

Introduction

Oh hey, it's another one of those textbook notes that I never complete. I've decided to try something different in order to develop my understanding of measure theory. One of the primary for understanding measure theory is Gerald B. Folland's *Real Analysis and Applications* — and one of the benefits it has over a lot of other texts is that it has a significant number of exercises. I'm going to try to do them all — I'll start with Chapters 1–3, and if that goes well enough, continue up through whatever chapter I end up having to tap out at. Interspersed, I will include various notes. I figure that in order to make a subject like measure theory really stick, I need to deal with it consistently.

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Chapter 1

Section 1.2

Definition (σ -Algebra). An algebra of sets on X is a nonempty collection \mathcal{A} of X that is closed under finite unions and complements.

A σ -algebra is an algebra that is closed under countable unions.

Exercise (Exercise 1): A family of sets $\mathcal{R} \subseteq \mathcal{P}(X)$ is called a ring if it is closed under finite unions and differences. A ring that is closed under countable unions is called a σ -ring.

- (a) Rings (σ -rings) are closed under finite (countable) intersections.
- (b) If \mathcal{R} is a ring (σ -ring), then \mathcal{R} is an algebra (σ -algebra) if and only if $X \in \mathcal{R}$.
- (c) If \mathcal{R} is a σ -ring, then $\{E \subseteq X \mid E \in \mathcal{R} \text{ or } E^c \in \mathcal{R}\}$ is a σ -algebra.
- (d) If \mathcal{R} is a σ -ring, then $\{E \subseteq X \mid E \cap F \in \mathcal{R} \text{ for all } F \in \mathcal{R}\}$ is a σ -algebra.

Solution:

- (a) Note that for any $E, F \in \mathcal{R}$, that $E \cap F = E \cup F \setminus ((E \setminus F) \cup (F \setminus E))$.
- (b) Let \mathcal{R} be a σ -ring. Then, \mathcal{R} is a σ -algebra if for some $E \in \mathcal{R}$, $E^c \in \mathcal{R}$. Since $E^c = X \setminus E \in \mathcal{R}$, we have $X \setminus E \cup E \in \mathcal{R}$ as \mathcal{R} is closed under (countable) unions. Hence, $X \in \mathcal{R}$.

If $X \in \mathcal{R}$, then for any $E \in \mathcal{R}$, $E^c = X \setminus E \in \mathcal{R}$. Thus, \mathcal{R} is closed under intersections.

- (c) Since \mathcal{R} is a σ -ring, we only need show that the set $\mathcal{A} = \{E \subseteq X \mid E \in \mathcal{R} \text{ or } E^c \in \mathcal{R}\}$ is closed under complements. We see that for any $E \in \mathcal{A}$, it is the case that either $E \in \mathcal{R}$ or $E^c \in \mathcal{R}$, so $E^c \in \mathcal{A}$ if and only if $E^c \in \mathcal{R}$ or $E \in \mathcal{R}$, so \mathcal{A} is closed under complements.
- (d) Let \mathcal{R} be a σ -ring, and let $\mathcal{A} = \{E \subseteq X \mid E \cap F \in \mathcal{R} \text{ for all } F \in \mathcal{R}\}$. We will show that \mathcal{A} is closed under unions and complements.

Let $E, F \in \mathcal{A}$. Then, for all $S \in \mathcal{R}$, we have $E \cap S \in \mathcal{R}$ and $F \cap S \in \mathcal{R}$. Since \mathcal{R} is closed under unions, we must have $(E \cup F) \cap S = (E \cap S) \cup (F \cap S) \in \mathcal{R}$, so $E \cup F \in \mathcal{A}$.

Let $E \in \mathcal{A}$.

