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1 Abstract Integration

The Concept of Measurability

1.2 Definition

- $\tau \subseteq \mathcal{P}(X)$, containing both \emptyset and X , is a **topology** if it is closed under finite intersections and arbitrary unions.
- (X, τ) is a **topological space** and the members of τ are **open sets**.
- $f : (X, \tau_X) \rightarrow (Y, \tau_Y)$ is **continuous** if open sets have open preimages.

1.3 Definition

- $\mathfrak{M} \subseteq \mathcal{P}(X)$, containing X , is a **σ -algebra** if it is closed under complementation and countable unions.
- (X, \mathfrak{M}) is a **measurable space**; elements of \mathfrak{M} are **measurable sets**.
- $f : (X, \mathfrak{M}) \rightarrow (Y, \tau)$ is **measurable** if open sets have measurable preimages (τ a topology).

Note: Instead of (X, \mathfrak{M}) we just refer to X as the measurable space.

1.6 Comments on Definition 1.3

- $\emptyset \in \mathfrak{M}$.
- Finite unions are in \mathfrak{M} .
- \mathfrak{M} is closed under finite and countable intersection.
- \mathfrak{M} is closed under set subtraction.

1.7 Composition with Continuous Functions

- f measurable, g continuous: $g \circ f$ is measurable.

1.8 Continuous Image of Cartesian Product of Measurable Functions.

- u, v real, measurable functions; ϕ continuous on the plane: $\phi(u(x), v(x))$ is measurable.

1.9 Creating Measurable Functions

- If u, v are real measurable then $f = u + iv$ is complex measurable.
- If $f = u + iv$ is complex measurable then u, v , and $|f|$ are real measurable.
- If f and g are complex measurable then so are $f + g$ and fg .
- Characteristic functions of measurable sets are measurable functions.
- If f is complex measurable then there is a complex measurable function α with $|\alpha| = 1$ and $f = \alpha|f|$.

1.10 σ -Algebra Generated by a Set

- $\mathcal{F} \subseteq \mathcal{P}(X)$ is contained in some smallest σ -algebra \mathfrak{M}^* .

1.11 Borel Sets

- The **Borel Sets**, \mathfrak{B} , is the σ -algebra generated by the topology of a space.
- G_δ sets are countable intersections of open sets.
- F_σ sets are countable unions of closed sets.
- Borel measurable functions are called **Borel mappings** or **Borel functions**.
- *Every* continuous function is Borel measurable.

1.12 σ -Algebras Associated with a Function

\mathfrak{M} a σ -algebra on X , Y a topological space, $f : X \rightarrow Y$ a function:

- $\Omega = \{E \subseteq Y : f^{-1}(E) \in \mathfrak{M}\}$ is a σ -algebra on Y .
- If f is measurable, E Borel in Y , then $f^{-1}(E) \in \mathfrak{M}$.
- If $Y = [-\infty, \infty]$ and $f^{-1}((a, \infty]) \in \mathfrak{M}$ for all $a \in \mathbb{R}$ then f is measurable.
- If f is measurable, Z a topological space, $g : Y \rightarrow Z$ Borel, then $g \circ f : X \rightarrow Z$ is measurable.

1.14 Supremum and Limit Supremum of Measurable Functions

- If $f_n : X \rightarrow [-\infty, \infty]$ are measurable then so are $\sup f_n$ and $\limsup f_n$.
- The limit of pointwise convergent sequence of complex measurable functions is measurable.
- f, g measurable then so are $\max\{f, g\}$ and $\min\{f, g\}$.

1.15 Positive and Negative parts of f

- $f^+ = \max\{f, 0\}$ is the **positive part** of f and $f^- = -\min\{f, 0\}$ is the **negative part**.
- $|f| = f^+ + f^-$ and $f = f^+ - f^-$.
- If $f = g - h$, $g \geq 0$ and $h \geq 0$ then $f^+ \leq g$ and $f^- \leq h$.

Simple Functions

1.16 Definition

- s , complex measurable on X , is **simple** if its range is finite. If $s(X) = \{\alpha_1, \dots, \alpha_n\}$ then

$$s = \sum_{i=1}^n \alpha_i \chi_{A_i}, \quad A_i = s^{-1}(\alpha_i).$$

- s is measurable if and only if each A_i is.

1.17 Approximation by Simple Functions

- If $f : X \rightarrow [0, \infty]$ is measurable then there exists measurable, simple functions s_n on X such that $0 \leq s_1 \leq \dots \leq f$ and $s_n(x) \rightarrow f(x)$ as $n \rightarrow \infty$ for all $x \in X$.

