

Encyclopaedia of Mathematics and Physics

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Chapter 1

Set Theory

Proposition 1.1. *Every infinite subset of a countably infinite set is countable.*

PROOF:

- $\langle 1 \rangle 1$. LET: $i : A \hookrightarrow \mathbb{N}$ be an infinite subset of \mathbb{N} .
- $\langle 1 \rangle 2$. Define $j : \mathbb{N} \rightarrow A$ by: $j(k)$ is the element such that $i(j(k))$ is least such that $i(j(k)) \notin \{i(j(0)), \dots, i(j(k-1))\}$.
- $\langle 1 \rangle 3$. j is a bijection.

□

Proposition 1.2. *A countable union of countable sets is countable.*

PROOF:

- $\langle 1 \rangle 1$. LET: (A_n) be a sequence of countable sets.
- $\langle 1 \rangle 2$. For $n \in \mathbb{N}$, PICK an enumeration $(e_{nm})_m$ of A_n .
- $\langle 1 \rangle 3$. LET: (p_k) be the following enumeration of $\mathbb{N} \times \mathbb{N}$:
 $(0, 0), (1, 0), (0, 1), (2, 0), (1, 1), (0, 2), \dots$
- $\langle 1 \rangle 4$. $(e_{\pi_1(p_k)\pi_2(p_k)})_k$ is an enumeration of $\bigcup_n A_n$.

□

Theorem 1.3. $2^{\mathbb{N}}$ is uncountable.

PROOF:

- $\langle 1 \rangle 1$. ASSUME: for a contradiction $f : \mathbb{N} \approx 2^{\mathbb{N}}$
- $\langle 1 \rangle 2$. LET: $S = \{n \in \mathbb{N} : n \notin f(n)\}$
- $\langle 1 \rangle 3$. For all n , we have $n \in S \Leftrightarrow n \notin f(n)$
- $\langle 1 \rangle 4$. For all n we have $S \neq f(n)$.
- $\langle 1 \rangle 5$. Q.E.D.

PROOF: This contradicts $\langle 1 \rangle 1$.

□

Chapter 2

Relations

Definition 2.1 (Antisymmetric). A relation R on a set A is *antisymmetric* iff, whenever xRy and yRx , then $x = y$.

Definition 2.2 (Transitive). A relation R on a type A is *transitive* iff, whenever xRy and yRz , then xRz .

Chapter 3

Order Theory

Definition 3.1 (Linear Order). A *linear order* on a set A is a binary relation \leq on A that is transitive, antisymmetric and:

$$\forall x, y \in A. x \leq y \vee y \leq x .$$

A *linearly ordered set* is a pair (A, \leq) where A is a set and \leq is a binary relation on A .

We write $x < y$ for $x \leq y$ and $x \neq y$.

Definition 3.2 (Upper Bound). Let S be a linearly ordered set, $u \in S$ and $E \subseteq S$. Then u is an *upper bound* in E iff $\forall x \in E. x \leq u$. We say E is *bounded above* iff it has an upper bound.

The *up-set* of E , denoted $E \uparrow$, is the set of upper bounds of E .

Definition 3.3 (Lower Bound). Let S be a linearly ordered set, $l \in S$ and $E \subseteq S$. Then l is a *lower bound* in E iff $\forall x \in E. l \leq x$. We say E is *bounded below* iff it has a lower bound.

The *down-set* of E , denoted $E \downarrow$, is the set of lower bounds of E .

Definition 3.4 (Supremum). Let S be a linearly ordered set, $u \in S$ and $E \subseteq S$. Then u is the *least upper bound* or *supremum* of E iff u is an upper bound for E and, for any upper bound u' for E , we have $u \leq u'$.

Definition 3.5 (Infimum). Let S be a linearly ordered set, $l \in S$ and $E \subseteq S$. Then l is the *greatest lower bound* or *infimum* of E iff l is a lower bound for E and, for any lower bound l' for E , we have $l' \leq l$.

Definition 3.6 (Least Upper Bound Property). A linearly ordered set S has the *least upper bound property* iff every nonempty subset of S that is bounded above has a least upper bound.

Proposition 3.7. Let S be a linearly ordered set and $E \subseteq S$.

1. If $E \downarrow$ has a supremum l , then l is the infimum of E .

2. If $E \uparrow$ has an infimum u , then U is the supremum of E .

PROOF:

- (1)1. If $E \downarrow$ has a supremum l , then l is the infimum of E .
 (2)1. l is a lower bound for E .
 (3)1. LET: $x \in E$
 (3)2. x is an upper bound for $E \downarrow$.
 PROOF: For all $y \in E \downarrow$ we have $y \leq x$.
 (3)3. $l \leq x$
 (2)2. For any lower bound l' for E , we have $l' \leq l$.
 PROOF: Since l is an upper bound for $E \downarrow$.
 (1)2. If $E \uparrow$ has an infimum u , then u is the supremum of E .
 PROOF: Dual.
 \square

Corollary 3.7.1. *A linearly ordered set has the least upper bound property if and only if every nonempty set bounded below has an infimum.*

Definition 3.8 (Closed Downwards). Let S be a linearly ordered set and $E \subseteq S$. Then E is *closed downwards* iff, whenever $x \in E$ and $y < x$, then $y \in E$.

Definition 3.9 (Closed Upwards). Let S be a linearly ordered set and $E \subseteq S$. Then E is *closed upwards* iff, whenever $x \in E$ and $x < y$, then $y \in E$.

Definition 3.10 (Greatest). Let S be a linearly ordered set and $u \in S$. Then u is *greatest* in S iff $\forall x \in S. x \leq u$.

Definition 3.11 (Least). Let S be a linearly ordered set and $l \in S$. Then l is *least* in S iff $\forall x \in S. l \leq x$.

Proposition 3.12. *Let \leq be a linear order on a set S and $E \subseteq S$. Then $\leq \cap E^2$ is a linear order on E .*

PROOF: Easy. \square

Given a linearly ordered set (S, \leq) and $E \subseteq S$, we write just E for the linearly ordered set $(E, \leq \cap E^2)$.

