Real Analysis Royden - Fourth Edition

Notes + Solved Exercises :)

Latex Symbols

J.B.

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Contents

I LEBESGUE INTEGRATION FOR FUNCTIONS OF A SINGLE REAL VARIABLE

Preliminaries on Sets, Mappings, and Relations

Definition. *A relation R on a set X is called an **equivalence relation** provided:*

(i) xRx *for all* $x \in X$ *(reflexive),*

(ii) xRy *implies* yRx *for all* $x, y \in X$ *(symmetric),*

(iii) xRy *and* yRz *imply* xRz *for all* $x, y, z \in X$ *(transitive).*

Partial Ordering on a set X. *A relation R on a nonempty set X is called a **partial ordering** provided:*

(i) xRx *for all* $x \in X$ *(reflexive),*

(ii) xRy *and* yRx *imply* $x = y$ *for all* $x, y \in X$ *(antisymmetric),*

(iii) xRy *and* yRz *imply* xRz *for all* $x, y, z \in X$ *(transitive).*

*A subset E of X is **totally ordered** provided either xRy or yRx for all $x, y \in E$. A member x of X is said to be an **upper bound** for a subset E of X provided that*

$$yRx \text{ for all } y \in E.$$

*A member x of X is said to be **maximal** provided that*

$$xRy \text{ implies that } y = x \text{ for } y \in X.$$

Strict Partial Ordering on a set X. *A relation R on a nonempty set X is called a **strict partial ordering** provided:*

(i) not xRx *for all* $x \in X$ *(irreflexive),*

(ii) xRy *implies not* yRx *for all* $x, y \in X$ *(asymmetric),*

(iii) xRy *and* yRz *imply* xRz *for all* $x, y, z \in X$ *(transitive).*

A subset E of X is ***strictly totally ordered*** *provided either xRy or yRx if $x \neq y$ for all $x, y \in E$.*

Zorn's Lemma. *Let X be a partially ordered set for which every totally ordered subset has an upper bound. Then X has a maximal member.*

Every vector space has a basis.

Proof. Let V be any vector space, and let L be the collection of all linearly independent subsets of V. L is nonempty as the singleton sets are linearly independent. Define a partial order on L in the form $C \subseteq C'$ for $C, C' \in L$. For any chain (a totally ordered subset of a partially ordered set) $\mathcal{C}$ of L, where $\mathcal{C}$ consists of the sets $C_1 \subseteq C_2 \subseteq \cdots$, we can construct a linearly independent set $C' = \bigcup_{C \in \mathcal{C}} C$ that is an upper bound of $\mathcal{C}$. By Zorn's Lemma, L has a maximal element, say M. This collection M is a basis for V. To show this, suppose by contradiction that there exists a vector $v \in V$ s.t. $v \notin$ Span$\{M\}$. Then $v \cup M$ is linearly independent and $M \subseteq v \cup M$, a contradiction to the fact that M is maximal. $\square$

Chapter 1

The Real Numbers: Sets, Sequences, and Functions

Contents

1.1 The Field, Positivity, and Completeness Axioms

The field axioms
Consider $a, b, c \in \mathbb{R}$:

1. Closure of Addition: $a + b \in \mathbb{R}$.
2. Associativity of Addition: $(a + b) + c = a + (b + c)$.
3. Additive Identity: $0 + a = a + 0 = a$.
4. Additive Inverse: $(-a) + a = a + (-a) = 0$.
5. Commutativity of Addition: $a + b = b + a$.
6. Closure of Multiplication: $ab \in \mathbb{R}$.
7. Associativity of Multiplication: $(ab)c = a(bc)$.
8. Distributive Property: $a(b + c) = ab + ac$.
9. Commutativity of Multiplication: $ab = ba$.
10. Multiplicative Identity: $1a = a1 = a$.
11. No Zero Divisors: $ab = 0 \implies a = 0$ or $b = 0$.

12. Multiplicative Inverse: $a^{-1}a = aa^{-1} = 1$.

13. Nontriviality: $1 \neq 0$.

The positivity axioms
The set of **positive numbers**, $\mathcal{P}$, has the following two properties:

P1 If a and b are positive, then ab and $a+b$ are both positive.

P2 For a real number a, exactly one of the three is true: a is positive, $-a$ is positive, $a = 0$.

We call a nonempty set I of real numbers an **interval** provided for any two points in I, all the points that lie between these two points also lie in I. That is, $\forall x, y \in I, \lambda x + (1-\lambda)y \in I$ for $\lambda \in [0,1]$.

The completeness axiom
A nonempty set E of real numbers is said to be **bounded above** provided there is a real number b such that $x \leq b$ for all $x \in E$: the number b is called an **upper bound** for E. We can similarly define a set being **bounded below** and having a **lower bound**. A set that is bounded above need not have a largest member.

The Completeness Axiom. *Let E be a nonempty set of real numbers that is bounded above. The among the set of upper bounds for E there is a smallest, or least, upper bound. (This least upper bound is called the* ***supremum*** *of E. Also, it can be shown that any nonempty set E that is bounded below has a greatest lower bound, called the* ***infimum*** *of E).*

The extended real numbers
The extended real numbers: $\mathbb{R} \cup \{-\infty, \infty\}$
Every set of real numbers has a supremum and infimum that belongs to the extended real numbers.

PROBLEMS

1. For $a \neq 0$ and $a \neq 0$, show that $(ab)^{-1} = a^{-1}b^{-1}$.

$$
\begin{aligned}
(ab)(ab)^{-1} &= 1 && \text{by multiplicative inverse} \\
a(b(ab)^{-1}) &= 1 && \text{by associativity of multiplication} \\
a^{-1}a(b(ab)^{-1}) &= a^{-1}1 && \\
1(b(ab)^{-1}) &= a^{-1}1 && \text{by multiplicative inverse} \\
b(ab)^{-1} &= a^{-1} && \text{by multiplicative identity} \\
b^{-1}b(ab)^{-1} &= b^{-1}a^{-1} && \\
1(ab)^{-1} &= b^{-1}a^{-1} && \text{by multiplicative inverse} \\
(ab)^{-1} &= b^{-1}a^{-1} && \text{by multiplicative identity} \\
(ab)^{-1} &= a^{-1}b^{-1} && \text{by commutativity of multiplication}
\end{aligned}
$$

2. Verify the following:

(i) For each real number $a \neq 0$, $a^2 > 0$. In particular, $1 > 0$ since $1 \neq 0$ and $1 = 1^2$.
By positivity axiom P2, since $a \neq 0$, either a is positive or $-a$ is positive.
In the case a is positive, a^2 is positive by positivity axiom P1.
In the case $-a$ is positive, $(-a)(-a)$ is positive by P1.

$$\begin{aligned}
(-a)(-a) &= (-a)(-a) + a(0) && \text{by additive identity} \\
&= (-a)(-a) + a(-a + a) && \text{by additive inverse} \\
&= (-a)(-a) + a(-a) + a(a) && \text{by distributive property} \\
&= (-a + a)(-a) + a^2 && \text{by distributive property} \\
&= 0(-a) + a^2 && \text{by additive inverse} \\
&= a^2 && \text{by additive identity}
\end{aligned}$$

Therefore a^2 is positive by equality.