Proposition (Proposition 1.2): The Borel σ -algebra, $\mathcal{B}_{\mathbb{R}}$, is generated by each of the following:

- (a) the open intervals, $\mathcal{E}_1 = \{(a, b) \mid a < b\}$;
- (b) the closed intervals, $\mathcal{E}_2 = \{[a, b] \mid a < b\}$;
- (c) the half-open intervals, $\mathcal{E}_3 = \{(a, b] \mid a < b\}$ or $\mathcal{E}_4 = \{[a, b) \mid a < b\}$;
- (d) the open rays, $\mathcal{E}_5 = \{(a, \infty) \mid a \in \mathbb{R}\}$ or $\mathcal{E}_6 = \{(-\infty, a) \mid a \in \mathbb{R}\}$;
- (e) the closed rays, $\mathcal{E}_7 = \{[a, \infty) \mid a \in \mathbb{R}\}$ or $\mathcal{E}_8 = \{(-\infty, a] \mid a \in \mathbb{R}\}$.

Proof. The elements for \mathcal{E}_j for $j \neq 3, 4$ are open or closed, and the elements of $\mathcal{E}_3, \mathcal{E}_4$ are G_δ sets — for instance,

$$(a, b] = \bigcap_{n=1}^{\infty} \left(a, b + \frac{1}{n} \right).$$

Thus, $\sigma(\mathcal{E}_j) \subseteq \mathcal{B}_{\mathbb{R}}$ for each j . On the other hand, every open set in \mathbb{R} is a countable union of open intervals, so $\mathcal{B}_{\mathbb{R}} \subseteq \sigma(\mathcal{E}_1)$. Thus, $\mathcal{B}_{\mathbb{R}} = \sigma(\mathcal{E}_1)$. \square

Section 1.3

Theorem (Theorem 1.9): Let (X, \mathcal{M}, μ) be a measure space. Let $\mathcal{N} = \{N \in \mathcal{M} \mid \mu(N) = 0\}$, and let $\overline{\mathcal{M}} = \{E \cup F \mid E \in \mathcal{M} \text{ and } F \subseteq N \text{ for some } N \in \mathcal{N}\}$. Then, $\overline{\mathcal{M}}$ is a σ -algebra, and there is a unique extension $\overline{\mu}$ of μ to a complete measure on $\overline{\mathcal{M}}$.

Proof. Since \mathcal{M} and \mathcal{N} are closed under countable unions, so is $\overline{\mathcal{M}}$. If $E \cup F \in \overline{\mathcal{M}}$, with $E \in \mathcal{M}$ and $F \subseteq N \in \mathcal{N}$, we may assume $E \cap N = \emptyset$ — else, we replace F with $F \setminus E$ and N with $N \setminus E$. Then, $E \cup F = (E \cup N) \cap (N^c \cup F)$, so $(E \cup F)^c = (E \cup N)^c \cup (N \setminus F)$. Since $(E \cup N)^c \in \mathcal{M}$ and $N \setminus F \subseteq N$, we have $(E \cup F)^c \in \overline{\mathcal{M}}$, so $\overline{\mathcal{M}}$ is a σ -algebra.

If $E \cup F \in \overline{\mathcal{M}}$ as above, we set $\overline{\mu}(E \cup F) = \mu(E)$. This is well-defined, since if $E_1 \cup F_1 = E_2 \cup F_2$, with $F_j \subseteq N_j \in \mathcal{N}$, then $E_1 \subseteq E_2 \cup N_2$, so $\mu(E_1) \leq \mu(E_2) + \mu(N_2) = \mu(E_2)$. Similarly, $\mu(E_2) \leq \mu(E_1)$. \square

Exercise (Exercise 6): Complete the proof of Theorem 1.9.

Solution: We now wish to show that every subset of a null set in \mathcal{M} is an element of $\overline{\mathcal{M}}$. This can be seen by the fact that for some $F \subseteq N \in \mathcal{N}$, we have $F = \emptyset \cup F \in \overline{\mathcal{M}}$.