Definition 3.13 (Lexicographic Order). Let A and B be linearly ordered sets. The *lexicographic order* or *dictionary order* on $A \times B$ is the order defined by

$$(a, b) \leq (a', b') \Leftrightarrow a = a' \vee (a < a' \wedge b \leq b') .$$

Proposition 3.14. *The lexicographic order is a linear order.*

Chapter 4

Field Theory

Definition 4.1 (Field). A *field* F consists of a set F , two operations $+, \cdot : F^2 \rightarrow F$ and an element $0 \in F$ such that:

- $+$ is commutative.
- $+$ is associative.
- $\forall x \in F. x + 0 = x$
- $\forall x \in F. \exists y \in F. x + y = 0$
- \cdot is commutative.
- \cdot is associative.
- There exists $1 \in F$ such that $1 \neq 0$ and $\forall x \in F. x1 = x$ and $\forall x \in F. x \neq 0 \Rightarrow \exists y \in F. xy = 1$
- *Distributive Law* $\forall x, y, z \in F. x(y + z) = xy + xz$

Proposition 4.2. *In any field F , the element 0 is the unique element such that $\forall x \in F. x + 0 = x$.*

PROOF: If 0 and $0'$ both have this property then $0 = 0 + 0' = 0'$. \square

Proposition 4.3. *In any field F , given $x \in F$, there is a unique $y \in F$ such that $x + y = 0$.*

PROOF: If $x + y = x + y' = 0$ then

$$\begin{aligned} y &= y + 0 \\ &= y + x + y' \\ &= 0 + y' \\ &= y' \end{aligned}$$

\square

Definition 4.4. Let F be a field. Let $x \in F$. We denote by $-x$ the unique element of F such that $x + (-x) = 0$.

Given $x, y \in F$, we write $x - y$ for $x + (-y)$.

Proposition 4.5. In any field F , if $x + y = x + z$ then $y = z$.

PROOF: If $x + y = x + z$ we have

$$-x + x + y = -x + x + z$$

$$\therefore 0 + y = 0 + z$$

$$\therefore y = z$$

□

Proposition 4.6. In any field F , we have $-(-x) = x$.

PROOF: Since $x + (-x) = 0$. □

Proposition 4.7. In any field F , the element 1 such that $\forall x \in F. x1 = x$ is unique.

PROOF: If 1 and $1'$ both have this property then $1 = 1 \cdot 1' = 1'$. □

Proposition 4.8. In any field F , given $x \in F$ with $x \neq 0$, the element y such that $xy = 1$ is unique.

PROOF: If y and y' both have this property then we have

$$y = y1$$

$$= yxy'$$

$$= 1y'$$

$$= y'$$

□

Definition 4.9. In any field F , if $x \neq 0$, we write x^{-1} for the unique element such that $xx^{-1} = 1$.

We write x/y for xy^{-1} .

Proposition 4.10. In any field F , if $xy = xz$ and $x \neq 0$ then $y = z$.

PROOF:

$$y = 1y$$

$$= x^{-1}xy$$

$$= x^{-1}xz$$

$$= 1z$$

$$= z$$

□

Proposition 4.11. In any field F , if $x \neq 0$ then $x^{-1} \neq 0$ and $(x^{-1})^{-1} = x$.

PROOF: Since $xx^{-1} = 1$. □

Proposition 4.12. In any field F , we have $x0 = 0$.

PROOF:

$$\begin{aligned}
 x0 + 0 &= x0 \\
 &= x(0 + 0) \\
 &= x0 + x0 \\
 \therefore 0 &= x0 \quad \square
 \end{aligned}$$

Proposition 4.13. *In any field F , if $xy = 0$ then $x = 0$ or $y = 0$.*

PROOF: If $xy = 0$ and $x \neq 0$ then we have $y = x^{-1}xy = x^{-1}0 = 0$. \square

Proposition 4.14. *In any field F , we have $(-x)y = -(xy)$.*

PROOF:

$$\begin{aligned}
 xy + (-x)y &= (x + (-x))y \\
 &= 0y \\
 &= 0 \quad (\text{Proposition 4.12}) \square
 \end{aligned}$$

Corollary 4.14.1. *In any field F , we have $(-x)(-y) = xy$.*

PROOF:

$$\begin{aligned}
 (-x)(-y) &= -(x(-y)) \\
 &= -(-(xy)) \\
 &= xy \quad (\text{Proposition 4.6}) \square
 \end{aligned}$$

Proposition 4.15. *Let K be a field. Let $a, b \in K$. If $a^2 = b^2$ then $a = b$ or $a = -b$.*

PROOF:

$$\begin{aligned}
 a^2 - b^2 &= 0 \\
 \therefore (a - b)(a + b) &= 0
 \end{aligned}$$

Hence either $a - b = 0$ or $a + b = 0$, and the conclusion follows. \square

4.1 Ordered Fields

Definition 4.16 (Ordered Field). An *ordered field* F consists of a field F and a linear order \leq on F such that:

- For all $x, y, z \in F$, if $y < z$ then $x + y < x + z$
- For all $x, y \in F$, if $x > 0$ and $y > 0$ then $xy > 0$.

We call x *positive* iff $x > 0$ and *negative* iff $x < 0$.

Example 4.17. \mathbb{Q} is an ordered field.

Proposition 4.18. *In any ordered field, if x is positive then $-x$ is negative.*

PROOF: If $x > 0$ then $0 = x + (-x) > 0 = (-x) = -x$. \square

Proposition 4.19. *In any ordered field, if $y < z$ and x is positive then $xy < xz$.*

PROOF: If $y < z$ then we have

$$\begin{aligned} 0 &< z - y \\ \therefore 0 &< x(z - y) \\ &= xz - xy \\ \therefore xy &< xz \end{aligned}$$

□

Proposition 4.20. *In any ordered field, if $y < z$ and x is negative then $xy > xz$.*

PROOF:

- <1>1. $-x$ is positive.
- <1>2. $(-x)y < (-x)z$
- <1>3. $-(xy) < -(xz)$
- <1>4. $xz < xy$

□

Proposition 4.21. *In any ordered field, if $x \neq 0$ then $x^2 > 0$.*

PROOF:

- <1>1. If $x > 0$ then $x^2 > 0$.

PROOF: Proposition 4.19.

- <1>2. If $x < 0$ then $x^2 > 0$.

PROOF: Proposition 4.20.

□

Corollary 4.21.1. *In any ordered field, we have $1 > 0$.*

Proposition 4.22. *In any ordered field, if x is positive then x^{-1} is positive.*

PROOF: If $x^{-1} < 0$ then we would have $1 = xx^{-1} < x0 = 0$ contradicting Corollary 4.21.1. □

Proposition 4.23. *In any ordered field, if $0 < x < y$ then $y^{-1} < x^{-1}$.*

PROOF:

- <1>1. ASSUME: $0 < x < y$
- <1>2. x^{-1} and y^{-1} are positive.