(ii) For each positive number a, its multiplicative inverse a^{-1} also is positive.
The multiplication of two positive numbers is positive by positivity axiom P1.
The multiplication of two non-positive numbers is positive: by reformulating the previous result from (i), we can see $0 < (-a)(-b) = ab$ for $a, b \neq 0$.
The multiplication of a positive number and a non-positive number is not positive. To see this, suppose a is positive and b is not positive, but ab is positive. By P1 and P2, $a(-b)$ is also positive. By P1, $ab + a(-b)$ is positive. However,

$$ab + a(-b) = a(b - b) = a(0) = 0.$$

This is a contradiction to P2. Therefore ab is not positive.
The result from (i) shows that 1 is positive. By multiplicative inverse, $aa^{-1} = 1 > 0$. Therefore a^{-1} must be positive because a is positive.

(iii) If $a > b$, then

$$ac > bc \text{ if } c > 0 \text{ and } ac < bc \text{ if } c < 0.$$

Proof that $a(-1) = -a$ for a real number a:

$$a + (-1)a = 1a + (-1)a = (1 + -1)a = 0a = 0.$$

$a > b$ implies that $a - b$ is positive.
If c is positive, then $(a - b)c = ac - bc$ is positive, and $ac > bc$.
If c is not positive, then $(a - b)c = ac - bc$ is not positive, and $-(ac - bc) = bc - ac$ is positive, so $bc > ac$.

3. For a nonempty set of real numbers E, show that $\inf E = \sup E$ iff E consists of a single point.

($\Longrightarrow$) Suppose $\inf E = \sup E$.

Then $\inf E \leq x \leq \sup E$ for all $x \in E$. But this implies $x = \inf E = \sup E$ for all $x \in E$, so E consists of the single point x.

($\Longleftarrow$) Suppose $E = x$ is a singleton set.

Clearly x is an upper bound and a lower bound for E, as $x \leq x$. By completeness of the reals, there exists $\sup E$ and $\inf E$ s.t. $x \leq \inf E \leq x \leq \sup E \leq x$, as $\inf E$ is the greatest lower bound, and $\sup E$ is the least upper bound. Therefore $\inf E = \sup E$.

4. Let a and b be real numbers.

   (i) Show that if $ab = 0$, then $a = 0$ or $b = 0$.

   Contrapositive: Let $a \neq 0$ and $b \neq 0$. In 2.(ii), it was shown that the multiplication of two nonzero numbers is either positive or not positive. Therefore $ab \neq 0$.

   (ii) Verify that $a^2 - b^2 = (a - b)(a + b)$ and conclude from part (i) that if $a^2 = b^2$, then $a = b$ or $a = -b$.

$$
\begin{aligned}
(a-b)(a+b) &= (a-b)(a) + (a-b)(b) && \text{by distributive property} \\
&= (a)(a) + (-b)(a) + (a)(b) + (-b)(b) && \text{by distributive property} \\
&= (a)(a) + (-b+b)(a) + (-b)(b) && \text{by distributive property} \\
&= (a)(a) + (-b)(b) && \text{by additive inverse} \\
&= a^2 - b^2
\end{aligned}
$$

   Suppose $a^2 = b^2$. Then $(a - b)(a + b) = a^2 - b^2 = 0$, and by (i), $(a - b) = 0 \implies a = b$ or $(a + b) = 0 \implies a = -b$.

   (iii) Let c be a positive real number. Define $E = \{x \in \mathbb{R} \mid x^2 < c\}$. Verify that E is nonempty and bounded above. Define $x_0 = \sup E$. Show that $x_0^2 = c$. Use part (ii) to show that there is a unique $x > 0$ for which $x^2 = c$. It is denoted by $\sqrt{c}$.

   We can consider $0 \in \mathbb{R}$. $0^2 = 0 < c$, so $0 \in E$ and E is nonempty. Also, $c+1$ is a real number and an upper bound for E; thus by the completeness axiom, E has a supremum, say x_0. We can see that for any upper bound b of E, $x \leq x_0 \leq b$ for all $x \in E$. Then $x^2 \leq x_0^2 \leq b^2$ implies $x_0^2 = c$, else x_0 is not the supremum.

   Suppose there exists $x_1, x_2 > 0$ such that $x_1^2 = c$ and $x_2^2 = c$. This implies $x_1^2 = x_2^2$, and by part (ii), $x_1 = x_2$ or $x_1 = -x_2$. Because x_1, x_2 are positive, $x_1 = x_2$.

5. Let a, b, c be real numbers s.t. $a \neq 0$ and consider the quadratic equation

$$ax^2 + bx + c = 0, x \in \mathbb{R}.$$

   (i) Suppose $b^2 - 4ac > 0$. Use the Field Axioms and the preceding problem to complete the square and thereby show that this equation has exactly two solutions given by

$$x = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \text{ and } x = \frac{-b - \sqrt{b^2 - 4ac}}{2a}.$$

$$
\begin{aligned}
ax^2 + bx + c &= 0 \\
4a(ax^2 + bx + c) &= 4a(0) \\
4a^2x^2 + 4abx + 4ac &= 0 && \text{by distributive property} \\
4a^2x^2 + 4abx + 4ac + b^2 - b^2 &= 0 && \text{by additive inverse} \\
4a^2x^2 + 4abx + b^2 &= b^2 - 4ac \\
(2ax + b)^2 &= b^2 - 4ac
\end{aligned}
$$

   By 4(iii), because $b^2 - 4ac > 0$, there is a unique $y > 0$ for which $y^2 = b^2 - 4ac$. It is denoted by $y = \sqrt{b^2 - 4ac}$.

By 4(ii), $(2ax+b)^2 = b^2 - 4ac = y^2$ implies $(2ax+b) = \sqrt{b^2-4ac} = y$ or $(2ax+b) = -\sqrt{b^2-4ac} = -y$.

$$\begin{aligned} 2ax+b &= \pm\sqrt{b^2-4ac} \\ 2ax &= -b \pm \sqrt{b^2-4ac} \\ x &= \frac{-b \pm \sqrt{b^2-4ac}}{2a}. \end{aligned}$$

6. Use the Completeness Axiom to show that every nonempty set of real numbers that is bounded below has an infimum and that

$$\inf E = -\sup\{-x \mid x \in E\}.$$

Let E be a set that is bounded below; that is, there exists $l \in \mathbb{R}$ such that $l \leq x$ for all $x \in E$. Then $-l \geq -x$ for all $x \in E$, and $-l$ is an upper bound for $-E = \{-x \mid x \in E\}$. Therefore the set $-E$ is bounded above, and by the completeness axiom, there exists a least upper bound $c = \sup(-E)$. Then for any upper bound u of $-E$, $u \geq c \geq -x$ for all $x \in E$. Then $-u$ is a lower bound of E, and $-u \leq c \leq x$ for all $x \in E$, and c is the greatest lower bound and thus infimum of E.