To show uniqueness, we suppose there is some other measure $\nu: \overline{\mathcal{M}} \rightarrow [0, \infty)$ such that ν agrees with μ on \mathcal{M} . For some $E \in \mathcal{M}$ and $F \subseteq N \in \mathcal{N}$, we have

$$\begin{aligned} \nu(E \cup F) &= \mu(E) \\ &= \overline{\mu}(E \cup F). \end{aligned}$$

Exercise (Exercise 7): If μ_1, \dots, μ_n are measures on (X, \mathcal{M}) , and $a_1, \dots, a_n \in [0, \infty)$, then $\mu = \sum_{j=1}^n a_j \mu_j$ is a measure on (X, \mathcal{M}) .

Solution: It is clear that $\mu(\emptyset) = 0$. If we have a sequence of disjoint sets $\{E_i\}_{i=1}^{\infty} \subseteq \mathcal{M}$, then

$$\begin{aligned} \mu\left(\bigcup_{i=1}^{\infty} E_i\right) &= \sum_{j=1}^n a_j \mu_j\left(\bigcup_{i=1}^{\infty} E_i\right) \\ &= \sum_{j=1}^n a_j \sum_{i=1}^{\infty} \mu_j(E_i) \\ &= \sum_{i=1}^{\infty} \left(\sum_{j=1}^n a_j \mu_j \right)(E_i) \end{aligned}$$

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

Exercise (Exercise 8): If (X, \mathcal{M}, μ) is a measure space, and $\{E_j\}_{j=1}^{\infty} \subseteq \mathcal{M}$, then $\mu(\liminf E_j) \leq \liminf \mu(E_j)$. Additionally, if $\mu\left(\bigcup_{j \geq 1} E_j\right) < \infty$, then $\mu(\limsup E_j) \geq \limsup \mu(E_j)$.

Solution: Note that

$$\liminf E_j = \bigcup_{n=1}^{\infty} \bigcap_{j=n}^{\infty} E_j.$$

Labeling

$$F_n = \bigcap_{j=n}^{\infty} E_j,$$

we have a sequence of inclusions

$$F_1 \subseteq F_2 \subseteq \cdots,$$

meaning that

$$\mu(\limsup E_j) = \inf_{n \geq 1} \mu(F_n).$$

Note that we have

$$\mu(F_n) = \mu\left(\bigcup_{j=n}^{\infty} E_j\right).$$

Exercise (Exercise 9): If (X, \mathcal{M}, μ) is a measure space, and $E, F \in \mathcal{M}$, then $\mu(E) + \mu(F) = \mu(E \cup F) + \mu(E \cap F)$.

Solution: We have

$$\begin{aligned} \mu(E) &= \mu(((E \cup F) \setminus F) \sqcup E \cap F) \\ \mu(E) &= \mu(E \cup F) - \mu(F) + \mu(E \cap F) \\ \mu(E) + \mu(F) &= \mu(E \cup F) + \mu(E \cap F). \end{aligned}$$

Exercise (Exercise 12): Let (X, \mathcal{M}, μ) be a finite measure space.

- If $E, F \in \mathcal{M}$ with $\mu(E \Delta F) = 0$, then $\mu(E) = \mu(F)$.
- Let $E \sim F$ if $\mu(E \Delta F) = 0$. Then, \sim is an equivalence relation on \mathcal{M} .
- For $E, F \in \mathcal{M}$, define $\rho(E, F) = \mu(E \Delta F)$. Then, $\rho(E, G) \leq \rho(E, F) + \rho(F, G)$, hence ρ defines a metric on the space \mathcal{M}/\sim of equivalence classes.

Solution:

- Note that $E = (E \setminus F) \sqcup (E \cap F)$, and $F = (F \setminus E) \sqcup (F \cap E)$. We also have $\mu(E \Delta F) = \mu(E \setminus F) + \mu(F \setminus E) = 0$, so $\mu(F \setminus E) = \mu(E \setminus F) = 0$. Thus,

$$\begin{aligned} \mu(F) &= \mu(F \cap E) \\ &= \mu(E \cap F) \\ &= \mu(E). \end{aligned}$$

Definition. Let (X, \mathcal{M}, μ) be a measure space.

- If $\mu(X) < \infty$, then μ is called finite.
- If $X = \bigcup_{j \geq 1} E_j$, where $E_j \in \mathcal{M}$ for each j and $\mu(E_j) < \infty$, then μ is called σ -finite.