Elementary Properties of Measures

1.18 Definition

- A **positive measure** is a function from a σ -algebra \mathfrak{M} to $[0, \infty]$ which is **countably additive**: i.e.

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

when A_i are pairwise disjoint members of \mathfrak{M} .

- A measurable space equipped with a measure is a **measure space**.
- A **complex measure** is a complex-valued countably additive function on a σ -algebra.

1.19 Basic Properties of a Positive Measure μ

- $\mu(\emptyset) = 0$.
- $\mu(A_1 \cup \cdots \cup A_n) = \mu(A_1) + \cdots + \mu(A_n)$ if the A_i are pairwise disjoint members of \mathfrak{M} .
- $A \subseteq B$ implies $\mu(A) \leq \mu(B)$ for $A, B \in \mathfrak{M}$.
- If $A_n \in \mathfrak{M}$ such that $A_1 \subseteq A_2 \subseteq A_3 \subseteq \cdots$ then $\mu(A_n) \rightarrow \mu(\bigcup_{n=1}^{\infty} A_n)$.
- If $A_n \in \mathfrak{M}$ such that $A_1 \supseteq A_2 \supseteq A_3 \supseteq \cdots$ and $\mu(A_1) < \infty$ then $\mu(A_n) \rightarrow \mu(\bigcap_{n=1}^{\infty} A_n)$.

1.20 Measure Space Examples

- **counting measure**: $\mu(E) = |E|$ if $|E| < \infty$ and $\mu(E) = \infty$ otherwise.
- **unit mass at x_0** : $\mu(E) = 1$ if $x_0 \in E$ and $\mu(E) = 0$ otherwise.

Arithmetic in $[0, \infty]$

1.22 Definition

- $a + \infty = \infty + a = \infty$
- $a \cdot \infty = \infty \cdot a = \begin{cases} \infty & a \in (0, \infty] \\ 0 & a = 0 \end{cases}$
- With $0 \cdot \infty = 0$ we have commutativity, associativity, and distributivity.
- Cancellation: $a + b = a + c \implies b = c$ only if $a \neq \infty$; $ab = ac \implies b = c$ only if $a \in (0, \infty)$.
- $0 \leq a_1 \leq a_2 \leq \cdots$, $0 \leq b_1 \leq b_2 \leq \cdots$ with $a_n \rightarrow a$ and $b_n \rightarrow b \implies a_n b_n \rightarrow ab$.

Integration of Positive Functions on (X, \mathfrak{M}, μ)

1.23 Definition

- $s : X \rightarrow [0, \infty]$ simple and measurable with $s(X) = \{\alpha_1, \dots, \alpha_n\}$. For $E \in \mathfrak{M}$ define

$$\int_E s d\mu = \sum_{i=1}^n \alpha_i \mu(A_i \cap E), \quad A_i = s^{-1}(\alpha_i).$$

- If $f : X \rightarrow [0, \infty]$ is measurable then for $E \in \mathfrak{M}$ define the **Lebesgue Integral of f over E** by

$$\int_E f d\mu = \sup \int_E s d\mu,$$

where the supremum is taken over all nonnegative measurable simple functions dominated by f .

1.24 Basic Properties of Lebesgue Integrals

- $0 \leq f \leq g$ implies $\int_E f d\mu \leq \int_E g d\mu$.
- $A \subseteq B$ and $f \geq 0$ implies $\int_A f d\mu \leq \int_B f d\mu$.
- If $f \geq 0$ and $c \in [0, \infty)$ then $\int_E cf d\mu = c \int_E f d\mu$.
- If $f \equiv 0$ on E then $\int_E f d\mu = 0$ even if $\mu(E) = \infty$.
- If $\mu(E) = 0$ then $\int_E f d\mu = 0$ if $f \equiv \infty$ on E .
- If $f \geq 0$ then $\int_E f d\mu = \int_X \chi_E f d\mu$.

1.25 Basic Properties of the Lebesgue Integral of Simple Functions

- If s is a nonnegative measurable simple function then $\varphi : \mathfrak{M} \rightarrow [0, \infty]$ sending E to $\int_E s d\mu$ is a measure.
- If s and t are nonnegative measurable simple functions then $\int_X (s + t) d\mu = \int_X s d\mu + \int_X t d\mu$.

