Solutions to the book: *H. L. Royden, Real Analysis, 3rd edition*

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Contents

Chapter 1: Set Theory

Problem 1.1.

Show that $\{x : x \neq x\} = \varnothing$.

Proof. Every element x of $\{x : x \neq x\}$ satisfying $x \neq x$, contrary to $x = x$. That is, there are no elements in $\{x : x \neq x\}$, or $\{x : x \neq x\} = \varnothing$. $\square$

Problem 1.2.

Show that if $x \in \varnothing$, *then* x *is a green-eyed lion.*

Proof. $\varnothing \subseteq \{\text{a green-eyed lion}\}$. $\square$

Problem 1.4.

Show that the well-ordering principle implies the principle of mathematical induction. (Hint: Consider the set $\{n \in \mathbb{N} : P(n) \text{ is false}\}$.*)*

Proof (Hint). Suppose that

(1) $P(n)$ be a proposition defined for each $n \in \mathbb{N}$,

(2) $P(1)$ is true,

(3) $[P(n) \Rightarrow P(n+1)]$ is true.

Consider the set

$$S = \{n \in \mathbb{N} : P(n) \text{ is false}\} \subseteq \mathbb{N}.$$

Want to show S *is empty, or the principle of mathematical induction holds.* If S were nonempty, by the well-ordering principle S has a smallest element m. m cannot be 1 by (2). Say $m > 1$. Therefore, $m - 1 \in \mathbb{N}$ and $P(m-1)$ is true by the minimality of m. By (3), $P((m-1)+1) = P(m)$ is true, which is absurd. $\square$

Problem 1.5.

Use mathematical induction to establish that the well-ordering principle. (Hint: Given a set S *of positive integers, let* $P(n)$ *be the proposition 'If* $n \in S$, *then* S

has a least element'.)

Proof (Modified hint).

(1) Given a set S of positive integers, let $P(n)$ be the proposition 'If $m \in S$ for some $m \leq n$, then S has a least element'. Want to show $P(n)$ is true for all $n \in \mathbb{N}$.

   (a) $P(1)$ is true. For $m \in S$ with $m \leq n = 1$, or $m = 1$ by the minimality of $1 \in \mathbb{N}$, S has a least element 1 (m itself) in $\mathbb{N}$.

   (b) Suppose $P(n)$ is true. If $n+1 \in S$, then there are only two possible cases.

      (i) There is a positive integer $m \in S$ less than $n+1$. So $n \geq m \in S$. Since $P(n)$ is true, S has a least element.

      (ii) There is no positive integer $m \in S$ less than $n+1$. In this case $n+1$ is the least element in S.

   In any cases (i)(ii), S has a least element, or $P(n+1)$ is true.

By mathematical induction, $P(n)$ is true for all $n \in \mathbb{N}$.

(2) *Show that the well-ordering principle holds.* Let T be a nonempty subset of $\mathbb{N}$, so there exists a positive integer $k \in T$. Notice that $P(k)$ is true by (1), thus T has a least element since $k \leq k$.

□

Problem 1.9.

Show that $A \subseteq B \Leftrightarrow A \cap B = A \Leftrightarrow A \cup B = B$.

Proof.

(1) $A \subseteq B \Longleftrightarrow A \cap B = A$.

   (a) ($\Longrightarrow$) It suffices to show $A \cap B \supseteq A$. For any $x \in A$, $x \in B$ by $A \subseteq B$, so $x \in A \cap B$, so $A \cap B \supseteq A$.

   (b) ($\Longleftarrow$) $A = A \cap B \subseteq B$.

(2) $A \subseteq B \Leftrightarrow A \cup B = B$.

   (a) ($\Longrightarrow$) It suffices to show $A \cup B \subseteq B$. For any $x \in A \cup B$, $x \in A$ or $x \in B$. By $A \subseteq B$, $x \in B$ or $x \in B$. $x \in B$, so $A \cup B \subseteq B$.

   (b) ($\Longleftarrow$) $A \subseteq A \cup B = B$.

□

Problem 1.11.