- If for each $E \in \mathcal{M}$ with $\mu(E) = \infty$, there exists $F \in \mathcal{M}$ with $F \subseteq E$ and $0 < \mu(F) < \infty$, then we say μ is semifinite.

Exercise (Exercise 13): Every σ -finite measure is semifinite.

Solution: Let (X, \mathcal{M}, μ) be a measure space such that $X = \bigcup_{j \geq 1} E_j$, where $\{E_j\}_{j \geq 1} \subseteq \mathcal{M}$ and $\mu(E_j) < \infty$ for each j .

Suppose $\mu(E) = \infty$. Then, we may find $F \subseteq E$ by finding j such that $\mu(E_j) > 0$, and taking $F = E_j \cap E$. Then, it must be the case that $0 < \mu(F) \leq \mu(E_j) < \infty$.

Exercise (Exercise 14): If μ is a semifinite measure and $\mu(E) = \infty$, then for any $C > 0$ there exists $F \subseteq E$ such that $C < \mu(F) < \infty$.

Solution: By the definition of a semifinite measure, there exists $F_1 \subseteq E$ such that $0 < \mu(F_1) < \infty$. We let $\delta_1 = \mu(F_1)$.

Now, it must be the case that $\mu(E \setminus F_1) = \infty$, else $\infty = \mu(E) = \mu(E \setminus F_1) + \mu(F_1) < \infty$, a contradiction.

Hence, there exists $F_2 \subseteq E \setminus F_1$ with $0 < \mu(F_2) < \infty$. We let $\delta_2 = \mu(F_2)$. Similarly, we find $\delta_n = \mu(F_n)$, where $F_n \subseteq E \setminus (F_1 \cup \dots \cup F_{n-1})$.

Now, consider the series $\sum_{n \geq 1} \delta_n = \sum_{n \geq 1} \mu(F_n) = \mu(\bigsqcup_{n \geq 1} F_n)$. This series must diverge, as otherwise we would have $\mu(E) = \mu(\bigsqcup_{n \geq 1} F_n) < \infty$, which is yet again a contradiction.

Thus, for a given $C > 0$, we find N so large such that $\sum_{n=1}^N \delta_n > C$. Then, $F = \bigsqcup_{n=1}^N F_n$ is our desired set.

Exercise (Exercise 15): Let μ be a measure on (X, \mathcal{M}) . Define μ_0 on \mathcal{M} by $\mu_0(E) = \sup\{\mu(F) \mid F \subseteq E \text{ and } \mu(F) < \infty\}$.

- μ_0 is a semifinite measure. It is called the semifinite part of μ .
- If μ is semifinite, then $\mu = \mu_0$.
- There is a measure ν on \mathcal{M} which only assumes the values 0 and ∞ such that $\mu = \mu_0 + \nu$.

Solution:

- Let $E \in \mathcal{M}$ be such that $\mu_0(E) = \infty$. Suppose toward contradiction that μ_0 is not semifinite. Then, for any $F \subseteq E$, it is the case that $\mu(F) = 0$ or $\mu(F) = \infty$, so it would then be the case that $\mu_0(E) = 0$, a contradiction.
- If $\mu(E) < \infty$, then $\mu_0(E) = \mu(E)$, as $E \subseteq E$ and $\mu(E) < \infty$.

If $\mu(E) = \infty$, then it is clear that $\mu_0(E) = \infty$, as for each $C > 0$ there is some $F \subseteq E$ such that $C < \mu(F) < \infty$.

Thus, $\mu = \mu_0$.

- We define the measure ν on \mathcal{M} by taking $\nu(E) = 0$ whenever $\mu(E) < \infty$ and $\nu(E) = \infty$ whenever $\mu(E) = \infty$.

Exercise: Let (X, \mathcal{M}, μ) be a measure space. A set $E \subseteq X$ is called locally measurable if $E \cap A \in \mathcal{M}$ for all $A \in \mathcal{M}$ such that $\mu(A) < \infty$. Let $\tilde{\mathcal{M}}$ be the collection of all locally measurable sets.