1.26 Lebesgue's Monotone Convergence Theorem

- If $f_n : X \rightarrow [0, \infty]$ is a (pointwise) non-decreasing sequence of measurable functions for which $f_n(x) \rightarrow f(x)$ for every $x \in X$ then f is measurable and

$$\int_X f_n d\mu \rightarrow \int_X f d\mu.$$

1.27 Interchange of Summation and Integration

- If $f_n : X \rightarrow [0, \infty]$ are measurable and $f(x) = \sum_{n=1}^{\infty} f_n(x)$ then

$$\int_X f d\mu = \sum_{n=1}^{\infty} \int_X f_n d\mu.$$

1.28 Fatou's Lemma

- If $f_n : X \rightarrow [0, \infty]$ are measurable then

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

1.29 Change of Measure

- If $f : X \rightarrow [0, \infty]$ is measurable then $\varphi : \mathfrak{M} \rightarrow [0, \infty]$ sending E to $\int_E f d\mu$ is a measure and

$$\int_X g d\varphi = \int_X gf d\mu.$$

Sometimes this is written as $d\varphi = f d\mu$, although no independent meaning is given to these symbols.

Integration of Complex Functions on (X, \mathfrak{M}, μ)

1.30 Definition

- The **Lebesgue Integrable Functions** or **Summable Functions** with respect to μ , denoted by $L^1(\mu)$ is the collection of all complex measurable functions f on X such that $\int_X |f| d\mu < \infty$.

1.31 Definition

- If $f = u + iv$ with u, v real measurable functions and $f \in L^1(\mu)$ then for $E \in \mathfrak{M}$:

$$\int_E f d\mu = \left(\int_E u^+ d\mu - \int_E u^- d\mu \right) + i \left(\int_E v^+ d\mu - \int_E v^- d\mu \right).$$

- It is useful define the integral of a function $f : X \rightarrow [-\infty, \infty]$ to be

$$\int_E f d\mu = \int_E f^+ d\mu - \int_E f^- d\mu$$

for $E \in \mathfrak{M}$ and provided only one term on the right is infinite.

1.32 Linearity of $L^1(\mu)$

- For $f, g \in L^1(\mu)$ and $\alpha, \beta \in \mathbb{C}$ we have $\alpha f + \beta g \in L^1(\mu)$ and

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

1.33 Interchange of Modulus and Integration

- $\left| \int_X f d\mu \right| \leq \int_X |f| d\mu$ for $f \in L^1(\mu)$.

1.34 Lebesgue's Dominated Convergence Theorem

- f_n are complex measurable functions such that $f(x) = \lim_{n \rightarrow \infty} f_n(x)$ exists for all $x \in X$. If

$$|f_n(x)| \leq g(x), \quad \text{for all } n \in \mathbb{N}$$

for some $g \in L^1(\mu)$ then $f \in L^1(\mu)$,

$$\lim_{n \rightarrow \infty} \int_X |f_n - f| d\mu = 0,$$

and

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

The Role Played by Sets of Measure Zero

1.35 Definition

- If μ is a measure on a σ -algebra \mathfrak{M} , $E \in \mathfrak{M}$, then a statement P holds **almost everywhere** (a.e.) on E if there exists $N \subseteq E$ with $\mu(N) = 0$ such that P is true on $E \setminus N$.

Example 1 If f and g are measurable and $\mu(\{x : f(x) \neq g(x)\}) = 0$ then $f = g$ a.e., written as $f \sim g$. \sim is an equivalence relation and if $f \sim g$ then for $E \in \mathfrak{M}$ we have $\int_E f d\mu = \int_E g d\mu$. Thus sets of measure zero are negligible with respect to integration.

Note: It is *not* the case that a subset of a negligible set is negligible as it may not even be measurable!

1.36 Existence of Completions

- If (X, \mathfrak{M}, μ) is a measure space, then define \mathfrak{M}^* to be all $E \subseteq X$ such that $A \subseteq E \subseteq B$ for $A, B \in \mathfrak{M}$ such that $\mu(B \setminus A) = 0$. Defining $\mu(E) = \mu(A)$ makes (X, \mathfrak{M}^*, μ) a measure space,
- The extended μ is **complete** as all subsets of negligible sets are measurable.
- \mathfrak{M}^* is the μ -**completion** of \mathfrak{M} .

1.37 Expanding the Definition of What is a Measurable Function

- Since integration is agnostic to functions equal a.e., we now call f defined on $E \in \mathfrak{M}$ **measurable on X** if $\mu(E^c) = 0$ and $f^{-1}(V) \cap E$ is measurable for every open set V .
- In the above, we can define $f \equiv 0$ on E^c to get a measurable function on X .

