$ and $T_m g \rightarrow g$ pointwise for $g \in C(\Omega)$, then $T_m f \rightarrow f$ a.e.

Proof. Take $\varepsilon > 0$ and $g \in C(\Omega)$ such that $\|f - g\|_{L^1(\Omega)} < \varepsilon$. Since $T_m g(x) \rightarrow g(x)$ pointwise, we have

$$\begin{aligned} & \mu(\{x : \limsup_m |T_m f(x) - f(x)| > \lambda\}) \\ & \leq \mu(\{x : \limsup_m |T_m f(x) - T_m g(x)| > \frac{\lambda}{2}\}) + \mu(\{x : |g(x) - f(x)| > \frac{\lambda}{2}\}) \\ & \leq \mu(\{x : M(f - g)(x) > \frac{\lambda}{2}\}) + \frac{2}{\lambda} \|f - g\|_{L^1(\Omega)} \\ & \lesssim \frac{1}{\lambda} \varepsilon \end{aligned}$$

for every $\lambda > 0$. Limiting $\varepsilon \rightarrow 0$, we get

$$\mu(\{x : \limsup_m |T_m f(x) - f(x)| > \lambda\}) = 0$$

for every $\lambda > 0$, hence the continuity from below implies

$$\mu(\{x : \limsup_m |T_m f(x) - f(x)| > 0\}) = 0.$$

□

Definition 11.1.1.

$$f^*(x) := \lim_{r \rightarrow 0^+} \frac{1}{\mu(B)} \int_B |f(y) - f(x)| dy.$$

Theorem 11.1.2 (Lebesgue differentiation). $f^* = 0$ a.e.

Proof. Note that $f^* \leq Mf + |f|$ implies

$$\|f^*\|_{1,\infty} \leq \|Mf\|_{1,\infty} + \|f\|_{1,\infty} \lesssim \|f\|_1.$$

Note that $g^* = 0$ for $g \in C_c$. Approximate using $f^* = (f - g)^*$.

□

Exercises

11.5 (Doubling measure).