7. For real numbers a and b, verify the following:

(i) $|ab| = |a||b|$.
We have

$$|ab| = \begin{cases} ab & \text{if } ab \geq 0, \\ -(ab) & \text{if } ab < 0. \end{cases}$$

The case where either a or b are zero is trivial. In problem 2(ii), it was shown that $ab > 0$ if a, b are the same sign, and $ab < 0$ if a, b are opposite signs.

Case $a, b > 0$: Then $ab > 0$ so $|ab| = ab$, and $|a| = a$ and $|b| = b$ so $|a||b| = ab$.

Case $a, b < 0$: Then $ab > 0$ so $|ab| = ab$, and $|a| = -a$ and $|b| = -b$ so $|a||b| = (-a)(-b) = ab$.

Case $a < 0, b > 0$: Then $ab < 0$ so $|ab| = -(ab) = (-1)ab$, and $|a| = -a = (-1)a$ and $|b| = b$ so $|a||b| = (-1)ab$.

(ii) $|a+b| \leq |a| + |b|$.
The case where both $a, b = 0$ is trivial.

Case $a, b > 0$: Then $a+b > 0$, so $|a+b| = a+b$ and $|a|+|b| = a+b$.

Case $a > 0, b = 0$: Then $a+b = a+0 = a > 0$, so $|a+b| = a$ and $|a|+|b| = a+0 = a$.

Case $a < 0, b = 0$: Then $a+b = a+0 = a < 0$, so $|a+b| = -a$ and $|a|+|b| = -a+0 = -a$.

Case $a, b < 0$: Then $a+b < 0$, so $|a+b| = -(a+b) = -a-b$ and $|a|+|b| = -a-b$.

That is, equality holds except for the case where a, b are nonzero opposite signs:

Case $a > 0, b < 0$: $|a+b| \in \{a+b, -(a+b)\}$.

$b < 0 < -b \implies a+b < a < a-b$, and $-a < 0 < a \implies -(a+b) = -a-b < -b < a-b$.

$|a|+|b| = a-b$, so $|a+b| < |a|+|b|$.

(iii) For $\epsilon > 0$,

$$|x-a| < \epsilon \text{ iff } a-\epsilon < x < a+\epsilon.$$

We have
$$|x-a| = \begin{cases} x-a & \text{if } x-a \geq 0, \\ -(x-a) & \text{if } x-a < 0. \end{cases}$$
($\Longrightarrow$) Suppose $|x-a| < \epsilon$.
Then $x - a < \epsilon$ and $a - x < \epsilon$.
Then $x < a + \epsilon$ and $a - \epsilon < x$.
($\Longleftarrow$) Suppose $a - \epsilon < x < a + \epsilon$.
Then
$$a - \epsilon - a < x - a < a + \epsilon - a$$
$$-\epsilon < x - a < \epsilon$$
So $x - a < \epsilon$ and $-\epsilon < x - a \implies -(x-a) < \epsilon$, so $|x - a| < \epsilon$.

1.2 The Natural and Rational Numbers

Definition. *A set E of real numbers is said to be* ***inductive*** *provided it contains 1 and if the number x belongs to E, the number $x+1$ also belongs to E.*
The set of **natural numbers**, denoted by $\mathbb{N}$, is defined to be the intersection of all inductive subsets of $\mathbb{R}$.

Theorem 1. *Every nonempty set of natural numbers has a smallest member.*

Proof. Let E be a nonempty set of natural numbers. Since the set $\{x \in \mathbb{R} \mid x \geq 1\}$ is an inductive set, by definition of intersection, $\mathbb{N} \subseteq \{x \in \mathbb{R} \mid x \geq 1\}$, and the natural numbers are bounded below by 1. Therefore E is bounded below by 1. By the Completeness Axiom, E has an infimum; let $c = \inf E$. Since $c + 1$ is not a lower bound for E, there is an $m \in E$ for which $m < c + 1$. We claim that m is the smallest member of E. Otherwise, there is an $n \in E$ for which $n < m$. Since $n \in E$, $c \leq n$. Thus $c \leq n < m < c + 1$ and therefore $m - n < 1$. Therefore the natural number m belongs to the interval $(n, n+1)$. However, an induction argument shows that $(n, n+1) \cap \mathbb{N} = \emptyset$ (Problem 8). This is a contradiction to $m \in E$. Therefore m is the smallest member of E. $\square$

Archimedean Property. *For each pair of positive real numbers a and b, there is a natural number n for which $na > b$. This can be reformulated: for each positive real number ϵ, there is a natural number n for which $\frac{1}{n} < \epsilon$.*

The set of **integers**, denoted $\mathbb{Z}$, is defined to be the set of numbers consisting of the natural numbers, their negatives, and zero.

Consider the number 2. From problem 4(iii), there is a unique $x > 0$ for which $x^2 = 2$. It is denoted by $\sqrt{2}$. This number is not rational. Suppose that x is rational: then there exist $p, q \in \mathbb{Z}$ such that $(\frac{p}{q})^2 = 2$. Then $p^2 = 2q^2$. By the unique prime factorizations of p and q, p^2 is divisible by 2^{2k} for some $k \in \mathbb{Z}_{\geq 0}$, while $2q^2$ is divisible by $2 \cdot 2^{2j} = 2^{2j+1}$ for some $j \in \mathbb{Z}_{\geq 0}$. $2^{2k} \neq 2^{2j+1}$ for any combinations of k, j so $p^2 = 2q^2$ is not possible, and $\sqrt{2}$ is not rational.

Definition. *A set E of real numbers is said to be* ***dense*** *in $\mathbb{R}$ provided that between any two real numbers there lies a member of E.*

Theorem 2. *The rational numbers are dense in $\mathbb{R}$.*

Proof. Let $a, b \in \mathbb{R}$ with $a < b$.
Case $a > 0$:
By the Archimedean Property, for $(b-a) > 0$, there exists $q \in \mathbb{N}$ for which $\frac{1}{q} < b - a$.
Again by the Archimedean Property, for $b, \frac{1}{q} > 0$, there exists $n \in \mathbb{N}$ for which $n(\frac{1}{q}) > b$.
Therefore the set $S = \{n \in \mathbb{N} \mid \frac{n}{q} \geq b\}$ is nonempty. Because S is a set of natural numbers, by Theorem 1, S has a smallest member p. Noticing $\frac{1}{q} < b - a < b$, we see that $1 \notin S$ and $p > 1$. Therefore $p - 1$ is a natural number (Problem 9). Because p is the smallest member of S, $p - 1 \notin S$ and $\frac{(p-1)}{q} < b$. Also,

$$a = b - (b - a) < \frac{p}{q} - (\frac{1}{q}) = \frac{(p-1)}{q}.$$

Therefore the rational number $\frac{(p-1)}{q}$ lies between a and b.
Case $a < 0$:
By the Archimedean Property, for $1, -a > 0$, there exists $n \in \mathbb{N}$ for which $n(1) > -a$, which implies $n + a > 0$, and $b > a$ implies $n + b > n + a > 0$. Then we can use the first case to show that there exists a rational number r such that $n + a < r < n + b$. Therefore the rational number $r - n$ lies between a and b. $\square$

PROBLEMS

8. Use an induction argument to show that for each natural number n, the interval $(n, n+1)$ fails to contain any natural number.