1.38 Lebesgue's Dominated Convergence Theorem with Negligible Sets

- f_n complex measurable functions defined a.e. on X such that

$$\sum_{n=1}^{\infty} \int_X |f_n| d\mu < \infty.$$

Then $f(x) = \sum_{n=1}^{\infty} f_n(x)$ converges for almost all x and $f \in L^1(\mu)$ with

$$\int_X f d\mu = \sum_{n=1}^{\infty} \int_X f_n d\mu.$$

1.39 Integration and Properties That Hold Almost Everywhere

- If $f : X \rightarrow [0, \infty]$ measurable and $E \in \mathfrak{M}$ with $\int_E f d\mu = 0$ then $f = 0$ a.e. on E .
- If $f \in L^1(\mu)$ with $\int_E f d\mu = 0$ for every $E \in \mathfrak{M}$ then $f = 0$ a.e. on X .
- If $f \in L^1(\mu)$ and

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

then there exists $\alpha \in \mathbb{C}$ such that $\alpha f = |f|$ a.e. on X .

1.40 Averages Lying in a Closed Set

- If $\mu(X) < \infty$, $f \in L^1(\mu)$, $S \subseteq \mathbb{C}$ is closed, and the averages

$$A_E(f) = \frac{1}{\mu(E)} \int_E f d\mu$$

lie in S for every $E \in \mathfrak{M}$ with positive measure then $f(x) \in S$ for almost all $x \in X$.

1.41 Finite Set Membership

- If $E_k \subseteq X$ are measurable with $\sum_{k=1}^{\infty} \mu(E_k) < \infty$ then almost all $x \in X$ lie in finitely many E_k .

2 Positive Borel Measures

Vector Spaces

2.1 Definition

- A **complex vector space** is one with complex scalars.
- A function Λ between vector spaces is a **linear transformation** if $\Lambda(\alpha x + \beta y) = \alpha \Lambda x + \beta \Lambda y$.
- A **linear functional** is a linear transformation where the codomain is the field of scalars of the domain.

2.2 Integration as a Linear Functional

- For any positive measure μ , $f \mapsto \int_X f d\mu$ is a linear functional on $L^1(\mu)$.
- If g is a bounded measurable function then $f \mapsto \int_X fg d\mu$ is a linear functional on $L^1(\mu)$.
- A **positive linear functional** is a linear functional Λ such that $\Lambda f \geq 0$ whenever $f \geq 0$.
- If C is the vector space of continuous complex functions on $[0, 1]$ then

$$\Lambda f = \int_0^1 f(x) dx$$

is a positive linear functional on C (with the integral being the Riemann integral).

Topological Preliminaries

2.3 Definitions

- E is **closed** if its complement is open.
- The **closure** of E , denoted \overline{E} , is the smallest closed set containing E .
- $K \subseteq X$ is **compact** if every open cover of K contains a finite subcover.
- A **neighborhood** of $p \in X$ is any open set containing p .
- X is **Hausdorff** if any two $p \neq q$ can be separated by open sets.
- X is **locally compact** if every points has a neighborhood with compact closure.
- Recall Heine-Borel: Subsets of Euclidean space are compact exactly when they are closed and bounded. Thus \mathbb{R}^n is locally compact.
- Recall: Every metric space is Hausdorff.

2.4 Closed Subsets of Compact Sets

- $F \subseteq K$, F closed, K compact. Then F is compact.
- If $A \subseteq B$ and B has compact closure then so does A .

2.5 Separating a Compact Set from a Point

- If X is Hausdorff with K compact in X then any $p \notin K$ can be separated from K by open sets.

2.6 Intersections of Compact Sets

- If $K_\alpha \subseteq X$ are compact, X Hausdorff, and $\cap_\alpha K_\alpha = \emptyset$ then some finite subset has empty intersection.

2.7 Sandwiching Sets

- If U is open in X , Hausdorff, and $K \subseteq U$ is compact then there exists V , open, with $K \subseteq V \subseteq \overline{V} \subseteq U$.

2.8 Definition

- f is **lower semicontinuous** if $f^{-1}((\alpha, \infty])$ is open.
- f is **upper semicontinuous** if $f^{-1}([\infty, \alpha))$ is open.
- χ_U is lower semicontinuous if U is open.
- χ_F is upper semicontinuous if F is closed.
- The supremum of any collection of lower semicontinuous functions is again lower semicontinuous.
- The infimum of any collection of upper semicontinuous functions is again upper semicontinuous.

2.9 Definition

- The **support** of $f : X \rightarrow \mathbb{C}$ is the closure of $f^{-1}(\mathbb{C} \setminus \{0\})$.
- $C_c(X)$ is the vector space of functions with compact support.