PROOF: Proposition 4.22.

- <1>3. $xy^{-1} < yy^{-1} = 1$
- <1>4. $y^{-1} = x^{-1}xy^{-1} < x^{-1}1 = x^{-1}$

□

Lemma 4.24. *Let K be an ordered field. Let $b \in K$ with $b > 1$. Let n be a positive integer. Then*

$$b^n - 1 \geq n(b - 1)$$

PROOF:

$$\begin{aligned} b^n - 1 &= (b - 1)(b^{n-1} + b^{n-2} + \cdots + 1) \\ &\geq (b - 1)(1 + 1 + \cdots + 1) \\ &= n(b - 1) \end{aligned}$$

□

Chapter 5

Real Analysis

5.1 Construction of the Real Numbers

Definition 5.1 (Cut). A *cut* is a subset α of \mathbb{Q} such that:

- $\emptyset \neq \alpha \neq \mathbb{Q}$
- α is closed downwards.
- α has no greatest element.

In this section, we write R for the set of all cuts.

Proposition 5.2. *R is linearly ordered by \subseteq .*

PROOF: The only difficult part is to prove that, for any cuts α and β , either $\alpha \subseteq \beta$ or $\beta \subseteq \alpha$.

$\langle 1 \rangle 1$. ASSUME: $\alpha \not\subseteq \beta$

PROVE: $\beta \subseteq \alpha$

$\langle 1 \rangle 2$. PICK $q \in \alpha$ such that $q \notin \beta$

$\langle 1 \rangle 3$. LET: $r \in \beta$

$\langle 1 \rangle 4$. $q \not\leq r$

$\langle 1 \rangle 5$. $r < q$

$\langle 1 \rangle 6$. $r \in \alpha$

□

Proposition 5.3. *R has the least upper bound property.*

PROOF:

$\langle 1 \rangle 1$. LET: $E \subseteq R$ be nonempty and bounded above.

$\langle 1 \rangle 2$. LET: $s = \bigcup E$

PROVE: s is a cut.

$\langle 1 \rangle 3$. $\emptyset \neq s$

PROOF: Since E is nonempty and every element of E is nonempty.

$\langle 1 \rangle 4$. $s \neq \mathbb{Q}$

- ⟨2⟩1. PICK an upper bound u for E .
- ⟨2⟩2. PICK $q \notin u$
 PROVE: $q \notin s$
- ⟨2⟩3. $\forall \alpha \in E. \alpha \subseteq u$
- ⟨2⟩4. $s \subseteq u$
- ⟨2⟩5. $q \notin s$
- ⟨1⟩5. s is closed downwards.
- ⟨2⟩1. LET: $q \in s$ and $r < q$.
- ⟨2⟩2. PICK $\alpha \in E$ such that $q \in \alpha$.
- ⟨2⟩3. $r \in \alpha$
- ⟨2⟩4. $r \in s$
- ⟨1⟩6. s has no greatest element.
- ⟨2⟩1. LET: $q \in s$
- ⟨2⟩2. PICK $\alpha \in E$ such that $q \in \alpha$.
- ⟨2⟩3. PICK $r \in \alpha$ such that $q < r$.
- ⟨2⟩4. $r \in s$

□

Definition 5.4 (Addition). Given cuts α and β , we define

$$\alpha + \beta = \{q + r : q \in \alpha, r \in \beta\} .$$

Proposition 5.5. *Given cuts α and β , we have $\alpha + \beta$ is a cut.*

PROOF:

- ⟨1⟩1. $\alpha + \beta$ is nonempty.
 PROOF: Since α and β are nonempty.
- ⟨1⟩2. $\alpha + \beta \neq \mathbb{Q}$
 - ⟨2⟩1. PICK $q \in \mathbb{Q} - \alpha$ and $r \in \mathbb{Q} - \beta$.
 PROVE: $q + r \notin \alpha + \beta$
 - ⟨2⟩2. ASSUME: for a contradiction $q + r \in \alpha + \beta$.
 - ⟨2⟩3. PICK $x \in \alpha$ and $y \in \beta$ such that $q + r = x + y$
 - ⟨2⟩4. $x < q$
 - ⟨2⟩5. $y < r$
 - ⟨2⟩6. $x + y < q + r$
 - ⟨2⟩7. Q.E.D.
- PROOF: This is a contradiction.
- ⟨1⟩3. $\alpha + \beta$ is closed downwards.
 - ⟨2⟩1. LET: $q \in \alpha, r \in \beta$ and $x < q + r$
 - ⟨2⟩2. $x - q < r$
 - ⟨2⟩3. $x - q \in \beta$
 - ⟨2⟩4. $x \in \alpha + \beta$
- ⟨1⟩4. $\alpha + \beta$ has no greatest element.
 - ⟨2⟩1. LET: $q \in \alpha$ and $r \in \beta$.
 PROVE: $q + r$ is not greatest in $\alpha + \beta$.
 - ⟨2⟩2. PICK $q' \in \alpha$ with $q < q'$ and $r' \in \beta$ with $r < r'$.
 - ⟨2⟩3. $q + r < q' + r' \in \alpha + \beta$

□

Proposition 5.6. *Addition is commutative and associative on R .*

PROOF: Immediate from definitions and the fact that addition is commutative and associative on \mathbb{Q} . □

Definition 5.7. For any $q \in \mathbb{Q}$, let $q^* = \{r \in \mathbb{Q} : r < q\}$.

Proposition 5.8. *For any $q \in \mathbb{Q}$, we have q^* is a cut.*

PROOF:

⟨1⟩1. $q^* \neq \emptyset$

PROOF: Since $q - 1 \in q^*$.

⟨1⟩2. $q^* \neq \mathbb{Q}$

PROOF: Since $q \notin q^*$.

⟨1⟩3. q^* is closed downwards.

PROOF: Immediate from definition.

⟨1⟩4. q^* has no greatest element.

PROOF: For all $r \in q^*$ we have $r < (q + r)/2 \in q^*$.

□

Proposition 5.9. *For any cut α we have $\alpha + 0^* = \alpha$.*

PROOF:

⟨1⟩1. $\alpha + 0^* \subseteq \alpha$

⟨2⟩1. LET: $q \in \alpha$ and $r \in 0^*$

PROVE: $q + r \in \alpha$

⟨2⟩2. $r < 0$

⟨2⟩3. $q + r < q$

⟨2⟩4. $q + r \in \alpha$

⟨1⟩2. $\alpha \subseteq \alpha + 0^*$

⟨2⟩1. LET: $q \in \alpha$

⟨2⟩2. PICK $r \in \alpha$ such that $q < r$

⟨2⟩3. $q = r + (q - r) \in \alpha + 0^*$

□

Proposition 5.10. *For any cut α , there exists a cut β such that $\alpha + \beta = 0$.*

PROOF:

⟨1⟩1. LET: $\beta = \{p \in \mathbb{Q} : \exists r > 0. -p - r \notin \alpha\}$

⟨1⟩2. β is a cut.