It is obvious that $\mathcal{M} \subseteq \tilde{\mathcal{M}}$. If $\mathcal{M} = \tilde{\mathcal{M}}$, then μ is called saturated.

- If μ is σ -finite, then μ is saturated.
- $\tilde{\mathcal{M}}$ is a σ -algebra.
- Define $\tilde{\mu}$ on $\tilde{\mathcal{M}}$ by $\tilde{\mu}(E) = \mu(E)$ if $E \in \mathcal{M}$ and $\tilde{\mu}(E) = \infty$ otherwise. Then, $\tilde{\mu}$ is a saturated measure on $\tilde{\mathcal{M}}$ called the saturation of μ .
- If μ is complete, so is $\tilde{\mu}$.
- Suppose that μ is semifinite. For $E \in \tilde{\mathcal{M}}$, define $\underline{\mu}(E) = \sup\{\mu(A) \mid A \in \mathcal{M} \text{ and } A \subseteq E\}$. Then, $\underline{\mu}$ is a saturated measure on $\tilde{\mathcal{M}}$ that extends μ .
- Let X_1 and X_2 be disjoint uncountable sets, $X = X_1 \sqcup X_2$, and \mathcal{M} the σ -algebra of countable and cocountable sets in X . Let μ_0 be the counting measure on $\mathcal{P}(X_1)$ and define μ on \mathcal{M} by $\mu(E) = \mu_0(E \cap X_1)$. Then,
 - μ is a measure on \mathcal{M} ;

- $\tilde{\mathcal{M}} = \mathcal{P}(X)$;
- and $\tilde{\mu} \neq \underline{\mu}$.

Solution:

- (a) Let μ be σ -finite, and let $E \in \tilde{\mathcal{M}}$. We know that $E \cap A \in \mathcal{M}$ for all $A \in \mathcal{M}$ with $\mu(A) < \infty$. In particular, we can select a disjoint collection $\{A_j\}_{j=1}^{\infty}$ such that $\mu(A_j) < \infty$ and $\bigcup_{j \geq 1} A_j = X$. Thus, since $E = X \cap E$, we must have $E \in \mathcal{M}$ as E is locally measurable.

Section 1.4

Definition. An outer measure on a nonempty set X is a function $\mu^*: \mathcal{P}(X) \rightarrow [0, \infty]$ such that

- $\mu^*(\emptyset) = 0$;
- $\mu^*(A) \leq \mu^*(B)$ if $A \subseteq B$;
- $\mu^*(\bigcup_{j \geq 1} A_j) \leq \sum_{j=1}^{\infty} \mu^*(A_j)$.

Proposition: Let $\mathcal{E} \subseteq \mathcal{P}(X)$, and $\rho: \mathcal{E} \rightarrow [0, \infty]$ be such that $\emptyset \in \mathcal{E}$, $X \in \mathcal{E}$, and $\rho(\emptyset) = 0$. For any $A \subseteq X$, define

$$\mu^*(A) = \inf \left\{ \sum_{j \geq 1} \rho(E_j) \mid E_j \in \mathcal{E} \text{ and } A \subseteq \bigcup_{j \geq 1} E_j \right\}.$$

Then, μ^* is an outer measure.

Proof. For any $A \subseteq X$, there exists $\{E_j\}_{j \geq 1} \subseteq \mathcal{E}$ such that $A \subseteq \bigcup_{j \geq 1} E_j$ (taking $E_j = X$). Clearly, $\mu^*(\emptyset) = 0$.

Additionally, since $A \subseteq B$, we the infimum taken to define $\mu^*(A)$ includes the corresponding set in the definition of $\mu^*(B)$, so $\mu^*(A) \leq \mu^*(B)$.