2.10 Image of a Compact Set

- The continuous image of a compact set is compact.
- The range of $f \in C_c(X)$ is compact subset of \mathbb{C} .

2.11 Notation

- $K \prec f$ means K is compact, $0 \leq f(x) \leq 1$ and $f = 1$ on K .
- $f \prec V$ means V is open and f 's support lies in V .
- $K \prec f \prec V$ combines the above.

2.12 Urysohn's Lemma

- For $K \subseteq V \subseteq X$ with K compact, V open, and both X locally compact and Hausdorff, there exists $f \in C_c(X)$ with $K \prec f \prec V$.
- In terms of characteristic functions this means there is a continuous f with $\chi_K \leq f \leq \chi_V$.

2.13 Partition of Unity

- For X locally compact and Hausdorff and V_1, \dots, V_n open in X and $K \subseteq V_1 \cup \dots \cup V_n$ is compact, there exists functions $h_i \prec V_i$ with $h_1 + \dots + h_n = 1$ on K .
- This is called a **partition of unity on K** subordinate to the cover $\{V_1, \dots, V_n\}$.

The Riesz Representation Theorem

2.14 The Riesz Representation Theorem

- For X locally compact and Hausdorff with Λ a positive linear functional on $C_c(X)$ there exists:
 1. a σ -algebra \mathfrak{M} containing all the Borel sets of X ;
 2. a *unique* positive measure μ on \mathfrak{M} representing Λ :
 - $\Lambda f = \int_X f d\mu$ for all $f \in C_c(X)$
 - $\mu(K) < \infty$ for any compact K
 - $\mu(E) = \inf \{\mu(V) : E \subseteq V, V \text{ open}\}$ for all $E \in \mathfrak{M}$
 - $\mu(E) = \sup \{\mu(K) : K \subseteq E, K \text{ compact}\}$ for every $E \in \mathfrak{M}$ open or $\mu(E) < \infty$
 - $E \in \mathfrak{M}, \mu(E) = 0$ implies every subset of E is in \mathfrak{M} .

Regularity Properties of Borel Measures

2.15 Definition

- μ is a **Borel measure** if it is defined on the Borel sets.
- Let μ be a positive Borel measure and $E \subseteq X$ be Borel. Then:
- E is **outer regular** if the infimum property in 2.14 holds.
 - E is **inner regular** if the supremum property in 2.14 holds.
 - E is **regular** if both hold.

2.16 Definition

- E is **σ -compact** if it is the countable union of compact sets.
- E is **σ -finite** if it is the countable union of sets with finite measure.

2.17 Regularity of σ -Compact Spaces

- X a locally compact, σ -compact Hausdorff space and \mathfrak{M}, μ are as in 2.14. Then:
 - For $E \in \mathfrak{M}, \epsilon > 0$, there is $F \subseteq E \subseteq V$ with F closed, V open, and $\mu(V \setminus F) < \epsilon$.
 - μ is a regular Borel measure on X .
 - There exists an $F_\sigma A$ and a $G_\delta B$ with $A \subseteq E \subseteq B$ and $\mu(B \setminus A) = 0$.
Thus, every $E \in \mathfrak{M}$ is the union of an F_σ and a negligible set.

2.18 Regularity in the Presence of σ -Compact Open Sets

- X a locally compact Hausdorff space in which every open set is σ -compact. Then any positive Borel measure that is finite on compact sets is regular.

Lebesgue Measure

2.19 Euclidean Spaces

- \mathbb{R}^k is the **k -dimension Euclidean space** with all the familiar operations.
- If $E \subseteq \mathbb{R}^k$ and $x \in \mathbb{R}^k$ then $E + x = \{y + x : y \in E\}$ is a **translate** of E .
- A **k -cell** is a set of the form $\{(\xi_1, \dots, \xi_k) \in \mathbb{R}^k : \alpha_i < \xi_i < \beta_i, 1 \leq i \leq k\}$. Either inequality may be replaced with \leq . The **volume** of a k -cell is $\text{vol}(W) = \prod_{i=1}^k (\beta_i - \alpha_i)$.
- If $a \in \mathbb{R}^k$ and $\delta > 0$ then a **δ -box with corner at a** is

$$Q(a, \delta) = \{(\xi_1, \dots, \xi_k) \in \mathbb{R}^k : \alpha_i \leq \xi_i < \alpha_i + \delta, 1 \leq i \leq k\}.$$

- If P_n are points whose coordinates are multiples of 2^{-n} and Ω_n are the 2^{-n} boxes with corners at the elements of P_n then we use the following properties:
 - Ω_n covers \mathbb{R}^k disjointly.
 - If $r < n$ and $Q' \in \Omega_n$, $Q'' \in \Omega_r$ then either $Q' \subseteq Q''$ or $Q' \cap Q'' = \emptyset$.
 - $\text{vol } Q = 2^{-rk}$ for $Q \in \Omega_r$ and if $n > r$ then $|P_n \cap Q| = 2^{(n-r)k}$.
 - Any non-empty open set is the countable disjoint union of elements of $\cup_{n=1}^{\infty} \Omega_n$.