⟨2⟩1. $\beta \neq \emptyset$

⟨3⟩1. PICK $q \notin \alpha$

⟨3⟩2. $-q - 1 \in \beta$

⟨2⟩2. $\beta \neq \mathbb{Q}$

⟨3⟩1. PICK $q \in \alpha$

PROVE: $-q \notin \beta$

⟨3⟩2. ASSUME: for a contradiction $-q \in \beta$

- $\langle 3 \rangle 3$. PICK $r > 0$ such that $q - r \notin \alpha$
- $\langle 3 \rangle 4$. $q - r < q$
- $\langle 3 \rangle 5$. Q.E.D.

PROOF: This contradicts the fact that α is closed downwards.

- $\langle 2 \rangle 3$. β is closed downwards.
 - $\langle 3 \rangle 1$. LET: $p \in \beta$ and $q < p$.
 - $\langle 3 \rangle 2$. PICK $r > 0$ such that $-p - r \notin \alpha$
 - $\langle 3 \rangle 3$. $-p - r < -q - r$
 - $\langle 3 \rangle 4$. $-q - r \notin \alpha$
 - $\langle 3 \rangle 5$. $q \in \beta$
- $\langle 2 \rangle 4$. β has no greatest element.
 - $\langle 3 \rangle 1$. LET: $p \in \beta$
 - $\langle 3 \rangle 2$. PICK $r > 0$ such that $-p - r \notin \alpha$
 - $\langle 3 \rangle 3$. $-(p + r/2) - r/2 \notin \alpha$
 - $\langle 3 \rangle 4$. $p + r/2 \in \beta$
- $\langle 1 \rangle 3$. $\alpha + \beta \subseteq 0^*$
 - $\langle 2 \rangle 1$. LET: $p \in \alpha$ and $q \in \beta$.
 - $\langle 2 \rangle 2$. PICK $r > 0$ such that $-q - r \notin \alpha$.
 - $\langle 2 \rangle 3$. $p < -q - r$
 - $\langle 2 \rangle 4$. $p + q < -r$
 - $\langle 2 \rangle 5$. $p + q < 0$
 - $\langle 2 \rangle 6$. $p + q \in 0^*$
- $\langle 1 \rangle 4$. $0^* \subseteq \alpha + \beta$
 - $\langle 2 \rangle 1$. LET: $v \in 0^*$
 - $\langle 2 \rangle 2$. LET: $w = -v/2$
 - $\langle 2 \rangle 3$. $w > 0$
 - $\langle 2 \rangle 4$. PICK an integer n such that $nw \in \alpha$ and $(n + 1)w \notin \alpha$.
 - $\langle 2 \rangle 5$. LET: $p = -(n + 2)w$
 - $\langle 2 \rangle 6$. $p \in \beta$
 - $\langle 2 \rangle 7$. $v = nw + p$
 - $\langle 2 \rangle 8$. $v \in \alpha + \beta$

□

Proposition 5.11. *Given $\alpha, \beta, \gamma \in R$, if $\beta < \gamma$, then $\alpha + \beta < \alpha + \gamma$.*

PROOF:

- $\langle 1 \rangle 1$. $\alpha + \beta \subseteq \alpha + \gamma$
 PROOF: Immediate from definitions.
- $\langle 1 \rangle 2$. $\alpha + \beta \neq \alpha + \gamma$
 PROOF: If $\alpha + \beta = \alpha + \gamma$ then $\beta = \gamma$ by cancellation.

□

Definition 5.12. Given cuts α and β , define $\alpha\beta$ by:

$$\alpha\beta = \begin{cases} \{p \in \mathbb{Q} : \exists r \in \alpha. \exists s \in \beta (p \leq rs \wedge r > 0 \wedge s > 0)\} & \text{if } \alpha > 0^* \text{ and } \beta > 0^* \\ (-\alpha)(-\beta) & \text{if } \alpha < 0^* \text{ and } \beta < 0^* \\ -((-\alpha)\beta) & \text{if } \alpha < 0^* \text{ and } \beta > 0^* \\ -(\alpha(-\beta)) & \text{if } \alpha > 0^* \text{ and } \beta < 0^* \\ 0^* & \text{if } \alpha = 0^* \text{ or } \beta = 0^* \end{cases}$$

Proposition 5.13. For any cuts α and β , we have $\alpha\beta$ is a cut.

PROOF:

(1)1. If $\alpha > 0^*$ and $\beta > 0^*$ then $\alpha\beta$ is a cut.

(2)1. $\alpha\beta \neq \emptyset$

(3)1. PICK $q \in \alpha$ and $r \in \beta$ such that $q, r \notin 0^*$

(3)2. ASSUME: w.l.o.g. $0 < q$ and $0 < r$.

PROOF: Since α and β have no greatest element.

(3)3. $qr \in \alpha\beta$

(2)2. $\alpha\beta \neq \mathbb{Q}$

(3)1. PICK $r \notin \alpha$ and $s \notin \beta$

PROVE: $rs \notin \alpha\beta$

(3)2. ASSUME: for a contradiction $rs \in \alpha\beta$.

(3)3. PICK $r' \in \alpha$ and $s' \in \beta$ such that $rs \leq r's'$ and $r' > 0$ and $s' > 0$.

(3)4. $r' < r$ and $s' < s$

(3)5. $r's' < rs$

(3)6. Q.E.D.

PROOF: This is a contradiction.

(2)3. $\alpha\beta$ is closed downwards.

(3)1. LET: $p \in \alpha\beta$ and $p' < p$

(3)2. PICK $r \in \alpha$ and $s \in \beta$ such that $p \leq rs$, $r > 0$ and $s > 0$

(3)3. $p' \leq rs$

(3)4. $p' \in \alpha\beta$

(2)4. $\alpha\beta$ has no greatest element.

(3)1. LET: $p \in \alpha\beta$

(3)2. PICK $r \in \alpha$ and $s \in \beta$ such that $p \leq rs$, $r > 0$ and $s > 0$.

(3)3. PICK $r' \in \alpha$ and $s' \in \beta$ with $r < r'$ and $s < s'$.