Show that $A \subseteq B \Leftrightarrow \widetilde{B} \subseteq \widetilde{A}$.

Proof.

$$\begin{aligned} A \subseteq B &\iff x \in A \Rightarrow x \in B \\ &\iff x \notin B \Rightarrow x \notin A \\ &\iff \widetilde{B} \subseteq \widetilde{A}. \end{aligned}$$

□

Problem 1.14.

Show that

$$B \cap \left[\bigcup_{A \in \mathscr{C}} A \right] = \bigcup_{A \in \mathscr{C}} (B \cap A).$$

Proof.

$$\begin{aligned} x \in B \cap \left[\bigcup_{A \in \mathscr{C}} A \right] &\iff x \in B \text{ and } x \in \bigcup_{A \in \mathscr{C}} A \\ &\iff x \in B \text{ and } x \in A \text{ for some } A \in \mathscr{C} \\ &\iff x \in B \cap A \text{ for some } A \in \mathscr{C} \\ &\iff x \in \bigcup_{A \in \mathscr{C}} (B \cap A). \end{aligned}$$

□

Chapter 2: The Real Number System

Problem 2.1.

Show that $1 \in P$.

Proof. By the field axioms,

(a) $1 \in \mathbb{R}$ such that $1 \neq 0$.

(b) $-1 \in \mathbb{R}$.

(c) $(-1) \cdot (-1) = 1$.

By the axioms of order, $1 = 0$ or $1 \in P$ or $-1 \in P$. Consider three possible cases,

(1) $1 = 0$, contrary to the field axioms $1 \neq 0$.

(2) $1 \in P$.

(3) $-1 \in P$. By the axioms of order, $(-1)(-1) \in P$. Since $(-1)(-1) = 1$ by the field axioms, $1 \in P$. By the axioms of order, $-1 \notin P$, contrary to $-1 \in P$.

By (1)(2)(3), $1 \in P$. $\square$

Applying the similar argument to $\sqrt{-1}$, we get $\sqrt{-1} \notin \mathbb{R}$ as our expectation.

Chapter 3: Lebesgue Measure

§3.1: Introduction

Problem 3.1. (Monotonicity)

If A and B are two sets in $\mathfrak{M}$ with $A \subseteq B$, then $mA \leq mB$. This property is called monotonicity.

Proof. Write

$$B = B \cap X = B \cap (A \cup \widetilde{A}) = (B \cap A) \cup (B \cap \widetilde{A}) = A \cup (B - A).$$

Here $B \cap A = A$ comes from $A \subseteq B$ (Problem 1.9). Notice that A and $B - A$ are disjoint. Since m is a countably additive measure (m is nonnegative) on a σ-algebra $\mathfrak{M}$,

$$mB = mA + m(B - A) \geq mA.$$

□

Problem 3.2. (Countable subadditivity)

Let $\langle E_n \rangle$ be any sequence of sets in $\mathfrak{M}$. Then $m(\bigcup E_n) \leq \sum mE_n$. (Hint: Use Proposition 1.2) This property of a measure is called countable subadditivity.

As the argument in Problem 3.1.

Proof. Since $\langle E_n \rangle$ is a sequence of sets in σ-algebra $\mathfrak{M}$, by Proposition 1.2 and its proof, there is a sequence $\langle F_n \rangle$ of sets in σ-algebra $\mathfrak{M}$ such that all F_n are pairwise disjoint, $F_n \subseteq E_n$, and

$$\bigcup E_n = \bigcup F_n.$$

Since m is a countably additive measure on a σ-algebra $\mathfrak{M}$,

$$m\left(\bigcup E_n\right) = m\left(\bigcup F_n\right) = \sum mF_n \geq \sum mE_n.$$

The last inequality holds by applying Problem 3.1 on $F_n \subseteq E_n$ for any n. □

Problem 3.3.

If there is a set A in $\mathfrak{M}$ such that $mA < \infty$, then $m\varnothing = 0$.