2.20 Existence of the Lebesgue Measure

- There exists $(\mathbb{R}^k, \mathfrak{M}, m)$ such that
 - $m(W) = \text{vol}(W)$ for every k -cell W .
 - \mathfrak{M} contains the Borel sets of \mathbb{R}^k
 - $E \in \mathfrak{M}$ iff $A \subseteq E \subseteq B$ with A is F_σ , B is G_δ , and $m(B \setminus A) = 0$.
 - m is regular.
 - $m(x + E) = m(E)$ for all $E \in \mathfrak{M}$ and $x \in \mathbb{R}^k$.
 - If μ is any positive translation-invariant Borel measure on \mathbb{R}^k which is finite on compact sets then $\mu(E) = cm(E)$ for some $c \in \mathbb{R}$ and all Borel sets E .
 - $m(T(E)) = \Delta(T)m(E)$, $\Delta(T) \in \mathbb{R}$, for every linear transformation $T : \mathbb{R}^k \rightarrow \mathbb{R}^k$ and $E \in \mathfrak{M}$. More specifically, $\Delta(T) = 1$ if T is a rotation.
- Elements of \mathfrak{M} are **Lebesgue measurable** sets and m is the **Lebesgue measure** on \mathbb{R}^k .

2.21 Remarks

- If m is the Lebesgue measure on \mathbb{R}^k we write $L^1(\mathbb{R}^k)$ instead of $L^1(m)$.
- Instead of $f \in L^1$ on E we write $f \in L^1(E)$ (in the measure space with m restricted to subsets of E).
- If I is an interval in \mathbb{R} and $f \in L^1(I)$ we write $\int_a^b f(x) dx$ instead of $\int_I f dm$.
- If f is continuous on $[a, b]$ then the Riemann and Lebesgue integrals agree.
- Most sets are *not* Borel sets.

2.22 Sufficient Condition for Measure Zero

- If $A \subseteq \mathbb{R}$ and every subset of A is Lebesgue measurable then $m(A) = 0$.
- Every set of positive measure has unmeasurable subsets.

2.23 Determinants

- The $\Delta(T)$ in 2.20 is $|\det T|$.

Continuity Properties of Measurable Functions

We assume in this section that μ is a measure on a locally compact Hausdorff space with the properties listed in 2.14 – μ could be the Lebesgue measure on some \mathbb{R}^k .

2.24 Lusin's Theorem

- f complex measurable, $\mu(A) < \infty$, and $f = 0$ outside A . Then for $\epsilon > 0$ there exists $g \in C_c(X)$ with

$$\mu(\{x : f(x) \neq g(x)\}) < \epsilon.$$

We may pick g so that

$$\sup_{x \in X} |g(x)| \leq \sup_{x \in X} |f(x)|.$$

- If $|f| \leq 1$ then there is a sequence $g_n \in C_c(X)$, $|g_n| \leq 1$, with

$$f(x) = \lim_{n \rightarrow \infty} g_n(x) \text{ a.e.}$$

2.25 Vitali-Carathéodory Theorem

- If $f \in L^1(\mu)$ is real valued and $\epsilon > 0$ then there exists u , upper semicontinuous and bounded from above, and v , lower semicontinuous and bounded from below, such that $u \leq f \leq v$ and $\int_X (v - u) d\mu < \epsilon$.

3 L^p -Spaces

Convex Functions and Inequalities

3.1 Definition

- φ is **convex** on (a, b) if $x, y \in (a, b)$ and $\lambda \in [0, 1]$ imply

$$\varphi((1 - \lambda)x + \lambda y) \leq (1 - \lambda)\varphi(x) + \lambda\varphi(y).$$

That is, the segment between $(x, \varphi(x))$ and $(y, \varphi(y))$ lies above the graph of φ .

- The above is equivalent to $a < s < t < u < b$ implying

$$\frac{\varphi(t) - \varphi(s)}{t - s} \leq \frac{\varphi(u) - \varphi(t)}{u - t}.$$

Note: The mean value theorem for differentiation with the above imply that φ , real differentiable, is convex in (a, b) iff $a < s < t < b$ implies $\varphi'(s) \leq \varphi'(t)$.

