

Solutions Notebook for
Principles of Mathematical Analysis
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Chapter 1

The Real and Complex Number Systems

1.1 Exercises

Exercise 1.1. If r is rational and x is irrational, prove that $r + x$ and rx are irrational.

We will proceed by proving the irrationality of the product rx first, from which the irrationality of the sum $r + x$ will naturally follow.

Proposition. For any rational number r and irrational number x , the product rx is irrational.

Proof. Suppose to the contrary that the product rx is rational, implying the existence of some integers m and $n \neq 0$ such that $r = \frac{m}{n}$ and $rx = \frac{m}{n} \cdot x = \frac{mx}{n}$. If rx was rational, we could multiply by $\frac{1}{r} = \frac{n}{m}$, giving us $\frac{mx}{n} \cdot \frac{n}{m} = x$. Since we have simply multiplied two (allegedly) rational numbers and the rational numbers are a field and thus closed under multiplication, the result must be a rational number. Since the result is x , and we began by supposing x was irrational, we've arrived at our contradiction.

The product of a rational number r and an irrational number x yields an irrational number rx . \square

Proposition. For any rational number r and irrational number x , the sum $r + x$ is irrational.

Proof. Suppose again to the contrary that $r + x$ is rational. Then there exist some integers m and n such that $n \neq 0$ and $r = \frac{m}{n}$. By the standard rules of adding rational numbers, this implies the following.

$$\begin{aligned} r + x &= \frac{m}{n} + x \\ &= \frac{m}{n} + x \cdot \frac{n}{n} \\ &= \frac{m}{n} + \frac{xn}{n} \\ &= \frac{m + xn}{n} \end{aligned}$$

Since we've supposed $r + x$ to be a rational number and the field of rational numbers \mathbb{Q} is by definition closed under arithmetic operations, we should be able to add, subtract, multiply, or divide $r + x$ by any non-zero rational number and still get a rational number as a result. To verify this, we begin with the expression $\frac{(r+x)n-m}{n}$.

$$\begin{aligned} \frac{(r+x)n-m}{n} &= \frac{\left(\frac{m+nx}{n}\right)n-m}{n} \\ &= \frac{m+nx-m}{n} \\ &= \frac{nx}{n} \\ &= x \end{aligned}$$

Since the above expression simplifies to x , an irrational number, the supposition that $r + x$ is rational would imply that the field of rational numbers \mathbb{Q} is not closed under its addition and multiplication operations. This is false, by the definition of a field, and this contradiction leads us to conclude that for any rational number r and irrational number x , the sum $r + x$ is irrational. \square

Exercise 1.2. Prove that there is no rational number whose square is 12.

Suppose there did exist some rational number r such that its square was 12. From the assumption that $r^2 = 12$, we deduce that $r = \sqrt{12}$, and therefore $r = \sqrt{4 \cdot 3} \equiv 2\sqrt{3}$. We will show that $\sqrt{3}$ is irrational, and by Proposition 1.1 the product $2\sqrt{3}$ is as well.

Proposition. The real number $\sqrt{3}$ is irrational.

Proof. Suppose to the contrary there exists some rational number r such that its square is 3. This implies the existence of some non-zero integers

m and n such that $r = \frac{m}{n}$ and $\frac{m^2}{n^2} = 3$. Since m and n are in reduced form, they cannot both be even.

We thus have $m^2 = 3n^2$ **TODO: Finish proof**

□

Proposition. There is no rational number whose square is 12.

Exercise 1.18. If $k \geq 2$ and $\mathbf{x} \in \mathbb{R}^k$, prove that there exists $\mathbf{y} \in \mathbb{R}^k$ such that $\mathbf{y} \neq \mathbf{0}$ but $\mathbf{x} \cdot \mathbf{y} = 0$. Is this also true if $k = 1$?

Proposition. Let $k \geq 2$ and $\mathbf{x} \in \mathbb{R}^k$. There exists some $\mathbf{y} \in \mathbb{R}^k$ where $\mathbf{y} \neq \mathbf{0}$ such that $\mathbf{x} \cdot \mathbf{y} = 0$.

Proof. Let $\mathbf{x} = (1, 0)$ and $\mathbf{y} = (0, 1)$. By the definition of the inner product of two vectors,

$$\begin{aligned}\mathbf{x} \cdot \mathbf{y} &= \sum_{i=1}^2 x_i y_i \\ &= x_1 y_1 + x_2 y_2 \\ &= (1 \cdot 0) + (0 \cdot 1) \\ &= (0) + (0) \\ &= 0.\end{aligned}$$

Therefore, there exists some $\mathbf{y} \in \mathbb{R}^k$ where $\mathbf{y} \neq \mathbf{0}$ such that $\mathbf{x} \cdot \mathbf{y} = 0$. □

This is not true for vector spaces of dimension one.