Proof. For such A, write $A = A \cup \varnothing$. A and $\varnothing$ are disjoint. Since m is a countably additive measure on a σ-algebra $\mathfrak{M}$,

$$mA = mA + m\varnothing.$$

Since $mA < \infty$, we can cancel out mA on the both sides to get $m\varnothing = 0$. □

Problem 3.4. (Counting measure)

Let nE be ∞ for an infinite set E and be equal to the number of elements of E for a finite set. Show that n is a countably additive set function that is translation invariant and defined for all sets of real numbers. This measure is called the ***counting measure****.*

Proof.

(1) *Show that n is a countably additive set function.* Note that n is defined on any subset of real numbers since the finiteness is defined on any subset of real numbers. Suppose $\langle E_m \rangle$ is a sequence of disjoint sets of real numbers. We need to show that $n\left(\bigcup E_m\right) = \sum nE_m$.

(2) If E_m is infinite for some $m = k$, then $\bigcup E_m$ is also infinite. Hence, $n\left(\bigcup E_m\right) = \infty$, and $\sum nE_m \geq nE_k = \infty \Longrightarrow \sum nE_m = \infty$.

(3) Suppose all E_n are finite. Note that $\bigcup E_m$ is infinite if and only if all but finitely many $E_m \neq \varnothing$ if and only if $\sum nE_m = \infty$. Besides, if $\bigcup E_m$ is finite, then all but finitely many $E_m = \varnothing$ and thus

$$n\left(\bigcup_m E_m\right) = \sum_{E_m \neq \varnothing} nE_m = \sum_m nE_m < \infty.$$

(4) Since

$$\begin{aligned} n(E+y) &= n(\{x+y : x \in E\}) \\ &= \text{the number of elements } x \in E \\ &= n(E), \end{aligned}$$

n is translation invariant.

□

§3.2: Outer Measure

Problem 3.5.

Let A be the set of rational numbers between 0 and 1, and let $\{I_n\}$ be a finite collection of open intervals covering A. Then $\sum \ell(I_n) \geq 1$.

Idea. If $\{I_n\}$ is a covering of $[0,1]$ then we are done since the length of $[0,1]$ is 1. However, $\{I_n\}$ only covers A and not necessarily covers $[0,1]$. (For example, $\{I_n\} = \left\{\left(-89, \frac{1}{\sqrt{2}}\right), \left(\frac{1}{\sqrt{2}}, 64\right)\right\}$ covers A but not $\frac{1}{\sqrt{2}}$.) Hence, it is natural to consider the closure of A and the closure of I_n. Now $\{\overline{I_n}\}$ is a (closed) covering of $\overline{A} = [0,1]$.

Proof.

$$\begin{aligned}
1 &= m^*[0,1] && \text{(Proposition 3.1)} \\
&= m^*\overline{A} && \text{(A is dense in $[0,1]$)} \\
&\leq m^*\left(\overline{\bigcup I_n}\right) && \text{(Proposition 2.10)} \\
&= m^*\left(\bigcup \overline{I_n}\right) && \text{(Proposition 2.10)} \\
&\leq \sum m^*(\overline{I_n}) && \text{(Proposition 3.2)} \\
&= \sum \ell(\overline{I_n}) && \text{(Proposition 3.1)} \\
&= \sum \ell(I_n). && \text{(Definition of length)}
\end{aligned}$$

□

Supplement 3.5.

Exercise about considering the closure. (Exercise 4.52 in the textbook: *T. M. Apostol, Mathematical Analysis, 2nd edition.*) *Assume that f is uniformly continuous on a bounded set S in $\mathbb{R}^n$. Prove that f must be bounded on S.*

Proof.

(1) Since $f : S \to T$ is uniformly continuous, given any $\varepsilon > 0$, there is $\delta > 0$ such that $d_T(f(x), f(y)) < \varepsilon$ whenever $d_S(x, y) < \delta$. Choose $\varepsilon = 1 > 0$.