   For $n \in \mathbb{N}$, let $P(n)$ be the assertion that $(n, n+1) \cap \mathbb{N} = \emptyset$.

   $P(1)$: $(1, 2) = \{x \mid 1 < x < 2\}$. Suppose there exists a natural number $q \in (1, 2)$. Then $q > 1$ and by problem 9, $q - 1$ is a natural number. However, $1 < q < 2 \implies 0 < q - 1 < 1$, which is a contradiction to the fact that the natural numbers are bounded below by 1 (Theorem 1). Therefore there are no natural numbers in $(1, 2)$.

   Suppose $P(k)$ is true for some natural number k.

   $P(k+1)$: Suppose there exists a natural number $p \in (k+1, (k+1)+1)$; that is, $k+1 < p < k+2$.

   Case $p = 1$: then $k + 1 < 1 < k + 2$. but $k \in \mathbb{N}$ so $k + 1 > 1$. Thus $p = 1$ is not possible.

   Case $p > 1$: then by problem 9, $p - 1 \in \mathbb{N}$, so $k + 1 < p < k + 2 \implies k < p - 1 < k + 1$. This is a contradiction to $P(k)$, the assumption that there are no natural numbers between $(k, k + 1)$. Therefore $P(k + 1)$ is true.

9. Use an induction argument to show that if $n > 1$ is a natural number, then $n - 1$ also is a natural number. The use another induction argument to show that if m and n are natural numbers with $n > m$, then $n - m$ is a natural number.

   For $n \in \mathbb{N}$, let $P(n)$ be the assertion that $n = 1$ or $n - 1 \in \mathbb{N}$.

   $P(1)$: $1 = 1$, true.

   Suppose $P(k)$ is true for some $k \in \mathbb{N}$.

   $P(k + 1)$: $(k + 1) - 1 = k \in \mathbb{N}$, true.

For $n \in \mathbb{N}$, let $Q(n)$ be the assertion that for all $m \in \mathbb{N}$ such that $n > m$, then $n - m \in \mathbb{N}$.

$Q(1)$: true trivially, because there are no natural numbers less than 1.

Suppose $Q(k)$ is true for some $k \in \mathbb{N}$; that is, for all $m \in \mathbb{N}$ such that $k > m$, then $k - m \in \mathbb{N}$.

$Q(k+1)$: For all the m from $Q(k)$, we have $(k+1) > k > m$.

We want to show that $(k+1) - m \in \mathbb{N}$.

This is clearly true for $m = 1$ because $(k+1) - 1 = k \in \mathbb{N}$. Otherwise, $m > 1$, so by $P(m)$, $m - 1 \in \mathbb{N}$ and $(k+1) - m = k - (m-1)$. $Q(k)$ is true tells us that because $(m-1) \in \mathbb{N}$ and $k > m > m - 1$, then $k - (m-1) \in \mathbb{N}$. Therefore $Q(k+1)$ is true.

10. Show that for any real number r, there is exactly one integer in the interval $[r, r+1)$.

    This is trivial if $r \in \mathbb{Z}$.

    Consider the smallest integer p less than $[r, r+1)$. Then $p < r < r+1$ (and $r < p+1$, because $r = p+1 \implies r \in \mathbb{Z}$ and $r > p+1 \implies p$ is not the smallest integer less than $[r, r+1)$), therefore $r < p+1 < r+1$. Because the integers are inductive, $p+1 \in \mathbb{Z}$.

    To show that there is not more than one integer between $[r, r+1)$: let q be a natural number such that $r \leq q < r+1$. Then $q - 1 < r \leq q$ and $q < r+1 \leq q+1$. From problem 8, we see that there are no integers between $(q-1, q)$ and $(q, q+1)$, so there is only one integer in $(q-1, q) \cup q \cup (q, q+1) \supseteq [r, r+1)$.

11. Show that any nonempty set of integers that is bounded above has a largest member.

    Let E be a nonempty set of integers that is bounded above. By the completeness axiom, there exists $c = \sup E$. That is, $x \leq c$ for all $x \in E$. Then $c - 1 < z \leq c$ for some $z \in E$ because $c - 1$ is not an upper bound of E. Suppose c is not in E. Then $c - 1 < z < c$. This implies that $c - 1 < z < w \leq c$ for some $w \in E$ because z is not an upper bound of E. But then there exists two integers in the interval $(c-1, c]$, which is a contradiction to problem 10. Therefore c is an element of E, and it is the largest member.

12. Show that the irrational numbers are dense in $\mathbb{R}$.

    Choose any two real numbers a, b and any irrational number z. Then $\frac{a}{z}, \frac{b}{z}$ are real numbers. By density of the rationals in $\mathbb{R}$, there exists a rational r such that $\frac{a}{z} < r < \frac{b}{z}$. This implies $a < rz < b$, where rz is an irrational number.

    Proof that rz is irrational:
    Let $r = \frac{p}{q}$ and suppose that rz is rational; then $rz = \frac{m}{n}$.

    $$\begin{aligned} \frac{p}{q} z &= \frac{m}{n} \\ z &= \frac{m}{n}\frac{q}{p} \\ z &= \frac{mq}{np} \end{aligned}$$

    Then z is rational, a contradiction.

13. Show that each real number is the supremum of a set of rational numbers and also the supremum of a set of irrational numbers.

Choose any real number a. Let $S = \{r \in \mathbb{Q} \mid r \leq a\}$. Then a is an upper bound for this set. To show that a is the supremum, suppose by contradiction that it is not. Then there exists $c \in \mathbb{R}$ such that $r \leq c < a$. However, the rational numbers are dense in $\mathbb{R}$, so there exists a rational between c and a, a contradiction to the assumption that c is an upper bound to S.

The same argument can easily be shown for the irrational numbers.

14. Show that if $r > 0$, then, for each natural number n, $(1 + r)^n \geq 1 + n \cdot r$.

    Let $r > 0$.

    For $n \in \mathbb{N}$, let $P(n)$ be the assertion that $(1 + r)^n \geq 1 + n \cdot r$.

    $P(1)$: $(1 + r)^1 = 1 + 1 \cdot r$, true.

    Suppose $P(k)$ is true for some $k \in \mathbb{N}$. Then $(1 + r)^k \geq 1 + k \cdot r$.