Chapter 2

Basic Topology

Theorem 2.12. Let $\{E_n\}$ for $n = 1, 2, 3, \dots$ be a sequence of countable sets, and put

$$S = \bigcup_{n=1}^{\infty} E_n. \quad (2.1)$$

Then S is countable.

Corollary. Suppose A is at most countable, and, for every $\alpha \in A$, B_α is at most countable. Put

$$T = \bigcup_{\alpha \in A} B_\alpha.$$

Then T is at most countable.

Theorem 2.13. Let A be a countable set, and let B_n be the set of all n -tuples (a_1, \dots, a_n) , where $a_k \in A$ for $(k = 1, \dots, n)$, and the elements a_1, \dots, a_n need not be distinct. Then B_n is countable.

Theorem 2.19. Every neighborhood is an open set.

Theorem 2.20. If p is a limit point of a set E , then every neighborhood of p contains infinitely many points of E .

Theorem 2.23. A set E is open if and only if its complement is closed.

Corollary. A set F is closed if and only if its complement is open.

Definition 2.31. By an **open cover** of a set E in a metric space X we mean a collection $\{G_\alpha\}$ of open subsets of X such that $E \subset \bigcup_\alpha G_\alpha$.

Definition 2.32. A subset K of a metric space X is said to be **compact** if every open cover of K contains a *finite* subcover.

Theorem 2.41. If a set in \mathbb{R}^k has one of the following three properties, then it has the other two:

- (a) E is closed and bounded.
- (b) E is compact.
- (c) Every infinite subset of E has a limit point in E .

2.1 Exercises

Exercise 2.1. Prove that the empty set is a subset of every set.

Proposition. The empty set, denoted by \emptyset , is a subset of every set.

Proof. Let A be an arbitrary set. In order to prove that the empty set is a subset of A , we must show that for any element x in \emptyset , x is also an element of A . Since –by definition– the empty set contains no elements, this statement is vacuously true and thus not very interesting.

Consider instead the contrapositive: for any element x , if x is not an element of A , then x is not an element of \emptyset . Again, since \emptyset contains no elements, this statement is true for all elements $x \notin A$, as required. \square

Exercise 2.2. A complex number z is said to be *algebraic* if there are integers a_0, \dots, a_n , not all zero, such that

$$a_0 z^n + a_1 z^{n-1} + \dots + a_{n-1} z + a_n = 0.$$

Prove that the set of all algebraic numbers is countable. *Hint:* For every positive integer N there are only finitely many equations with

$$n + |a_0| + |a_1| + \dots + |a_n| = N.$$

Proposition. The set of all algebraic numbers is countable.

Exercise 2.3. Prove that there exist real numbers which are not algebraic.

Exercise 2.4. Is the set of all irrational real numbers countable?

Exercise 2.12. Let $K \subset \mathbb{R}^1$ consist of 0 and the numbers $\frac{1}{n}$, for $n = 1, 2, 3, \dots$. Prove that K is compact directly from the definition (without using the Heine-Borel Theorem).

Proposition. Let $K \subset \mathbb{R}^1$ consist of 0 and the numbers $\frac{1}{n}$ for $n = 1, 2, 3, \dots$. The space K is compact.

Proof. Any open cover must include the interval $a < 0 < b$. By the Archimedean property of \mathbb{R} , there are an infinite number of points $k \in K$ between 0 and b , irrespective of the value of b . The covering set for the rest of the points in K from b to 1 is therefore finite.

Since any cover of K contains some finite subcover, K is compact. \square

Exercise 2.16. Regard \mathbb{Q} , the set of all rational numbers, as a metric space, with $d(p, q) = |p - q|$. Let E be the set of all $p \in \mathbb{Q}$ such that $2 < p^2 < 3$. Show that E is closed and bounded in \mathbb{Q} , but that E is not compact. Is E open in \mathbb{Q} ?

Chapter 3

Numerical Sequences and Series

3.1 Exercises

Exercise 3.25. Let X be the metric space whose points are the rational numbers, with the metric $d(x, y) = |x - y|$. What is the completion of this space? (Compare Exercise 24.)

Solution. The completion of this space is the real numbers, within which the rational numbers are dense. In fact, one of the axiomatic constructions of the real numbers is precisely the completion of the rational numbers by the use of Cauchy sequences.

Chapter 4

Continuity

Chapter 5

Differentiation

Chapter 6

The Riemann-Stieltjes Integral

Chapter 7

Sequences and Series of Functions

Chapter 8

Some Special Functions

Chapter 9

Functions of Several Variables

Chapter 10

Integration on Differential Forms

Chapter 11

The Lebesgue Theory

Glossary

compact A subset K of a metric space X is said to be *compact* if every open cover of K contains a *finite* subcover. 5

open cover An *open cover* of a set E in a metric space X is a collection $\{G_\alpha\}$ of open subsets of X such that $E \subset \cup_\alpha G_\alpha$. 5

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