(2) For such $\delta > 0$, construct an open covering of $\overline{S} \subseteq \mathbb{R}^n$. Pick a collection $\mathscr{F}$ of open balls $B(a; \delta) \subseteq \mathbb{R}^n$ where a runs over all elements of S. $\mathscr{F}$ covers $\overline{S}$ (by the definition of accumulation points). Since $\overline{S}$ is closed and bounded (since S is bounded), $\overline{S}$ is compact So there is a finite subcollection $\mathscr{F}'$ of

$\mathscr{F}$ also covers $\overline{S}$, say

$$\mathscr{F}' = \{B(a_1;\delta)), B(a_2;\delta), \ldots, B(a_m;\delta)\}.$$

(3) Given any $x \in S \subseteq \overline{S}$, there is some $a_i \in S$ ($1 \leq i \leq m$) such that $x \in B(a_i;\delta)$. In such ball, $d_S(x, a_i) < \delta$. By (1), $\|f(x) - f(a_i)\| < 1$, or $\|f(x)\| < 1 + \|f(a_i)\|$. Therefore, for any $x \in S$,

$$\|f(x)\| < 1 + \max_{1 \leq i \leq m} \|f(a_i)\|.$$

□

Problem 3.6.

Prove Proposition 5: Given any set A and any $\varepsilon > 0$, there is an open set O such that $A \subseteq O$ and $m^*O \leq m^*A + \varepsilon$. There is a $G \in G_\delta$ such that $m^*G = m^*A$.

Proof.

(1) *Use the definition of the outer measure.* By the definition of m^*, for such $\varepsilon > 0$ there exists a countable collection $\{I_n\}$ of open intervals that covers A and

$$m^*A + \varepsilon \geq \sum \ell(I_n).$$

(2) *Construct an open set O.* Let $O = \bigcup I_n \supseteq A$ which is the union of any collection of open sets I_n. By Proposition 2.7, O is open.

(3) *Show that $m^*O \leq m^*A + \varepsilon$.* By Proposition 3.2 and 3.1,

$$m^*O = m^*\left(\bigcup I_n\right) \leq \sum m^*I_n = \sum \ell(I_n) \leq m^*A + \varepsilon.$$

Therefore, given any set A and any $\varepsilon > 0$, there is an open set O such that $A \subseteq O$ and $m^*O \leq m^*A + \varepsilon$.

(4) *Construct $G \in G_\delta$ in a natural way.* Given any $n \in \mathbb{N}$, there exists an open set O_n such that $O_n \supseteq A$ and $m^*O_n \leq m^*A + \frac{1}{n}$. Let

$$G = \bigcap_{n=1}^{\infty} O_n \in G_\delta.$$

(5) *Show that $m^*G = m^*A$.*

   (a) Since $A \subseteq O_n$ for any $n \in \mathbb{N}$, $A \subseteq \bigcap_{n=1}^{\infty} O_n = G$. Thus $m^*A \leq m^*G$.

(b) Since $O_n \supseteq \bigcap_{n=1}^{\infty} O_n = G$ for any $n \in \mathbb{N}$,

$$m^*A + \frac{1}{n} \geq m^*O_n \geq m^*G$$

for any $n \in \mathbb{N}$. Since $n \in \mathbb{N}$ is arbitrary, $m^*A \geq m^*G$.

By (a)(b), $m^*A = m^*G$.

□

Problem 3.7. (Translation invariant)

Prove that m^* is translation invariant.

Proof. Given $E \in \mathfrak{M}$ and $y \in \mathbb{R}$.

(1) $m^*(E+y) \leq m^*E$. Let $\{I_n\}$ of open intervals that cover E. Then $\{I_n+y\}$ of open intervals that cover $E + y$. Notice that the definition of m^* and $\ell(I_n + y) = \ell(I_n)$, then

$$m^*(E + y) \leq \sum \ell(I_n + y) = \sum \ell(I_n).$$

Take the infimum of all such sum $\sum \ell(I_n)$, $m^*(E + y) \leq m^*E$.

(2) $m^*(E) \leq m^*(E + y)$. Similar to (1).

By (1)(2), $m^*(E + y) = m^*E$, that is, m^* is translation invariant. □

Problem 3.8.

Prove that if $m^*A = 0$, then $m^*(A \cup B) = m^*B$.

Proof.

