Lebesgue Theory

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Contents

Part I

Measure theory

Chapter 1

Measures and σ-algebras

1.1 Measures

1.1 (Definition of measures)**.** Let $(\Omega, \mathcal{M})$ be a measurable space. A *measure* on $\mathcal{M}$ is a set function $\mu : \mathcal{M} \to [0, \infty]$ with $\mu(\varnothing) = 0$ that is *countably additive*:

$$\mu\Big(\bigsqcup_{i=1}^{\infty} E_i\Big) = \sum_{i=1}^{\infty} \mu(E_i) \quad \text{in } \mathcal{M}.$$

Here the squared cup notation reads the disjoint union.

1.2 (Continuity of measures)**.**

1.2 Carathéodory extension

1.3 (Outer measures)**.** Let Ω be a set. An *outer measure* on Ω is a set function $\mu^* : \mathcal{P}(\Omega) \to [0, \infty]$ with $\mu^*(\varnothing) = 0$ such that

(i) $E_1 \subset E_2 \Rightarrow \mu^*(E_1) \le \mu^*(E_2)$ in $\mathcal{P}(\Omega)$, (monotonicity)

(ii) $\mu^*(\bigcup_{i=1}^{\infty} E_i) \le \sum_{i=1}^{\infty} \mu^*(E_i)$ in $\mathcal{P}(\Omega)$. (countable subadditivity)

Compairing 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 $\mu^* : \mathcal{P}(\Omega) \to [0, \infty]$ with $\mu^*(\varnothing) = 0$ is an outer measure if and only if μ^* is *monotonically countably subadditive*, that is, $E \subset \bigcup_{i=1}^{\infty} E_i \Rightarrow \mu^*(E) \le \sum_{i=1}^{\infty} \mu^*(E_i)$ in $\mathcal{P}(\Omega)$.

(b) For a set function $\rho : \mathcal{A} \to [0, \infty]$ with $\rho(\varnothing) = 0$, where $\varnothing \in \mathcal{A} \subset \mathcal{P}(\Omega)$, we can associate an outer measure $\mu^* : \mathcal{P}(\Omega) \to [0, \infty]$ by defining as

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

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

Proof. (a)

(b)

□

1.4 (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 $A \subset \Omega$ is called *Carathéodory measurable* relative to μ^* if

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

for every subset $E \subset \Omega$. 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 $\mathcal{M}$.

(c) The measure $\mu := \mu^*|_{\mathcal{M}} : \mathcal{M} \to [0, \infty]$ is complete.

Proof. $\square$

1.5 (Carathéodory extension theorem). Let $\rho : \mathcal{A} \to [0, \infty]$ with $\rho(\varnothing) = 0$, where $\varnothing \in \mathcal{A} \subset \mathcal{P}(\Omega)$. Consider two conditions

(i) $A \subset \bigcup_{i=1}^\infty A_i \Rightarrow \rho(A) \le \sum_{i=1}^\infty \rho(A_i)$ in $\mathcal{A}$, (monotonically countably subadditive)

(ii) For every $B, A \in \mathcal{A}$, and for any $\varepsilon > 0$, there are $\{B_j'\}_{j=1}^\infty$ and $\{B_j''\}_{j=1}^\infty \subset \mathcal{A}$ such that

$$B \cap A \subset \bigcup_{j=1}^\infty B_j' \quad \text{and} \quad B \setminus A \subset \bigcup_{j=1}^\infty B_j'',$$

and

$$\rho(B) + \varepsilon > \sum_{j=1}^\infty \rho(B_j') + \sum_{j=1}^\infty \rho(B_j'').$$

Let $\mu^* : \mathcal{P}(\Omega) \to [0, \infty]$ be the associated outer measure of ρ, and $\mu : \mathcal{M} \to [0, \infty]$ the measure defined by the restriction of μ^* on Carathéodory measurable subsets. The above two conditions give a sufficient condition for μ to be a measure on a σ-algebra containing $\mathcal{A}$.

(a) $\mu^*|_{\mathcal{A}} = \rho$ if (i) is satisfied.

(b) $\mathcal{A} \subset \mathcal{M}$ if (ii) is satisfied.