(3)4. $p < r's' \in \alpha\beta$

(1)2. For any cuts α and β , we have $\alpha\beta$ is a cut.

PROOF: Since if α is a cut then $-\alpha$ is a cut.

□

Proposition 5.14. For any cuts α and β we have $\alpha\beta = \beta\alpha$.

PROOF: Easy from the definitions. □

Proposition 5.15. For any cuts α , β and γ we have

$$\alpha(\beta\gamma) = (\alpha\beta)\gamma .$$

PROOF:

$\langle 1 \rangle 1$. CASE: α , β and γ are all positive.

PROOF: In this case $\alpha(\beta\gamma) = (\alpha\beta)\gamma = \{p \in \mathbb{Q} : \exists r \in \alpha. \exists s \in \beta. \exists t \in \gamma. (p \leq rst \wedge r > 0 \wedge s > 0 \wedge t > 0)\}$.

$\langle 1 \rangle 2$. CASE: One of α , β or γ is 0^* .

PROOF: Then $\alpha(\beta\gamma) = (\alpha\beta)\gamma = 0^*$.

$\langle 1 \rangle 3$. CASE: α and β are positive, γ is negative.

PROOF:

$$\begin{aligned} \alpha(\beta\gamma) &= \alpha(-(\beta(-\gamma))) \\ &= -(\alpha(\beta(-\gamma))) \\ &= -((\alpha\beta)(-\gamma)) & (\langle 1 \rangle 1) \\ &= (\alpha\beta)\gamma \end{aligned}$$

$\langle 1 \rangle 4$. CASE: α is positive, β is negative, γ is positive.

PROOF:

$$\begin{aligned} \alpha(\beta\gamma) &= \alpha(-((- \beta)\gamma)) \\ &= -(\alpha((- \beta)\gamma)) \\ &= -((\alpha(- \beta))\gamma) & (\langle 1 \rangle 1) \\ &= (-(\alpha(- \beta)))\gamma \\ &= (\alpha\beta)\gamma \end{aligned}$$

$\langle 1 \rangle 5$. CASE: α is positive, β and γ are negative.

PROOF:

$$\begin{aligned} \alpha(\beta\gamma) &= \alpha((- \beta)(- \gamma)) \\ &= (\alpha(- \beta))(- \gamma) & (\langle 1 \rangle 1) \\ &= (-(\alpha\beta))(- \gamma) \\ &= (\alpha\beta)\gamma \end{aligned}$$

$\langle 1 \rangle 6$. CASE: α is negative, β and γ are positive.

PROOF: Similar to $\langle 1 \rangle 3$.

$\langle 1 \rangle 7$. CASE: α is negative, β is positive, γ is negative.

PROOF:

$$\begin{aligned} \alpha(\beta\gamma) &= \alpha(-(\beta(-\gamma))) \\ &= (-\alpha)(\beta(-\gamma)) \\ &= ((-\alpha)\beta)(-\gamma) & (\langle 1 \rangle 1) \\ &= (-(\alpha\beta))(-\gamma) \\ &= (\alpha\beta)\gamma \end{aligned}$$

$\langle 1 \rangle 8$. CASE: α and β are negative, γ is positive.

PROOF: Similar to $\langle 1 \rangle 5$.

$\langle 1 \rangle 9$. CASE: α , β and γ are all negative.

PROOF:

$$\begin{aligned}
 \alpha(\beta\gamma) &= \alpha(-(-\beta)(-\gamma)) \\
 &= -((- \alpha)((-\beta)(-\gamma))) \\
 &= -(((- \alpha)(-\beta))(-\gamma)) & ((1)1) \\
 &= -((\alpha\beta)(-\gamma)) \\
 &= (\alpha\beta)\gamma
 \end{aligned}$$

□

Proposition 5.16. *For any cut α we have $\alpha 1^* = \alpha$.*

PROOF:

$\langle 1 \rangle 1$. CASE: α is positive.

$\langle 2 \rangle 1$. $\alpha 1^* \subseteq \alpha$

$\langle 2 \rangle 2$. $\alpha \subseteq \alpha 1^*$

$\langle 1 \rangle 2$. CASE: $\alpha = 0^*$

$\langle 1 \rangle 3$. CASE: α is negative.

□

Theorem 5.17. *There exists an ordered field with the least upper bound property.*

Proposition 5.18. *There is no rational p such that $p^2 = 2$.*

PROOF:

$\langle 1 \rangle 1$. ASSUME: for a contradiction $p^2 = 2$.

$\langle 1 \rangle 2$. PICK integers m, n not both even such that $p = m/n$.

$\langle 1 \rangle 3$. $m^2 = 2n^2$

$\langle 1 \rangle 4$. m is even.

$\langle 1 \rangle 5$. PICK an integer k such that $m = 2k$.

$\langle 1 \rangle 6$. $4k^2 = 2n^2$

$\langle 1 \rangle 7$. $2k^2 = n^2$

$\langle 1 \rangle 8$. n is even.

$\langle 1 \rangle 9$. Q.E.D.

PROOF: $\langle 1 \rangle 2$, $\langle 1 \rangle 4$ and $\langle 1 \rangle 8$ form a contradiction.

□

Theorem 5.19. *Any two complete ordered fields are isomorphic.*

Definition 5.20. Let \mathbb{R} be the complete ordered field. We call its elements *real numbers*.

5.2 Properties of the Real Numbers

Theorem 5.21. \mathbb{Q} is a subfield of \mathbb{R} .

Theorem 5.22 (Archimedean Property). *Let $x, y \in \mathbb{R}$ with $x > 0$. There exists a positive integer n such that $nx > y$.*

PROOF:

- (1)1. LET: $A = \{nx : n \in \mathbb{Z}^+\}$
- (1)2. ASSUME: for a contradiction there is no positive integer n such that $nx > y$.
- (1)3. y is an upper bound for A .
- (1)4. LET: $\alpha = \sup A$
- (1)5. $\alpha - x$ is not an upper bound for A .
- (1)6. PICK a positive integer m such that $\alpha - x < mx$
- (1)7. $\alpha < (m+1)x \in A$
- (1)8. Q.E.D.

PROOF: This contradicts (1)4.

□

Theorem 5.23. \mathbb{Q} is dense in \mathbb{R} .