(1) $m^*(A \cup B) \geq m^*B$ since $A \cup B \supseteq B$ and the definition of m^*. (Any covering of $A \cup B$ by open intervals is also a covering of B so that the latter infimum is taken over a larger collection than the former.)

(2) $m^*(A \cup B) \leq m^*B$. By Proposition 3.2,

$$m^*(A \cup B) \leq m^*A + m^*B = 0 + m^*B = m^*B.$$

By (1)(2), $m^*(A \cup B) = m^*B$. □

§3.3: Measurable Sets and Lebesgue Measure

Problem 3.9.

Show that if E is a measurable set, then each translate $E + y$ of E is also measurable.

Proof.

(1) *E is measurable if and only if for each set A, each $y \in \mathbb{R}$,*

$$m^*(A + y) = m^*((A + y) \cap E) + m^*((A + y) \cap \widetilde{E}).$$

   (a) ($\Longrightarrow$) E is measurable and $A + y$ is a set (for any set A and $y \in \mathbb{R}$).

   (b) ($\Longleftarrow$) $A = (A - y) + y$ for any set A and $y \in \mathbb{R}$.

(2) For any set E and $y \in \mathbb{R}$, $\widetilde{E + y} = \widetilde{E} + y$ by the definition of translation.

(3) For any sets E_1, E_2 and $y \in \mathbb{R}$, $(E_1 \cap E_2) + y = (E_1 + y) + (E_2 + y)$ by the definition of translation.

(4) For each set A and $y \in \mathbb{R}$,

$$\begin{aligned}
&m^*((A + y) \cap (E + y)) + m^*((A + y) \cap (\widetilde{E + y})) \\
&= m^*((A + y) \cap (E + y)) + m^*((A + y) \cap (\widetilde{E} + y)) && ((2)) \\
&= m^*((A \cap E) + y) + m^*((A \cap \widetilde{E}) + y) && ((3)) \\
&= m^*(A \cap E) + m^*(A \cap \widetilde{E}) && \text{(Problem 3.7)} \\
&= m^* A && \text{(Measurability of } E\text{)} \\
&= m^*(A + y). && \text{(Problem 3.7)}
\end{aligned}$$

By (1), $E + y$ is measurable.

□

Problem 3.10.

Show that if E_1 and E_2 are measurable, then

$$m(E_1 \cup E_2) + m(E_1 \cap E_2) = mE_1 + mE_2.$$

Proof. Since the collection $\mathfrak{M}$ of measurable sets is a σ-algebra (Theorem 3.10) and m is countable additive (Proposition 3.13),

$$\begin{aligned} m(E_1 \cup E_2) + m(E_1 \cap E_2) &= \left(m(E_1) + m(E_2 \cap \widetilde{E_1})\right) + m(E_2 \cap E_1) \\ &= m(E_1) + \left(m(E_2 \cap \widetilde{E_1}) + m(E_2 \cap E_1)\right) \\ &= m(E_1) + m(E_2). \end{aligned}$$

(E_1 and $E_2 \cap \widetilde{E_1}$ are disjoint. $E_2 \cap \widetilde{E_1}$ and $E_2 \cap E_1$ are disjoint too.) □

Problem 3.11.

Show that the condition $mE_1 < \infty$ is necessary in Proposition 3.14 by giving a decreasing sequence $\langle E_n \rangle$ of measurable sets with $\varnothing = \bigcap E_n$ and $mE_n = \infty$ for each n.

Proof. Set

$$E_n = (n, \infty)$$

for each $n \in \mathbb{N}$.

(1) *$\langle E_n \rangle$ is a decreasing sequence of measurable sets.* $E_n \supseteq E_{n+1}$ by definition. Besides, each E_n is measurable by Lemma 3.11.

(2) $\bigcap E_n = \varnothing$. For each $x \in \mathbb{R}$, $x \notin E_1$ if $x \leq 1$; $x \notin E_{[x]}$ if $x \geq 1$ where $x \mapsto [x]$ is the floor function.

(3) *$mE_n = \infty$ for each n.* The length of each E_n is ∞ (Proposition 3.1).

□

Problem 3.12.