Proof. (a) Clearly $\mu^*(A) \le \rho(A)$ for $A \in \mathcal{A}$. We may assume $\mu^*(A) < \infty$. For arbitrary $\varepsilon > 0$ there is $\{A_i\}_{i=1}^\infty$ such that $A \subset \bigcup_{i=1}^\infty A_i$ and

$$\mu^*(A) + \varepsilon > \sum_{i=1}^\infty \rho(A_i) \ge \rho(A).$$

(b) Let $E \in \mathcal{P}(\Omega)$ and $A \in \mathcal{A}$. Since it is enough to check the inequality $\mu^*(E) \ge \mu^*(E \cap A) + \mu^*(E \setminus A)$ for E with finite $\mu^*(E)$, we may assume there is a countable family $\{B_i\}_{i=1}^\infty \subset \mathcal{A}$ such that $E \subset \bigcup_{i=1}^\infty B_i$. Then, we have $B_i \cap A \subset \bigcup_{j=1}^\infty B_{i,j}'$ and $B_i \setminus A \subset \bigcup_{j=1}^\infty B_{i,j}''$ satisfying

$$\mu^*(E) + \varepsilon > \sum_{i=1}^\infty (\rho(B_i) + \frac{\varepsilon}{2^{i+1}}) > \sum_{i,j=1}^\infty \rho(B_{i,j}') + \sum_{i,j=1}^\infty \rho(B_{i,j}'') \ge \mu^*(E \cap A) + \mu^*(E \setminus A).$$ $\square$

1.6 (Uniqueness of Carathéodory extensions). The Carathéodory extension theorem provides with a uniqueness theorem for measures.

Proof. $\square$

Exercises

1.7 (Semi-rings and semi-algebras)**.** We will prove a simplified Carathéodory extension with respect to *semi-rings* and *semi-algebras*. Let $\mathcal{A}$ be a collection of subsets of a set Ω such that $\varnothing \in \mathcal{A}$. We say $\mathcal{A}$ is a semi-ring if it is closed under finite intersection, and the complement is a finite union of elements of $\mathcal{A}$. We say $\mathcal{A}$ is a semi-algebra

Let $\mathcal{A}$ be a semi-ring of sets over Ω. Suppose a set function $\rho : \mathcal{A} \to [0, \infty]$ with $\rho(\varnothing) = 0$ satisfies

(i) $\rho(\bigsqcup_{i=1}^{\infty} A_i) \le \sum_{i=1}^{\infty} \rho(A_i)$ in $\mathcal{A}$, (disjoint countable subadditivity)

(ii) $\rho(A_1 \sqcup A_2) = \rho(A_1) + \rho(A_2)$ in $\mathcal{A}$. (finite additivity)

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

(a)

(b)

1.8 (Monotone class lemma)**.** alternative direct proof method without using Carathéodory extension.

Chapter 2

Measures on the real line

distribution functions helly's selection non-measurable set

Exercises

2.1 (Steinhaus theorem).

2.2. * A Lebesgue measurable set in $\mathbb{R}$ with positive measure contains an arbitrarily long subsequence of an arithmetic progression.

Chapter 3

Measurable functions

3.1 Extended real numbers

3.2 Simple functions

Pointwise limit of simple functions is measurable.

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

$\square$

Every measurable extended real-valued function is a pointwise limit of simple functions.

3.1 (Egorov's theorem)**.** Let (Ω, μ) be a finite measure space. Let $(f_n : \Omega \to \mathbb{R})_n$ be a sequence of a.e. convergent measurable functions. For $\varepsilon > 0$, there exists a measurable $E_\varepsilon \subset \Omega$ such that $\mu(\Omega \setminus E_\varepsilon) < \varepsilon$ and f_n uniformly convergent on E_ε.

Proof. Assume $f_n \to 0$. The set of convergence is

$$\bigcap_{k>0} \bigcup_{n_0>0} \bigcap_{n\geq n_0} \{\, x : |f_n(x)| < \tfrac{1}{k} \,\},$$

which is a full set. We want to get rid of the dependence on the point x of n_0 in the union $\bigcup_{n_0>0}$. Since

$$\bigcap_{n\geq n_0} \{\, x : |f_n(x)| < \frac{1}{k} \,\}$$

is increasing as $n_0 \to \infty$ to a full set for each $k > 0$, we can find $n_0(k, \varepsilon)$ such that

$$\mu(\bigcap_{n\geq n_0} \{\, x : |f_n(x)| < \tfrac{1}{k} \,\}) > \mu(\Omega) - \frac{\varepsilon}{2^k}.$$

Then,

$$\mu(\bigcap_{k>0} \bigcap_{n\geq n_0} \{\, x : |f_n(x)| < \tfrac{1}{k} \,\}) > \mu(\Omega) - \varepsilon.$$