    $P(k + 1)$:

    $(1+r)^{k+1} = (1+r)^k(1+r) \geq (1+kr)(1+r) = 1+kr+r+kr^2 > 1+kr+r = 1+(k+1)\cdot r.$

15. Use induction arguments to prove that for every natural number n,

    (i)
    $$\sum_{j=1}^{n} j^2 = \frac{n(n+1)(2n+1)}{6},$$

    $P(1)$: $\sum_{j=1}^{1} j^2 = 1 = \dfrac{1(1+1)(2+1)}{6}$.
    Suppose $P(k)$ is true for $k \in \mathbb{N}$.
    $P(k + 1)$:

    $$\begin{aligned}\sum_{j=1}^{k+1} j^2 &= \sum_{j=1}^{k} j^2 + (k+1)^2 \\ &= \frac{k(k+1)(2k+1)}{6} + (k+1)^2 \\ &= \frac{k(2k^2+k+2k+1)}{6} + \frac{6(k^2+2k+1)}{6} \\ &= \frac{(2k^3+k^2+2k^2+k)+(6k^2+12k+6)}{6} \\ &= \frac{2k^3+9k^2+13k+6}{6} \\ &= \frac{(k+1)(2k^2+7k+6)}{6} \\ &= \frac{(k+1)(k+2)(2(k+1)+1)}{6}.\end{aligned}$$

    (ii)
    $$1^3 + 2^3 + \cdots + n^3 = (1 + 2 + \cdots + n)^2,$$

    $P(1)$: $a^3 = 1 = (1)^3$.
    Suppose $P(k)$ is true for $k \in \mathbb{N}$.

$P(k+1)$:

$$\begin{aligned}
1^3+2^3+\cdots+(k+1)^3 &= 1^3+2^3+\cdots+k^3+(k+1)^3 \\
&= (1+2+\cdots+k)^2+(k+1)^3 \\
&= \left(\frac{k(k+1)}{2}\right)^2+(k+1)^3 \\
&= \frac{k^2(k+1)^2}{4}+\frac{4(k+1)^3}{4} \\
&= \frac{k^2(k+1)^2+(4k+4)(k+1)^2}{4} \\
&= \frac{(k^2+4k+4)(k+1)^2}{4} \\
&= \frac{(k+2)^2(k+1)^2}{2^2} \\
&= \left(\frac{(k+2)(k+1)}{2}\right)^2 \\
&= \left(\frac{((k+1)+1)(k+1)}{2}\right)^2 \\
&= \left(1+2+\cdots+(k+1)\right)^2.
\end{aligned}$$

(iii)

$$1+r+\cdots+r^n = \frac{1-r^{n+1}}{1-r} \text{ if } r \neq 1.$$

$P(1)$: $1+r^1 = \dfrac{(1+r)(1-r)}{1-r} = \dfrac{1-r^2}{1-r}$.

Suppose $P(k)$ is true for $k \in \mathbb{N}$.

$P(k+1)$:

$$\begin{aligned}
1+r+\cdots+r^{k+1} &= 1+r+\cdots+r^k+r^{k+1} \\
&= \frac{1-r^{k+1}}{1-r}+r^{k+1} \\
&= \frac{1-r^{k+1}}{1-r}+\frac{(1-r)r^{k+1}}{1-r} \\
&= \frac{1-r^{k+1}+r^{k+1}-r^{(k+1)+1}}{1-r} \\
&= \frac{1-r^{(k+1)+1}}{1-r}.
\end{aligned}$$

1.3 Countable and Uncountable Sets

Two sets A and B are **equipotent** provided there exists a bijection between them.
A set E is **countable** if it is equipotent to a set of natural numbers.
For a countably infinite set X, we say that $\{x_n \mid n \in \mathbb{N}\}$ is an **enumeration** of X provided

$$X = \{x_n \mid n \in \mathbb{N}\} \text{ and } x_n \neq x_m \text{ if } n \neq m.$$

Theorem 3. *A subset of a countable set is countable. In particular, every set of natural numbers is countable.*

Corollary 4. *The following sets are countably infinite:*

(i) For each natural numbers n, the Cartesian product $\mathbb{N}^n = \mathbb{N} \times \cdots \times \mathbb{N}$.

(ii) The set of natural numbers $\mathbb{Q}$.

The rationals are countable: $\mathbb{Q} = \{0, \frac{1}{1}, -\frac{1}{1}, \frac{1}{2}, -\frac{1}{2}, \frac{2}{1}, -\frac{2}{1}, \frac{3}{1}, -\frac{3}{1}, \frac{1}{3}, -\frac{1}{3}, \frac{1}{4}, -\frac{1}{4}, \frac{2}{3}, -\frac{2}{3}, \cdots\}$.

Corollary 6. *The union of a countable collection of countable sets is countable.*

An interval of real numbers is called degenerate if it is empty or contains a single member.

Theorem 7. *A nondegenerate interval of real numbers is uncountable.*

Proof. Let I be a nondegenerate interval of real numbers. Clearly I is not finite. Suppose I is countably infinite. Let $\{x_n \mid n \in \mathbb{N}\}$ be an enumeration of I. For each $n \in \mathbb{N}$, choose a nondegenerate compact subinterval $[a_n, b_n] \subseteq I$ such that $x_n \notin [a_n, b_n]$. Let the set of such intervals $\{[a_n, b_n]\}_{n=1}^{\infty}$ be descending: $[a_{n+1}, b_{n+1}] \subseteq [a_n, b_n]$ (That is, $a_n \leq a_{n+1} < b_{n+1} \leq b_n$.) Now, the nonempty set $E = \{a_n \mid n \in \mathbb{N}\}$ is bounded above by b_1. Then the Completeness Axiom implies that E has a supremum, say $x^* = \sup E$. Then for each n, $a_n \leq x^* \leq b_n$ because x^* is the supremum of E and each b_n is an upper bound for E. Therefore x^* belongs to $[a_n, b_n]$ for each n. But then x^* is an element of I and thus has an index $n_0 \in \mathbb{N}$ such that $x^* = x_{n_0}$. But $x^* \in [a_{n_0}, b_{n_0}]$, a contradiction. Therefore I is not countable. $\square$

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16. Show that the set $\mathbb{Z}$ of integers is countable.

    There exists a bijection $\phi : \mathbb{Z} \to \mathbb{N}$ with

$$\phi(x) = \begin{cases} 2x & \text{if } x > 0, \\ -2x + 1 & \text{if } x \leq 0. \end{cases}$$

$$\mathbb{Z} = \{0, 1, -1, 2, -2, 3, -3, 4, -4, \cdots\}$$
$$\mathbb{N} = \{1, 2, 3, 4, 5, 6, 7, 8, 9, \cdots\}$$

17. Show that a set A is countable iff there is an injective mapping of A to $\mathbb{N}$.

    ($\Longrightarrow$) Suppose A is countable.