PROOF:

- (1)1. LET: $x, y \in \mathbb{R}$ with $x < y$
- (1)2. PICK a positive integer n such that $n(y-x) > 1$.
- PROOF: Archimedean property.
- (1)3. PICK a positive integer m_1 such that $m_1 > nx$
- PROOF: Archimedean property.
- (1)4. PICK a positive integer m_2 such that $m_2 > -nx$
- PROOF: Archimedean property.
- (1)5. $-m_2 < nx < m_1$
- (1)6. LET: m be the integer such that $m-1 \leq nx < m$.
- (1)7. $nx < m \leq 1 + nx < ny$
- (1)8. $x < m/n < y$

□

Theorem 5.24. For every real number $x > 0$ and positive integer n , there exists a unique positive real number y such that $y^n = x$.

PROOF:

- (1)1. There exists a real $y > 0$ such that $y^n = x$.
- (2)1. LET: $E = \{t \in \mathbb{R}^+ : t^n < x\}$
- (2)2. LET: $y = \sup E$
- (3)1. $E \neq \emptyset$
- (4)1. LET: $t = x/(x+1)$
- (4)2. $0 < t < 1$
- (4)3. $t^n < t < x$
- (4)4. $t \in E$
- (3)2. $x+1$ is an upper bound for E .
- (4)1. LET: $t > x+1$
- (4)2. $t^n > t > x$
- (4)3. $t \notin E$

⟨2⟩3. $y^n = x$

⟨3⟩1. $y^n \not\leq x$

⟨4⟩1. ASSUME: for a contradiction $y^n < x$.

⟨4⟩2. PICK h such that $0 < h < 1$ and

$$h < \frac{x - y^n}{n(y + 1)^{n-1}} .$$

⟨4⟩3. $(y + h)^n - y^n < x - y^n$

PROOF:

$$\begin{aligned} (y + h)^n - y^n &= ((y + h) - y) \sum_{i=0}^{n-1} (y + h)^{n-1-i} y^i \\ &= h \sum_{i=0}^{n-1} (y + h)^{n-1-i} y^i \\ &\leq hn(y + h)^{n-1} \\ &\leq hn(y + 1)^{n-1} \\ &< x - y^n \end{aligned}$$

⟨4⟩4. $(y + h)^n < x$

⟨4⟩5. $y + h \in E$

⟨4⟩6. Q.E.D.

PROOF: This contradicts the fact that y is an upper bound for E .

⟨3⟩2. $y^n \not\geq x$

⟨4⟩1. ASSUME: for a contradiction $y^n > x$

⟨4⟩2. LET:

$$k = \frac{y^n - x}{ny^{n-1}}$$

⟨4⟩3. $0 < k < y$

⟨4⟩4. $y - k$ is an upper bound for E .

⟨5⟩1. LET: $t \geq y - k$

⟨5⟩2. $y^n - t^n \leq y^n - x$

PROOF:

$$\begin{aligned} y^n - t^n &\leq y^n - (y - k)^n \\ &= (y - (y - k)) \sum_{i=0}^{n-1} y^{n-i} (y - k)^i \\ &= k \sum_{i=0}^{n-1} y^{n-i} (y - k)^i \\ &\leq kny^{n-1} \\ &= y^n - x \end{aligned}$$

⟨5⟩3. $t^n \geq x$

⟨5⟩4. $t \notin E$

⟨4⟩5. Q.E.D.

PROOF: This contradicts the fact that y is the least upper bound of E .

⟨1⟩2. If y and y' are positive reals with $y^n = y'^n$ then $y = y'$.

PROOF: Since the function that sends y to y^n is strictly monotone.
 \square

Definition 5.25 (*n th Root*). Given any real number $x > 0$ and positive integer n , the n th root of x , denoted $x^{1/n}$, is the unique positive real such that

$$(x^{1/n})^n = x .$$

We write \sqrt{x} for $x^{1/2}$.

Proposition 5.26. Let a and b be positive real numbers and n a positive integer. Then

$$(ab)^{1/n} = a^{1/n}b^{1/n} .$$

PROOF: Since $(a^{1/n}b^{1/n})^n = ab$. \square

Lemma 5.27. Let b be a real number with $b > 1$. Let n be a positive integer. Then

$$b - 1 \geq n(b^{1/n} - 1) .$$

PROOF: From Lemma 4.24. \square

Lemma 5.28. Let b and t be real numbers with $b > 1$ and $t > 1$. For any positive integer n , if $n > \frac{b-1}{t-1}$ then $b^{1/n} < t$.

PROOF:

$$\begin{aligned} b - 1 &\geq n(b^{1/n} - 1) \\ \therefore \frac{b - 1}{n} &\geq b^{1/n} - 1 \\ \therefore t - 1 &> b^{1/n} - 1 \\ \therefore t &> b^{1/n} \end{aligned}$$

\square

Lemma 5.29. Let b be a real number with $b > 0$. Let m, n, p, q be integers with $n > 0$ and $q > 0$. Assume $m/n = p/q$. Then

$$(b^m)^{1/n} = (b^p)^{1/q} .$$

PROOF:

$$\langle 1 \rangle 1. (b^m)^{1/n} = (b^{1/n})^m$$

PROOF:

$$\begin{aligned} ((b^{1/n})^m)^n &= ((b^{1/n})^n)^m \\ &= b^m \end{aligned}$$

$$\langle 1 \rangle 2. ((b^m)^{1/n})^q = b^p$$

PROOF:

$$\begin{aligned} ((b^m)^{1/n})^q &= (b^{1/n})^{mq} \\ &= (b^{1/n})^{np} \\ &= b^p \end{aligned}$$

\square

Definition 5.30. For a a positive real and q a rational number, we may therefore define a^q by

$$a^{m/n} = (a^m)^{1/n}$$

for m and n integers with $n > 0$.

Proposition 5.31. Let a be a positive real and r, s rational numbers. Then

$$a^{r+s} = a^r a^s .$$

PROOF:

$$\begin{aligned} a^{m/n+p/q} &= a^{(mq+np)/nq} \\ &= (a^{mq+np})^{1/nq} \\ &= (a^{mq})^{1/nq} (a^{np})^{1/nq} \\ &= a^{m/n} a^{p/q} \end{aligned} \quad \square$$

Proposition 5.32. Let $b > 1$ be a real number and q a rational number. Then

$$b^q = \sup\{b^t : t \in \mathbb{Q}, t \leq q\}$$

PROOF: It is the greatest element of this set. \square

Definition 5.33. Let $b > 1$ be a real number and x a real number. Then

$$b^x = \sup\{b^t : t \in \mathbb{Q}, t \leq x\} .$$

Lemma 5.34. Let b, w and y be real numbers with $b > 1$. Assume $b^w < y$. Then there exists a positive integer n such that $b^{w+1/n} < y$.

