Measure Theory

Mark Ibrahim
*based on Principles of Real Analysis by Aliprantis and Burkinshaw

Contents

1 Preliminaries

a function $f : A \to B$ is **continuous** $\iff$ f^{-1}(open set) is an open set.

a bounded sequence a_n has a $\limsup$ defined as $\lim\limits_{N\to\infty} \sup\{a_N, a_{N+1}, \dots\}$ "largest tail" a_n converges if $\limsup = \liminf$.

A **Hausdorff** topological space (T2 space) is a topological space where any two points can be seperated by open sets.

$$\max\{a,b\} = \frac{a+b}{2} + \frac{|a-b|}{2}.$$

union of countably sets is countable.

2 Algebras and Measures

2.1 Semirings and Sigma-algebras of Sets (section 12)

2.1.1 semirings

a collection S of subsets of a set X is called a **semiring** if

1. $\emptyset \in S$,
2. $A \cap B \in S$, and
3. $A - B = C_1 \cup \dots C_n$ for $C_1, \dots C_n \in S$.

Any countable union in S can be written as a countable **disjoint** union.

e.g., $S = \{[a,b) | a \leq b \in \mathbb{R}\}$ is a semiring, not an algebra.
* note $[a,a) = \emptyset$.

2.1.2 algebras

a nonempty collection S of subsets of a set X is an **algebra** if

1. $A \cap B \in S$
2. and $A^c \in S$.

Nice properties of algebras are:

- $\emptyset, X \in S$
- S is closed under finite unions and finite intersections.

a σ-**algebra** is an algebra that is closed under countable unions.

Borel sets of a topological space (X, T) [1] is a σ-algebra generated by the open sets.

2.2 Measures on Semirings (section 13)

A function μ from a semiring S to $[0, \infty$ is a **measure on** S if

1. $\mu(\emptyset) = 0$
2. countably additive: $\mu(\cup_{n=1}^{\infty} A_n) = \sum_{n=1}^{\infty} \mu(A_n)$.

• If $A \subseteq B$, ($A, B \in S$), then $\mu(A) \leq \mu(B)$.

Alternatively, can show μ is a measure if and only if "squeeze"

1. $\mu(\emptyset) = 0$
2. $\sum_{i=1}^{n} \mu(A_i) \leq \mu(A)$ if $\cup_{i=1}^{n} A_i \subseteq A$ and A_i are disjoint.
3. $\mu(B) \leq \sum_{n=1}^{\infty} \mu(B_n)$, "subadditive" if $B \subseteq \cup_{n=1}^{\infty} B_n$.

2.2.1 Examples of Measures on S

- **Counting Measure** $\mu(A) = |A|$
- **Dirac Measure** Fix $a \in X$, $\mu_a(A) = 0$ if $a \notin A$, else 1.
- **Lebesgue Stieltjes** For $f : \mathbb{R} \to \mathbb{R}$, increasing, left continuous and $S = \{[a, b) | a \leq b \in \mathbb{R}\}$, $\mu([a, b)) = f(b) - f(a)$.
  - **Lebesgue Measure on** S, denoted λ is defined by $\lambda([a, b)) = b - a$.

2.3 Outer Measures (section 14)

an **outer measure** is a function $\bar{\mu} : P(X) \to [0, \infty$ such that

1. $\bar{\mu}(\emptyset) = 0$
2. if $A \subseteq B$, $\bar{\mu}(A) \leq \mu(B)$
3. countably subadditive: $\bar{\mu}(\cup_{n=1}^{\infty} A_n) \leq \sum_{n=1}^{\infty} \mu(A_n)$

*an outer measure is not always a measure!

A subset E of X is **measurable** if for all $A \subseteq X$,

$$\bar{\mu}(A) = \bar{\mu}(A \cap E) + \bar{\mu}(A \cap E^c)$$

A nicer equivalent way to show E is measurable is by considering all A in S with $\mu^*(A) < \infty$ and showing

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

Nice Properites

- every A in S is μ^*-measurable
- if $\bar{\mu}(E) = 0$, E is measurable
- for E_i measurable and any $A \subseteq X$, $\bar{\mu}(\cup_{i=1}^{n} A \cap E_i) = \sum_{i=1}^{n} \bar{\mu}(A \cap E_i)$

[1](X, T) is a topological space with a set X and subsets T if $\emptyset, X \in T$, and T is closed under unions (even uncountable), finite intersections.

the collection of measurable subsets is denoted by Λ. This collection is a σ-algebra!

Remarkably, the outer measure $\bar{\mu}$ restricted to Λ is a measure!

2.4 Outer Measures generated by a measure (section 15)

The outer measure μ^* generated by a measure μ is defined for any subset A of X,

$$\mu^*(A) = \inf\{\sum_{n=1}^{\infty} \mu(A_n) : A \subseteq \cup_{n=1}^{\infty} A_n \text{ for } A_n \in S\}$$

μ^* is called the Cathéodory extension of μ. By convention $\mu^*(A) = \infty$ if no cover exits in S.

On semiring S, $\mu * = \mu$.

For E_n measurable, if $E_n \uparrow E$, then $\mu^*(E_n) \uparrow \mu^*(E)$ For B_n measurable with $\mu^*(B_n) < \infty$, if $B_n \downarrow B$, then $\mu^*(B_i) \downarrow \mu^*(B)$. k

a measure space if **finite** if $\mu^*(X) < \infty$.

For X a **finite measure** space E is measurable, if and only if

$$\mu^*(E) + \mu^*(E^c) = \mu^*(X)$$

For all $A \subseteq X$, there is a measurable set E such that $A \subseteq E$ and $\mu^*(A) = \mu^*(E)$.

2.4.1 Cantor Set

Cantor set $C = \cap_{n=1}^{\infty} c_n$, where
$c_1 = [0, 1] - (1/3, 2/3)$
$c_2 = c_1 - ((1/9, 2/9) \cup (7/9, 8/9))$

each c_n is closed, because it's a closed set minus open sets.

- C has measure 0
- $|C| = |\mathbb{R}|$
- every point of C is an accumulation point of C

Vitali set is an example of a **non-measurable** subset of $\mathbb{R}$.

2.5 Lebesgue Measure (section 18)

Outer Lebesgue measure λ^* is defined as $\lambda^*(A) = \inf\{\sum_{i=n}^{\infty} \lambda^*(a_n, b_n) : A \subset \cup_{n=1}^{\infty}(a_n, b_n)\}$

* often, we say Lebesgue measure instead of outer Lebesgue measure.

$E \subseteq \mathbb{R}$ is **Lebesgue measurable** $\iff$ there is open $O \subseteq \mathbb{R}$ for each ϵ such that $E \subsetneq O$ and $\lambda(O - E) < \epsilon$.

2.5.1 Regular Borel Measure

For X, a Hausdorff topological space and B the borel sets in X, a measure μ on B is called a **regular borel measure** if

1. $\mu(K) < \infty$ if K is compact
2. for B a borel set, $\mu(B) = \inf\{\mu(O) | O \text{ is open } B \subseteq O\}$
3. for O open, $\mu(O) = \sup\{\mu(K) | K \text{ is compact and } K \subseteq O\}$

1. λ is a regular borel measure
2. Durac measure is a regular borel measures
3. Counting measure is not
4. any **translation invariant** regular borel measure on $\mathbb{R}$ is $c\lambda$ for some $c \in \mathbb{R}^+$

3 Integration: functions

3.1 Measurable Functions (section 16)

3.2 Simple and step functions (section 17)

4 Questions

1. If $A \subseteq B$, is $\mu^*(B - A) = \mu^*(B) - \mu^*(A)$?