If we define

$$E_\varepsilon := \bigcap_{k>0} \bigcap_{n\geq n_0} \{\, x : |f_n(x)| < \tfrac{1}{k} \,\},$$

then for any $k > 0$ and $x \in E_\varepsilon$, and with the $n_0(k, \varepsilon)$ we have chosen, we have

$$n \geq n_0 \quad \Rightarrow \quad |f_n(x)| < \frac{1}{k}.$$

$\square$

Since $\{f_n(x)\}_n$ diverges if and only if

$$\exists k > 0, \quad \forall n_0 > 0, \quad \exists n > n_0 : \quad |f_n(x) - f(x)| > \tfrac{1}{k},$$

we have

$$\begin{aligned}\{x : \{f_n(x)\}_n \text{ diverges}\} &= \bigcup_{k>0} \bigcap_{n_0>0} \bigcup_{n>n_0} \{x : |f_n - f| > \tfrac{1}{k}\} \\ &= \bigcup_{k>0} \limsup_n \{x : |f_n - f| > \tfrac{1}{k}\}.\end{aligned}$$

Since for every k we have

$$\begin{aligned}\limsup_n \{x : |f_n - f| > \tfrac{1}{k}\} &\subset \limsup_{n>k} \{x : |f_n - f| > \tfrac{1}{n}\} \\ &= \limsup_n \{x : |f_n - f| > \tfrac{1}{n}\},\end{aligned}$$

we have

$$\{x : \{f_n(x)\}_n \text{ diverges}\} \subset \limsup_n \{x : |f_n - f| > \tfrac{1}{n}\}.$$

Exercises

3.2 (Cauchy's functional equation)**.** Let $f : \mathbb{R} \to \mathbb{R}$ 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 conitnuous at a point, then f is linear.

(c) If f is Lebesgue measurable, then f is linear.

Part II

Lebesgue integral

Chapter 4

Convergence theorems

4.1 Definition of Lebesgue integral

4.2 Convergence theorems

Stein: Egorov → BCT → Fatou → MCT → L1 is a measure
Stein: BCT + L1 is a measure → DCT
Folland: MCT → Fatou → DCT → BCT

4.3 Radon-Nikodym theorem

4.4 Modes of convergence

4.1 (Convergence in measure)**.** Let (X,μ) be a measure space. Let f_n be a sequence of measurable functions. If f_n converges to f in measure, then f_n has a subsequence that converges to f μ-a.e.

Proof. We can extract a subsequence f_{n_k} such that

$$\mu(\{x : |f_{n_k} - f| > \tfrac{1}{k}\}) > \tfrac{1}{2^k}.$$

Since

$$\sum_{k=1}^{\infty} \mu(\{x : |f_{n_k} - f| > \tfrac{1}{k}\}) < \infty,$$

by the Borel-Canteli lemma, we get

$$\mu(\limsup_k \{x : |f_{n_k} - f| > \tfrac{1}{k}\}) = 0.$$

Therefore, f_{n_k} converges μ-a.e. □

Chapter 5

Product measures

5.1 Fubini-Tonelli theorem

5.2 Lebesgue measure on Euclidean spaces

Chapter 6

Measures on metric spaces

6.1 Compact metric spaces

Part III

Linear operators

Chapter 7

Lebesgue spaces

7.1 L^p spaces

7.2 L^1 spaces

7.3 L^2 spaces

7.4 L^∞ spaces

Chapter 8

Bounded linear operators

8.1 Continuity

Schur test

8.2 Density arguments

extension of operators

8.3 Interpolation

weak Lp, marcinkiewicz

Chapter 9

Convergence of linear operators

9.1 Translation and multiplication operators

9.2 Convolution type operators

approximation of identity

9.3 Computation of integral transforms

Part IV

Fundamental theorem of calculus

Chapter 10

Weak derivatives

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

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 $\partial_{x_i}(uv) = \partial_{x_i}uv + u\partial_{x_i}v$.

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

10.2 (Interchange of differentiation and integration)**.** Let $f : \Omega \to \mathbb{R}$ such that $f(x, y)$ and $\partial_{x_i} f(x, y)$ are both locally integrable in x and integrable y. Then,

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

where ∂_{x_i} denotes the weak partial derivative.

Chapter 11

Absolutely continuity

(a) f is $\mathrm{Lip}_{\mathrm{loc}}$ iff f' is L^∞_{loc}
(b) f is $\mathrm{AC}_{\mathrm{loc}}$ iff f' is L^1_{loc}

(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

Chapter 12

Lebesgue differentiation theorem