PROOF:

- $\langle 1 \rangle 1$. LET: $t = yb^{-w}$
- $\langle 1 \rangle 2$. PICK a positive integer n such that $n > \frac{b-1}{t-1}$.
- $\langle 1 \rangle 3$. $b^{1/n} < t$

PROOF: Lemma 5.28.

- $\langle 1 \rangle 4$. $b^{w+1/n} < y$

\square

Lemma 5.35. Let b, w and y be real numbers with $b > 1$. Assume $b^w > y$. Then there exists a positive integer n such that $b^{w-1/n} < y$.

PROOF:

- $\langle 1 \rangle 1$. LET: $t = b^w/y$
- $\langle 1 \rangle 2$. PICK a positive integer n such that $n > \frac{b-1}{t-1}$
- $\langle 1 \rangle 3$. $b^{1/n} < t$

PROOF: Lemma 5.28.

- $\langle 1 \rangle 4$. $y < b^{w-1/n}$

\square

Proposition 5.36. *For b and x real numbers with $b > 1$ we have*

$$b^x = \sup\{b^t : t \in \mathbb{Q}, t < x\} .$$

PROOF:

- $\langle 1 \rangle 1.$ b^x is an upper bound for $\{b^t : t \in \mathbb{Q}, t < x\}$.
- $\langle 1 \rangle 2.$ LET: u be any upper bound for $\{b^t : t \in \mathbb{Q}, t < x\}$.
PROVE: $b^x \leq u$
- $\langle 1 \rangle 3.$ LET: q be a rational number with $q \leq x$.
PROVE: $b^q \leq u$
- $\langle 1 \rangle 4.$ ASSUME: for a contradiction $b^q > u$.
- $\langle 1 \rangle 5.$ PICK a positive integer n such that $b^{q-1/n} > u$.
PROOF: Lemma 5.35.
- $\langle 1 \rangle 6.$ $b^{q-1/n} \leq u$
PROOF: $\langle 1 \rangle 2$
- $\langle 1 \rangle 7.$ Q.E.D.
PROOF: This contradicts $\langle 1 \rangle 4$.

□

Lemma 5.37. *Let A be a set of positive real numbers with supremum $a > 0$ and B a set of positive real numbers with supremum $b > 0$. Then ab is the supremum of $\{xy : x \in A, y \in B\}$.*

PROOF:

- $\langle 1 \rangle 1.$ For all $x \in A$ and $y \in B$ we have $xy \leq ab$.
- $\langle 1 \rangle 2.$ If u is any upper bound for $\{xy : x \in A, y \in B\}$ then $ab \leq u$.
 - $\langle 2 \rangle 1.$ LET: u be an upper bound for $\{xy : x \in A, y \in B\}$.
 - $\langle 2 \rangle 2.$ For all $x \in A$ we have u/x is an upper bound for B .
 - $\langle 2 \rangle 3.$ For all $x \in A$ we have $b \leq u/x$
 - $\langle 2 \rangle 4.$ For all $x \in A$ we have $x \leq u/b$
 - $\langle 2 \rangle 5.$ $a \leq u/b$
 - $\langle 2 \rangle 6.$ $ab \leq u$

□

Proposition 5.38. *Let $b, x, y \in \mathbb{R}$ with $b > 1$. Then*

$$b^{x+y} = b^x b^y .$$

PROOF:

- $\langle 1 \rangle 1.$ For any rational number $q < x + y$, there exist rational numbers $r < x$ and $s < y$ such that $q = r + s$.
 - $\langle 2 \rangle 1.$ $q - x < y$
 - $\langle 2 \rangle 2.$ PICK a rational t such that $q - x < t < y$
 - $\langle 2 \rangle 3.$ $q = t + (q - t)$ and $t < y, q - t < x$
- $\langle 1 \rangle 2.$ $b^x b^y = b^{x+y}$

PROOF:

$$\begin{aligned}
 b^x b^y &= \sup\{b^q b^r : q, r \in \mathbb{Q}, q < x, r < y\} \\
 &= \sup\{b^{q+r} : q, r \in \mathbb{Q}, q < x, r < y\} \\
 &= \sup\{b^q : q \in \mathbb{Q}, q < x + y\} \\
 &= b^{x+y}
 \end{aligned}$$

□

5.2.1 Logarithms

Proposition 5.39. *Let b and y be real numbers with $b > 1$ and $y > 0$. There exists a unique real x such that $b^x = y$.*

PROOF:

⟨1⟩1. LET: $x = \sup\{w : b^w < y\}$

PROVE: $b^x = y$

⟨2⟩1. $\{w : b^w < y\} \neq \emptyset$

PROOF: It contains 0.

⟨2⟩2. $\{w : b^w < y\}$ is bounded above.

⟨3⟩1. LET: n be the least integer such that

$$n \geq \frac{y-1}{b-1}$$

PROOF: Archimedean property.

⟨3⟩2. LET: w be a real number with $b^w < y$

PROVE: $w < n$

⟨3⟩3. $b^w < n(b-1) + 1$

⟨3⟩4. $b^w < b^n$

⟨3⟩5. $w < n$

⟨1⟩2. $b^x \leq y$

⟨2⟩1. ASSUME: for a contradiction $b^x > y$

⟨2⟩2. PICK a positive integer n such that $b^{x-1/n} > y$

PROOF: Lemma 5.35.

⟨2⟩3. PICK w such that $x - 1/n < w$ and $b^w < y$

PROOF: Since $x - 1/n$ is not an upper bound for $\{w : b^w < y\}$.

⟨2⟩4. $b^{x-1/n} < y$

⟨2⟩5. Q.E.D.

PROOF: This contradicts ⟨2⟩2.

⟨1⟩3. $b^x \geq y$

⟨2⟩1. ASSUME: for a contradiction $b^x < y$.

⟨2⟩2. PICK a positive integer n such that $b^{x+1/n} < y$.

⟨2⟩3. $x + 1/n \leq x$

⟨2⟩4. Q.E.D.

PROOF: This is a contradiction.

□

Definition 5.40 (Logarithm). Let b and y be real numbers with $b > 1$ and $y > 0$. The *logarithm* of y to base b , denoted $\log_b y$, is the unique real number

such that

$$b^{\log_b y} = y .$$

5.2.2 Intervals

Definition 5.41 (Intervals). Let $a, b \in \mathbb{R}$.

The *open interval* (a, b) is $\{x \in \mathbb{R} : a < x < b\}$.