Let $\langle E_n \rangle$ be a sequence of disjoint measurable sets and A any set. Then $m^* \left(A \bigcap \bigcup_{i=1}^\infty E_i\right) = \sum_{i=1}^\infty m^*(A \cap E_i)$.

Proof.

(1) $A \bigcap \bigcup_{i=1}^\infty E_i = \bigcup_{i=1}^\infty (A \cap E_i)$ (Problem 1.14).

(2) $m^* \left(\bigcup_{i=1}^\infty (A \cap E_i)\right) \leq \sum_{i=1}^\infty m^*(A \cap E_i)$ by the subadditivity of m^* (Proposition 3.2).

(3) By Lemma 3.9,

$$m^*\left(\bigcup_{i=1}^{n}(A\cap E_i)\right)=\sum_{i=1}^{n}m^*(A\cap E_i)$$

for any $n\in\mathbb{N}$. Since $\bigcup_{i=1}^{\infty}(A\cap E_i)\supseteq\bigcup_{i=1}^{n}(A\cap E_i)$, $m^*\left(\bigcup_{i=1}^{\infty}(A\cap E_i)\right)\geq m^*\left(\bigcup_{i=1}^{n}(A\cap E_i)\right)$ by the monotonicity of m^*. Thus,

$$m^*\left(\bigcup_{i=1}^{\infty}(A\cap E_i)\right)\geq\sum_{i=1}^{n}m^*(A\cap E_i)$$

for any $n\in\mathbb{N}$. Since $\sum_{i=1}^{n}m^*(A\cap E_i)$ is bounded and increasing (by the non-negativity of m^*),

$$m^*\left(\bigcup_{i=1}^{\infty}(A\cap E_i)\right)\geq\sum_{i=1}^{\infty}m^*(A\cap E_i).$$

By (2)(3), $m^*\left(A\cap\bigcup_{i=1}^{\infty}E_i\right)=\sum_{i=1}^{\infty}m^*(A\cap E_i)$. $\square$

Problem 3.13.

Prove Proposition 15: Let E be a given set. The the following five statements are equivalent:

(i) *E is measurable.*

(ii) *Given $\varepsilon>0$, there is an open set $O\supseteq E$ with $m^*(O-E)<\varepsilon$.*

(iii) *Given $\varepsilon>0$, there is an open set $F\subseteq E$ with $m^*(E-F)<\varepsilon$.*

(iv) *There is an G in G_δ with $G\supseteq E$, $m^*(G-E)=0$.*

(v) *There is an F in F_σ with $F\subseteq E$, $m^*(E-F)=0$.*

If m^*E is finite, the above statements are equivalent to:

(vi) *Given $\varepsilon>0$, there is a finite union U of open intervals such that*

$$m^*(U\Delta E)<\varepsilon.$$

(Hints:

(a) *Show that for $m^*E<\infty$, (i) $\Rightarrow$ (ii) $\Leftrightarrow$ (vi) (cf. Proposition 5).*

(b) *Use (a) to show that for arbitrary sets E, (i) $\Rightarrow$ (ii) $\Rightarrow$ (vi) $\Rightarrow$ (i).*

(c) *Use (b) to show that (i) $\Rightarrow$ (iii).)*

Proof.

(1) *Show that for $m^*E < \infty$, (i) $\Rightarrow$ (ii).* Given $\varepsilon > 0$, there is a countable collections $\{I_n\}$ of open intervals that cover E such that

$$\sum \ell(I_n) < m^*E + \varepsilon = mE + \varepsilon$$

by the definition of the outer measure and measurable sets. Take $O = \bigcup I_n$ be an open set which contains E. Hence,

$$\begin{aligned} m^*(O - E) &= m(O - E) && (O,\ E\text{: measurable}) \\ &= mO - mE \\ &= m\left(\bigcup I_n\right) - mE \\ &\leq \sum \ell(I_n) - mE \\ &< \varepsilon. \end{aligned}$$

(2)

□

§3.4: A Nonmeasurable Set

§3.5: Measurable Functions

§3.5: Measurable Functions

§3.6: Littlewood's Three Principles