3.2 Convexity Implies Continuity

- If φ is convex on (a, b) then φ is continuous on (a, b) .

Note: This relies on the fact that we are working on an *open* segment.

3.3 Jensen's Inequality

- \mathfrak{M} a σ -algebra on Ω , μ a positive measure on it such that $\mu(\Omega) = 1$. If $f \in L^1(\mu)$ is real with $f(\Omega) \subseteq (a, b)$ and φ is convex on (a, b) then

$$\varphi\left(\int_{\Omega} f d\mu\right) \leq \int_{\Omega} (\varphi \circ f) d\mu.$$

Note: $a = -\infty$ or $b = \infty$ are not excluded values.

Note: If $\varphi \circ f \notin L^1(\mu)$ then the integral has value $+\infty$ (see 1.31).

Example 1 For $\varphi(x) = e^x$ we get

$$\exp\left\{\int_{\Omega} f d\mu\right\} \leq \int_{\Omega} e^f d\mu.$$

Example 2 If $\Omega = \{p_1, \dots, p_n\}$ and $\mu(\{p_i\}) = 1/n$, $f(p_i) = x_i$ then the example 1 becomes:

$$\exp\left\{\frac{1}{n} \sum_{i=1}^n x_i\right\} \leq \frac{1}{n} \sum_{i=1}^n e^{x_i}$$

for real x_i . Setting $y_i = e^{x_i}$ we can relate the arithmetic and geometric means of n positive numbers:

$$\left(\prod_{i=1}^n y_i\right)^{1/n} \leq \frac{1}{n} \sum_{i=1}^n y_i.$$

Given this, it is clear why

$$\exp\left\{\int_{\Omega} \log g d\mu\right\} \leq \int_{\Omega} g d\mu$$

are called the arithmetic and geometric means of the positive function g .

Example 3 If $\mu(\{p_i\}) = \alpha_i > 0$ with $\sum \alpha_i = 1$ then we get a more general version of the above:

$$\prod_{i=1}^n y_i^{\alpha_i} \leq \sum_{i=1}^n \alpha_i y_i.$$

3.4 Definition

- $p, q \in (1, \infty)$ are **conjugate exponents** if $p + q = pq$ (or, equivalently, $p^{-1} + q^{-1} = 1$).
- $p \rightarrow 1$ forces $q \rightarrow \infty$ and so 1 and ∞ are regarded as conjugate exponents.
- Many denote p 's conjugate exponent by p' .

3.5 Hölder and Minkowski's Inequalities

p and q are conjugate exponents with $p \in (1, \infty)$ and f and g are measurable with range in $[0, \infty]$:

- Hölder's inequality:

$$\int_X fg \, d\mu \leq \left\{ \int_X f^p \, d\mu \right\}^{1/p} \left\{ \int_X g^q \, d\mu \right\}^{1/q}.$$

If $p = q = 2$ then this is called Schwarz's inequality.

- Minkowski's inequality:

$$\left\{ \int_X (f + g)^p \, d\mu \right\}^{1/p} \leq \left\{ \int_X f^p \, d\mu \right\}^{1/p} + \left\{ \int_X g^p \, d\mu \right\}^{1/p}.$$

Note: Assuming the right hand side of Hölder's inequality has only finite factors, equality holds if and only if there are constants α and β , not both zero, such that $\alpha f^p = \beta g^q$ a.e.

The L^p -spaces

For this section, let X be arbitrary and μ a positive measure.

3.6 Definition

- If $0 \leq p \leq \infty$ and f is a complex measurable function, then the L^p -**norm** of f is

$$\|f\|_p = \left\{ \int_X |f|^p \, d\mu \right\}^{1/p}.$$

$L^p(\mu)$ is the collection of all f for which $\|f\|_p < \infty$ and is called the L^p -**space** of X .

- If u is the Lebesgue measure on \mathbb{R}^k then we write $L^p(\mathbb{R}^k)$ instead of $L^p(\mu)$.
- If μ is the counting measure on a countable set A we denote the L^p -space by $\ell^p(A)$ or just ℓ^p . $x \in \ell^p$ is a sequence $x = \{\xi_n\}$ and

$$\|x\|_p = \left\{ \sum_{n=1}^{\infty} |\xi_n|^p \right\}^{1/p}.$$

3.7 Definition

- For $g : X \rightarrow [0, \infty]$ measurable, let S be the set such that $\mu(g^{-1}((\alpha, \infty])) = 0$. If $S = \emptyset$ then set $\beta = \infty$, else $\beta = \inf S$. Since the countable union of sets of measure zero is a set of measure zero and

$$g^{-1}((\beta, \infty]) = \bigcup_{n=1}^{\infty} g^{-1}\left(\left(\beta + \frac{1}{n}, \infty\right]\right),$$

$\beta \in S$. β is the **essential supremum** of g .