Suppose $\{A_j\}_{j \geq 1} \subseteq \mathcal{P}(X)$, and let $\varepsilon > 0$. For each j , there exists $\{E_{j,k}\}_{k \geq 1} \subseteq \mathcal{E}$ such that $A_j \subseteq \bigcup_{k \geq 1} E_{j,k}$ and $\sum_{k \geq 1} \rho(E_{j,k}) \leq \mu^*(A_j) + \varepsilon 2^{-j}$. Thus, if $A = \bigcup_{j \geq 1} A_j$, we have $A \subseteq \bigcup_{j,k \geq 1} E_{j,k}$, and $\sum_{j,k \geq 1} \rho(E_{j,k}) \leq \sum_{j \geq 1} \mu^*(A_j) + \varepsilon$, meaning $\mu^*(A) \leq \sum_{j \geq 1} \mu^*(A_j) + \varepsilon$. Since this holds for all $\varepsilon > 0$, we must have $\mu^*(\bigcup_{j \geq 1} A_j) \leq \sum_{j \geq 1} \mu^*(A_j)$. \square

Definition. If μ^* is an outer measure, a set $A \subseteq X$ is called μ^* -measurable if

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

for all $E \subseteq X$. In other words, A is measurable if it serves as a well-behaved “cookie cutter” for any subset of X .

Note that it suffices to show that

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

Definition. If $\mathcal{A} \subseteq \mathcal{P}(X)$ is an algebra, a function $\mu_0: \mathcal{A} \rightarrow [0, \infty]$ is called a premeasure if $\mu_0(\emptyset) = 0$ and, for any sequence of disjoint sets $\{A_j\}_{j=1}^{\infty}$ in \mathcal{A} such that $\bigcup_{j=1}^{\infty} A_j \in \mathcal{A}$, we have

$$\mu_0\left(\bigcup_{j=1}^{\infty} A_j\right) = \sum_{j=1}^{\infty} \mu_0(A_j).$$

A premeasure induces an outer measure on X by

$$\mu^*(E) = \inf \left\{ \sum_{j=1}^{\infty} \mu_0(A_j) \mid A_j \in \mathcal{A}, E \subseteq \bigcup_{j=1}^{\infty} A_j \right\}.$$

Exercise (Exercise 18): Let $\mathcal{A} \subseteq \mathcal{P}(X)$ be an algebra, \mathcal{A}_σ the collection of countable unions of sets in \mathcal{A} , and $\mathcal{A}_{\sigma\delta}$ the collection of countable intersections in \mathcal{A}_σ . Let μ_0 be a premeasure on \mathcal{A} , and let μ^* be the induced outer measure.

- (a) For any $E \subseteq X$ and $\varepsilon > 0$, there exists $A \in \mathcal{A}_\sigma$ with $E \subseteq A$, $\mu^*(A) \leq \mu^*(E) + \varepsilon$.
- (b) If $\mu^*(E) < \infty$, then E is μ^* -measurable if and only if there exists $B \in \mathcal{A}_{\sigma\delta}$ with $E \subseteq B$ and $\mu^*(B \setminus E) = 0$.
- (c) If μ_0 is σ -finite, then the restriction $\mu^*(E) < \infty$ in (b) is superfluous.

Solution:

- (a) We know that

$$\mu^*(E) = \inf \left\{ \sum_{j=1}^{\infty} \mu_0(A_j) \mid A_j \in \mathcal{A}, E \subseteq \bigcup_{j=1}^{\infty} A_j \right\},$$

meaning that, by the definition of infimum, for any $\varepsilon > 0$, there exists some sequence $\{A_j\}_{j=1}^{\infty}$ in \mathcal{A} such that

$$\mu_0\left(\bigcup_{j=1}^{\infty} A_j\right) \leq \mu^*(E) + \varepsilon.$$

Defining $A = \bigcup_{j=1}^{\infty} A_j$, we have $A \in \mathcal{A}_\sigma$.

- (b) Let $\mu^*(E) < \infty$.

Suppose E is measurable. Then, for any $T \subseteq X$, we have

$$\mu^*(T) = \mu^*(E \cap T) + \mu^*(E^c \cap T).$$