    Then either A is equipotent to $\mathbb{N}$, or there is an $n \in \mathbb{N}$ such that A is equipotent to $\{1, 2, \cdots, n\}$. In the case A is countably infinite, we have a bijection with $\mathbb{N}$ and thus an injection. In the case A is finite, we have an injection with a subset of $\mathbb{N}$, and thus an injection with $\mathbb{N}$ (injection: $f(a) = f(b) \implies a = b$ for $a, b \in A$).

    ($\Longleftarrow$) Suppose there is an injective mapping of A to $\mathbb{N}$.

    Then there is a bijection from A to some subset B of $\mathbb{N}$. By Theorem 3, every subset of natural numbers is countable, and because A is equipotent to this countable set B, then A is countable.

18. Use an induction argument to complete the proof of part (i) of Corollary 4.

    (Not an induction argument)

    Consider the function $f : \mathbb{N}^2 \to \mathbb{N}$, where $f(m,n) = 2^m 3^n$. By the Fundamental Theorem of Arithmetic, $2^m 3^n = 2^{m'} 3^{n'} \implies m = m', n = n'$. Then clearly f is an injection. By problem 17, we see that $\mathbb{N}^2$ is countable.

    For any $k \in \mathbb{N}$ we can construct a function $f : \mathbb{N}^k \to \mathbb{N}$, where we have n primes such that $f(m_1, m_2, \cdots, m_k) = p_1^{m_1} p_2^{m_2} \cdots p_k^{m_k}$. By the fundamental theorem of arithmetic, this is an injection and thus $\mathbb{N}^k$ is countable.

19. Prove Corollary 6 in the case of a finite family of countable sets.

    Let $\{S_n\}_{n=1}^k$ be a finite family of countable sets. Then each set S_n is countable, and we can enumerate as follows: $S_n = \{s_{nm} \mid m \in \mathbb{N}\}$. Then because there is only a finite number of countable sets, we can construct a function $f : \bigcup_{n=1}^k S_n \to \mathbb{N}$ seeing that

$$\bigcup_{n=1}^{k} S_n = \{s_{11}, s_{21}, s_{31}, \cdots, s_{k1}, s_{12}, s_{22}, s_{32}, \cdots, s_{k2}, s_{13}, \cdots\}.$$

20. Let both $f : A \to B$ and $g : B \to C$ be injective and surjective. Show that the composition $g \circ f : A \to B$ and the inverse $f^{-1} : B \to A$ are also injective and surjective.

    $g \circ f$:

    By surjectivity of g, for all $c \in C$, there exists a $b \in B$ such that $g(b) = c$. Then by surjectivity of f, there exists an $a \in A$ such that $f(a) = b$.

    Therefore for any $c \in C$:

$$\begin{aligned} c &= g(b) && \text{for some } b \in B \\ &= g(f(a)) && \text{for some } a \in A \\ &= g \circ f(a) \end{aligned}$$

    Therefore $g \circ f$ is surjective.

    By injectivity of g, $g(b) = g(b') \implies b = b'$.

    By injectivity of f, $f(a) = f(a') \implies a = a'$.

$$\begin{aligned} g \circ f(a) &= g \circ f(a') \\ g(f(a)) &= g(f(a')) \\ f(a) &= f(a') && \text{by injectivity of } g \\ a &= a' && \text{by injectivity of } f \end{aligned}$$

    Therefore $g \circ f$ is injective.

    f^{-1}:

    Because f is a function from A to B, $f(a) \subseteq B$ is defined for all $a \in A$. That is, for all $a \in A$, there exists a $b \in B$ such that $f^{-1}(b) = a$. Thus f^{-1} is surjective.

    Because f is a function, for each $a \in A$, $f(a) = b$ and $f(a) = b'$ imply $b = b'$. That is, $f^{-1}(b) = f^{-1}(b') \implies b = b'$. Thus f^{-1} is injective.

21. Use an induction argument to establish the pigeonhole principle.

    For $n \in \mathbb{N}$, let $P(n)$ be the assertion that for any $m \in \mathbb{N}$, the set $\{1, 2, \cdots, n\}$ is not equipotent to the set $\{1, 2, \cdots, n + m\}$.

    $P(1)$: We have the sets $A = \{1\}$ and $B = \{1, 2, \cdots, 1 + m\}$, for $m \in \mathbb{N}$. In the case $m = 1$, $B = \{1, 1 + 1\} = \{1, 2\}$, and clearly A is not equipotent to B. Clearly A is also not equipotent to B for any other natural number $m > 1$.

    Suppose $P(k)$ is true for some $k \in \mathbb{N}$. Then $\{1, 2, \cdots, k\}$ is not equipotent to the set $\{1, 2, \cdots, k+m\}$, for any $m \in \mathbb{N}$.

    $P(k + 1)$: Then clearly $\{1, 2, \cdots, k + 1\}$ is not equipotent to the set $\{1, 2, \cdots, (k + 1), \cdots, (k + 1) + m\}$, for any $m \in \mathbb{N}$.

22. Show that $2^{\mathbb{N}}$, the collection of all sets of natural numbers, is uncountable.

    (Cantor's Theorem: for a set A, any function $f : A \to \mathcal{P}(A)$ is not surjective.)

    Let $f : \mathbb{N} \to \mathcal{P}(\mathbb{N})$ be any map. Let $E = \{n \in \mathbb{N} \mid n \notin f(n)\}$. Then E is a subset of the naturals that is not in the image of f, so f is not surjective. Therefore there is no bijection between $\mathbb{N}$ and $\mathcal{P}(\mathbb{N})$.

23. Show that the Cartesian product of a finite collection of countable sets is countable. Use the preceding theorem to show that $\mathbb{N}^{\mathbb{N}}$, the collection of all mappings of $\mathbb{N}$ into $\mathbb{N}$, is not countable.

    In problem 18, we showed that for any $k \in \mathbb{N}$, the set $\mathbb{N}^k = \mathbb{N} \times \mathbb{N} \times \cdots \times \mathbb{N}$ is countable. It is then trivial to see that the Cartesian product of any finite collection of countable sets $S_1 \times S_2 \times \cdots \times S_k$ is countable.

    Notation:
    $$0 = \emptyset, 1 = \{0\}, 2 = \{0, 1\}, 3 = \{0, 1, 2\}, \cdots$$
    We can let $2^{\mathbb{N}} = \{0, 1\}^{\mathbb{N}}$ be the set of functions $f : \mathbb{N} \to \{0, 1\}$.

    Then, for any subset $A \subseteq \mathbb{N}$, there exists a function $f \in \{0, 1\}^{\mathbb{N}}$ such that
    $$f(x) = \begin{cases} 1 & \text{if } x \in A, \\ 0 & \text{if } x \notin A, \end{cases}$$
    and we have a bijection between the elements of $\{0, 1\}^{\mathbb{N}}$ and the subsets of $\mathbb{N}$ ("Two sets that are equipotent are, from a set-theoretic point of view, indistinguishable"). Therefore $2^{\mathbb{N}} = \{0, 1\}^{\mathbb{N}}$ can be used to represent the collection of subsets of $\mathbb{N}$.