- If f is a complex measurable function then $\|f\|_{\infty}$ is the essential supremum of $|f|$. $L^{\infty}(\mu)$ is the set of all f with $\|f\|_{\infty} < \infty$, it's members called the **essentially bounded** measurable functions on X .
- $L^{\infty}(\mathbb{R}^k)$ is the class of Lebesgue measure essentially bounded functions on \mathbb{R}^k .
- $\ell^{\infty}(A)$ is the class of bounded functions on A .

Note: $|f(x)| \leq \lambda$ holds almost everywhere iff $\lambda \geq \|f\|_{\infty}$.

3.8 Hölder's Inequality With L^p -norms

- If p and q are conjugate exponents, $1 \leq p \leq \infty$, with $f \in L^p(\mu)$ and $g \in L^q(\mu)$ then $fg \in L^1(\mu)$ and $\|fg\|_1 \leq \|f\|_p \|g\|_q$.

3.9 Minkowski's Inequality With $L - p$ -norms

- If $1 \leq p \leq \infty$ and $f, g \in L^p(\mu)$ then $f + g \in L^p(\mu)$ and $\|f + g\|_p \leq \|f\|_p + \|g\|_p$.

3.10 Remarks

- $L^p(\mu)$ is a complex vector space.
- Triangle inequality holds: $\|f - h\|_p \leq \|f - g\|_p + \|g - h\|_p$.

Note: If $f \sim g$ (see 1.35) then $\|f - g\|_p = 0$.

- $L^p(\mu)$ is a complete metric space if we pass to equivalence classes under \sim .

3.11 Completeness of $L^p(\mu)$

- $L^p(\mu)$ is complete for every $1 \leq p \leq \infty$ and every positive measure μ .

3.12 Pointwise Convergence of Cauchy Subsequences

- For $1 \leq p \leq \infty$ and $f_n \rightarrow f$ Cauchy in $L^p(\mu)$, $\{f_n\}$ has a subsequence converging pointwise to f a.e.

3.13 Density of (some) Simple Functions

- For $1 \leq p < \infty$, the set of all complex, measurable, simple functions s with $\mu(\{x : s(x) \neq 0\}) < \infty$ is dense in $L^p(\mu)$.

Approximation by Continuous Functions

For this section X is locally compact and Hausdorff, μ a measure on σ -algebra with the features in 2.14.

3.14 Density of $C_c(X)$

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

3.15 Remarks

- $C_c(\mathbb{R}^k)$ has a metric that does not need to pass to equivalence classes.
- Likewise, the essential supremum there is the same as the supremum: $\|f\|_\infty = \sup_{x \in \mathbb{R}^k} |f(x)|$.
- If $1 \leq p < \infty$ then 3.14 gives $C_c(\mathbb{R}^k)$ is dense in $L^p(\mathbb{R}^k)$, which is complete by 3.11. $L^p(\mathbb{R}^k)$ is the completion of $C_c(\mathbb{R}^k)$ with respect to the $L^p(\mathbb{R}^k)$ metric.

Note: Keep in mind that we are having *different* completions of the same set under different metrics.

- If the distance between $f, g \in C_c(\mathbb{R}^1)$ is given by $\int_{-\infty}^{\infty} |f(t) - g(t)| dt$ then the completion of the resulting metric space is the space of equivalence classes (under \sim) of Lebesgue integrable functions.

Note: Important that the completion of functions on \mathbb{R}^k are again functions on \mathbb{R}^k .

- The L^∞ -completion is $C_0(\mathbb{R}^k)$ of functions which vanish at infinity (see below).

Reminder: For 3.16 and 3.17, please remember in this section that X is **locally compact** and **Hausdorff**.

3.16 Definition

- The complex function f **vanishes at infinity** if for $\epsilon > 0$ there is a K , compact, with $|f| < \epsilon$ on K^c .
- $C_0(X)$ is the class of all continuous functions f on X which vanish at infinity.
- $C_c(X) \subseteq C_0(X)$ with equality when X is compact, in which case $C(X)$ is used for either.

3.17 Completion of $C_c(X)$

- $C_0(X)$ is the completion of $C_c(X)$ relative to the supremum norm metric: $\|f\| = \sup_{x \in X} |f(x)|$.