    Now, because the set of functions $f : \mathbb{N} \to \{0, 1\}$ is uncountable, then clearly the set of functions $f : \mathbb{N} \to \mathbb{N} \supseteq \{0, 1\}$ is uncountable (including zero in the naturals for notation convenience).

24. Show that a nondegenerate interval of real numbers fails to be finite.

    Theorem 7 tells us that a nondegenerate interval of real numbers is uncountable, and thus, finite.

25. Show that any two nondegenerate intervals of real numbers are equipotent.

    We can prove this by showing that any interval is equipotent to the interval $(0, 1)$.

    For any bounded interval (a, b), $(a, b]$, $[a, b)$, $[a, b]$, there exists a bijection to $(0, 1)$, $(0, 1]$, $[0, 1)$, $[0, 1]$ respectively, of the form $f(x) = \dfrac{1}{b - a}(x - a)$.

26. Is the set $\mathbb{R} \times \mathbb{R}$ equipotent to $\mathbb{R}$?

    yes (Schröder-Bernstein theorem)

1.4 Open Sets, Closed Sets, and Borel Sets of Real Numbers

The Nested Set Theorem. *Let $\{F_n\}_{n=1}^\infty$ be a descending countable collection of nonempty closed sets of real numbers for which F_1 is bounded. Then*

$$\bigcap_{n=1}^\infty F_n \neq \emptyset.$$

Proof. By contradiction, suppose that $\bigcap_{n=1}^\infty F_n = \emptyset$. Then $\bigcup_{n=1}^\infty F_n^c = (\bigcap_{n=1}^\infty F_n)^c = \emptyset^c = \mathbb{R}$, and we have an open cover of $\mathbb{R}$ and thus an open cover of $F_1 \subseteq \mathbb{R}$. By the Heine-Borel Theorem, there exists an $N \in \mathbb{N}$ such that $F_1 \subseteq \bigcup_{n=1}^N F_n^c$. Because $\{F_n\}$ is descending, $F_n \supseteq F_{n+1}$ for any $n \geq 1$. This implies $F_n^c \subseteq F_{n+1}^c$, and thus $F_1 \subseteq \bigcup_{n=1}^N F_n^c = F_N^c = \mathbb{R} \setminus F_N$. This is a contradiction to the assumption that F_N is a nonempty subset of F_1. □

PROBLEMS

27. Is the set of rational numbers open or closed?

    The set of rationals is neither open nor closed. The rationals is not open because the irrationals are dense in the rationals; that is, between any two rationals there is an irrational. The rationals is not closed because it does not contain all its limit points; a sequence of rationals can be constructed that converges to an irrational. (Thus we see that the irrationals is neither open nor closed as well.)

28. What are the sets of real numbers that are both open and closed?

    It is clear that $\mathbb{R}$ is open, and $\emptyset$ is open (vacuously). Then because the complement of an open set is closed, $\mathbb{R}$ and $\emptyset$ are both closed as well.

29. Find two sets A and B such that $A \cap B = \emptyset$ and $\overline{A} \cap \overline{B} \neq \emptyset$.

    Let $A = (4, 5)$ and $B = (5, 20)$. Then $(4, 5) \cap (5, 20) = \emptyset$ and $\overline{A} = [4, 5]$ and $\overline{B} = [5, 20]$ so $[4, 5] \cap [5, 20] = \{5\} \neq \emptyset$.

    Let $A = \mathbb{Q}$ and $B = \mathbb{Q}^c$. Then $\mathbb{Q} \cap \mathbb{Q}^c = \emptyset$ and $\overline{A} = \mathbb{R}$ and $\overline{B} = \mathbb{R}$ so $\mathbb{R} \cap \mathbb{R} = \mathbb{R} \neq \emptyset$.

30. A point x is called an **accumulation point** of a set E provided it is a point of closure of $E \setminus \{x\}$.

    (i) Show that the set E' of accumulation points of E is a closed set.

    (ii) Show that $\overline{E} = E \cup E'$.

31. A point x is called an **isolated point** of a set E provided there is an $r > 0$ for which $(x - r, x + r) \cap E = \{x\}$. Show that if a set E consists of isolated points, then it is countable.

32. A point x is called an **interior point** of a set E if there is an $r > 0$ such that the open interval $(x - r, x + r)$ is contained in E. The set of interior points of E is called the **interior** of E denoted by int E. Show that

    (i) E is open iff $E =$ int E.

    (ii) E is dense iff int $(\mathbb{R} \setminus E) = \emptyset$.

33. Show that the nested set theorem is false if F_1 is unbounded.

34. Show that the assertion of the Heine-Borel Theorem is equivalent to the Completeness Axiom for the real numbers. Show that the assertion of the Nested Set Theorem is equivalent to the Completeness Axiom for the real numbers.

35. Show that the collection of Borel sets is the smallest σ-algebra that contains the closed sets.

36. Show that the collection of Borel sets is the smallest σ-algebra that contains the intervals of the form $[a, b)$, where $a < b$.

37. Show that each open set is an F_σ set.

1.5 Sequences of Real Numbers

PROBLEMS

38. We call an extended real number a **cluster point** of a sequence $\{a_n\}$ if a subsequence converges to this extended real number. Show that $\liminf\{a_n\}$ is the smallest cluster point of $\{a_n\}$ and $\limsup\{a_n\}$ is the largest cluster point of $\{a_n\}$.

39. Prove proposition 19.

40. Show that a sequence $\{a_n\}$ is convergent to an extended real number iff there is exactly one extended real number that is a cluster point of the sequence.

41. Show that $\liminf a_n \leq \limsup a_n$.

42. Prove that if, for all n, $a_n \geq 0$ and $b_n \geq 0$, then

$$\limsup[a_n \cdot b_n] \leq (\limsup a_n) \cdot (\limsup b_n),$$

provided the product on the right is not of the form $0 \cdot \infty$.

43. Show that every real sequence has a monotone subsequence. Use this to provide another proof of the Bolzano-Weierstrass Theorem.

44. Let p be a natural number greater than 1, and x a real number $0 \leq x \leq 1$. Show that there is a sequence $\{a_n\}$ of integers with $0 \leq a_n < p$ for each n such that

$$x = \sum_{n=1}^{\infty} \frac{a_n}{p^n}$$

and that this sequence is unique except when x is of the form q/p^n, $0 < q < p^n$, in which case there are exactly two such sequences. Show that, conversely, if $\{a_n\}$ is any sequence of integers with $0 \leq a_n < p$, the series

$$x = \sum_{n=1}^{\infty} \frac{a_n}{p^n}$$

converges to a real number x with $0 \leq x \leq 1$. If $p = 10$, this sequence is called the *decimal* expansion of x. For $p = 2$ it is called the *binary* expansion; and for $p = 3$, the *ternary* expansion.

45. Prove Proposition 20.

46. Show that the assertion of the Bolzano-Weierstrass Theorem is equivalent to the Completeness Axiom for the real numbers. Show that the assertion of the Monotone Convergence Theorem is equivalent to the Completeness Axiom for the real numbers.

1.6 Continuous Real-Valued Functions of a Real Variable

PROBLEMS

47. Let E be a closed set of real numbers and f a real-valued function that is defined and continuous on E. Show that there is a function g defined and continuous on all of $\mathbb{R}$ such that $f(x) = g(x)$ for each $x \in E$. (Hint: Take g to be linear on each of the intervals of which $\mathbb{R} \setminus E$ is composed.)

48. Define the real-valued function f on $\mathbb{R}$ by setting

$$f(x) = \begin{cases} x & \text{if x irrational} \\ p \sin \dfrac{1}{q} & \text{if } x = \dfrac{p}{q} \text{ in lowest terms.} \end{cases}$$

At what points is f continuous?

49. Let f and g be continuous real-valued functions with a common domain E.

    (i) Show that the sum, $f + g$, and product, fg, are also continuous functions.

    (ii) If h is a continuous function with image contained in E, show that the composition $f \circ h$ is continuous.

    (iii) Let $\max\{f, g\}$ be the function defined by $\max\{f, g\}(x) = \max\{f(x), g(x)\}$, for $x \in E$. Show that $\max\{f, g\}$ is continuous.

    (iv) Show that $|f|$ is continuous.

50. Show that a Lipschitz function is uniformly continuous but there are uniformly continuous functions that are not Lipschitz.

51. A continuous function ϕ on $[a, b]$ is called **piecewise linear** provided there is a partition $a = x_0 < x_1 < \cdots < x_n = b$ of $[a, b]$ for which ϕ is linear on each interval $[x_i, x_{i+1}]$. Let f be a continuous function on $[a, b]$ and ϵ a positive number. Show that there is a piecewise linear function ϕ on $[a, b]$ with $|f(x) - \phi(x)| < \epsilon$ for all $x \in [a, b]$.

52. Show that a nonempty set E of real numbers is closed and bounded if and only if every continuous real-valued function on E takes a maximum value.

53. Show that a set E of real numbers is closed and bounded iff every open cover of E has a finite subcover.

54. Show that a nonempty set E of real numbers is an interval iff every continuous real-valued function on E has an interval as its image.

55. Show that a monotone function on an open interval is continuous iff its image is an interval.

56. Let f be a real-valued function defined on $\mathbb{R}$. Show that the set of points at which f is continuous is a G_δ set.

57. Let $\{f_n\}$ be a sequence of continuous functions defined on $\mathbb{R}$. Show that the set of points x at which the sequence $\{f_n(x)\}$ converges to a real number is the intersection of a countable collection of F_σ sets.

58. Let f be a continuous real-valued function on $\mathbb{R}$. Show that the inverse image with respect to f of an open set is open, of a closed set is closed, and of a Borel set is Borel.

59. A sequence $\{f_n\}$ of real-valued functions defined on a set E is said to converge uniformly on E to a function f iff given $\epsilon > 0$, there is an N such that for all $x \in E$ and all $n \geq N$, we have $|f_n(x) - f(x)| < \epsilon$. Let $\{f_n\}$ be a sequence of continuous functions defined on a set E. Prove that if $\{f_n\}$ converges uniformly to f on E, then f is continuous on E.

Chapter 2

Lebesgue Measure

Contents

2.1 Introduction

In this chapter we construct a collection of sets called **Lebesgue measurable sets**, and a set function of this collection called **Lebesgue measure**, denoted by m. The collection of Lebesgue measurable sets is a σ-algebra which contains all open sets and all closed sets. The set function m possesses the following three properties:

The measure of an interval is its length. *Each nonempty interval I is Lebesgue measurable and*

$$m(I) = \ell(I).$$

Measure is translation invariant. *If E is Lebesgue measurable and y is any number then the translate of E by y, $E + y = \{x + y \mid x \in E\}$, also is Lebesgue measurable and*

$$m(E + y) = m(E).$$

Measure is countably additive over countable disjoint unions of sets. *IF $\{E_k\}_{k=1}^{\infty}$ is a countable disjoint collection of Lebesgue measurable sets, then*

$$m(\bigcup_{k=1}^{\infty} E_k) = \sum_{k=1}^{\infty} m(E_k).$$

It is not possible to construct a set function that possesses the above three properties and is defined for all sets of real numbers (See Vitali sets). We first construct a set function called **outer measure**, denoted by m^*, such that:

(i) the outer measure of an interval is its length,

(ii) outer measure is translation invariant,

(iii) outer measure is countably subadditive.

Then the Lebesgue measure m is the restriction of m^* to the Lebesgue measurable sets.

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In the first three problems, let m be a set function defined for all sets in a σ-algebra $\mathcal{A}$ with values in $[0, \infty]$. Assume m is countably additive over countable disjoint collections of sets in $\mathcal{A}$.

1. Prove that if A and B are two sets in $\mathcal{A}$ with $A \subseteq B$, then $m(A) \leq m(B)$. This property is called *monotonicity*.

   $A \subseteq B \implies B = A \cup (B \cap A^c)$, where $A \cap (B \cap A^c) = \emptyset$. The set $(B \cap A^c)$ is measurable because A^c is measurable and countable intersection is measurable, so $m(B) = m(A \cup (B \cap A^c)) = m(A) + m(B \cap A^c)$ by countable additivity, and thus $m(B) \geq m(A)$.

2. Prove that if there is a set A in the collection $\mathcal{A}$ for which $m(A) < \infty$, then $m(\emptyset) = 0$.

3. Let $\{E_k\}_{k=1}^{\infty}$ be a countable collection of sets in $\mathcal{A}$. Prove that $m(\bigcup_{k=1}^{\infty} E_k) \leq \sum_{k=1}^{\infty} m(E_k)$.

4. A set function c, defined on all subsets of $\mathbb{R}$, is defined as follows. Define $c(E)$ to be ∞ if E has infinitely many members and $c(E)$ to be equal to the number of elements in E if E is finite; define $c(\emptyset) = 0$. Show that c is a countably additive and translation invariant set function. This set function is called the **counting measure**.

2.2 Lebesgue Outer Measure

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5. By using properties of outer measure, prove that the interval $[0, 1]$ is not countable.

6. Let A be the set of irrational numbers in the interval $[0, 1]$. Prove that $m^*(A) = 1$.

7. A set of real numbers is said to be a G_δ set provided it is the intersection of a countable collection of open sets. Show that for any bounded set E, there is a G_δ set G for which

$$E \subseteq G \text{ and } m^*(G) = m^*(E).$$

2.3 The σ-Algebra of Lebesgue Measurable Sets

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