The *closed interval* $[a, b]$ is $\{x \in \mathbb{R} : a \leq x \leq b\}$.

The *half-open intervals* $[a, b)$ and $(a, b]$ are defined by

$$[a, b) := \{x \in \mathbb{R} : a \leq x < b\}$$

$$(a, b] := \{x \in \mathbb{R} : a < x \leq b\}$$

Proposition 5.42. Let (I_n) be a sequence of closed intervals with $I_0 \supseteq I_1 \supseteq \dots$. Then $\bigcap_{n=0}^{\infty} I_n$ is nonempty.

PROOF:

$\langle 1 \rangle 1$. LET: $I_n = [a_n, b_n]$

$\langle 1 \rangle 2$. LET: $x = \sup_n a_n$

PROOF: $\{a_n : n \in \mathbb{N}\}$ is bounded above by b_0 .

$\langle 1 \rangle 3$. $x \in \bigcap_{n=0}^{\infty} I_n$

PROOF: For all n we have $a_n \leq x \leq b_n$ since b_n is an upper bound for $\{a_n : n \in \mathbb{N}\}$.

□

Definition 5.43 (k -cell). Let k be a positive integer. A k -cell is a subset of \mathbb{R}^k of the form

$$\{\vec{x} \in \mathbb{R}^k : \forall i = 1, \dots, k. a_i \leq x_i \leq b_i\}$$

for some real numbers $a_1, \dots, a_k, b_1, \dots, b_k$ with $a_i \leq b_i$ for each i .

Proposition 5.44. Let (I_n) be a sequence of k -cells such that $I_0 \supseteq I_1 \supseteq \dots$. Then $\bigcap_{n=0}^{\infty} I_n \neq \emptyset$.

PROOF:

$\langle 1 \rangle 1$. LET: $I_n = J_{n1} \times \dots \times J_{nk}$ where each J_{ni} is a closed interval.

$\langle 1 \rangle 2$. For $i = 1, \dots, k$, PICK $a_i \in \bigcap_{n=0}^{\infty} J_{ni}$.

$\langle 1 \rangle 3$. $(a_1, \dots, a_k) \in \bigcap_{n=0}^{\infty} I_n$

□

5.2.3 The Cantor Set

Definition 5.45 (Cantor Set). Define a sequence E_n of unions of intervals as follows:

- $E_0 = [0, 1]$
- E_{n+1} is formed from E_n by replacing every interval $[a, b]$ with $[a, (2a+b)/3]$ and $[(a+2b)/3, b]$.

The *Cantor set* is $\bigcap_{n=0}^{\infty} E_n$.

5.3 The Extended Real Number System

Definition 5.46 (Extended Real Number System). The *extended real number system* is the set $\mathbb{R} \cup \{+\infty, -\infty\}$.

We extend the ordering \leq to the extended reals by defining

$$-\infty < x < +\infty$$

for every $x \in \mathbb{R}$.

We extend $+$, \cdot and $/$ to partial operations on the extended real by defining:

$$\begin{aligned} x + (+\infty) &= +\infty & (x \in \mathbb{R}) \\ x + (-\infty) &= -\infty & (x \in \mathbb{R}) \\ (+\infty) + x &= +\infty & (x \in \mathbb{R}) \\ (+\infty) + (+\infty) &\text{ is undefined} \\ (+\infty) + (-\infty) &\text{ is undefined} \\ (-\infty) + x &= -\infty & (x \in \mathbb{R}) \\ (-\infty) + (+\infty) &\text{ is undefined} \\ (-\infty) + (-\infty) &\text{ is undefined} \\ x \cdot (+\infty) &= +\infty & (x \in \mathbb{R}) \\ x \cdot (-\infty) &= -\infty & (x \in \mathbb{R}) \\ (+\infty) \cdot x &= +\infty & (x \in \mathbb{R}) \\ (+\infty) \cdot (+\infty) &\text{ is undefined} \\ (+\infty) \cdot (-\infty) &\text{ is undefined} \\ (-\infty) \cdot x &= -\infty & (x \in \mathbb{R}) \\ (-\infty) \cdot (+\infty) &\text{ is undefined} \\ (-\infty) \cdot (-\infty) &\text{ is undefined} \\ x / (+\infty) &= 0 & (x \in \mathbb{R}) \\ x / (-\infty) &= 0 & (x \in \mathbb{R}) \\ (+\infty) / x &\text{ is undefined} & (x \in \mathbb{R}) \\ (+\infty) / (+\infty) &\text{ is undefined} \\ (+\infty) / (-\infty) &\text{ is undefined} \\ (-\infty) / x &\text{ is undefined} & (x \in \mathbb{R}) \\ (-\infty) / (+\infty) &\text{ is undefined} \\ (-\infty) / (-\infty) &\text{ is undefined} \end{aligned}$$

Chapter 6

Complex Analysis

Definition 6.1 (Complex Numbers). A *complex number* is a pair of real numbers. We write \mathbb{C} for the set of complex numbers.

Define $+$ and \cdot on \mathbb{C} by:

$$\begin{aligned}(a, b) + (c, d) &= (a + c, b + d) \\ (a, b)(c, d) &= (ac - bd, ad + bc)\end{aligned}$$

Theorem 6.2. *The complex numbers form a field.*

Theorem 6.3. *The function that maps a to $(a, 0)$ is an embedding of \mathbb{R} in \mathbb{C} .*

Definition 6.4.

$$i = (0, 1)$$

Lemma 6.5.

$$(a, b) = a + ib$$

PROOF: Since $(a, 0) + (0, 1)(b, 0) = (a, b)$. \square

Lemma 6.6.

$$i^2 = -1$$

PROOF: Immediate from definitions. \square

Corollary 6.6.1. *There is no linear order on \mathbb{C} that makes \mathbb{C} into an ordered field.*

Definition 6.7 (Complex Conjugate). For any complex number z , the *complex conjugate* \bar{z} is defined by

$$\overline{a + ib} = a - ib \quad (a, b \in \mathbb{R}) .$$

Definition 6.8 (Real Part). For any complex number z , the *real part* of z , denoted $\operatorname{Re}(z)$, is defined by

$$\operatorname{Re}(a + ib) = a \quad (a, b \in \mathbb{R}) .$$

Definition 6.9 (Imaginary Part). For any complex number z , the *imaginary part* of z , denoted $\text{Im}(z)$, is defined by

$$\text{Im}(a + ib) = b \quad (a, b \in \mathbb{R}) .$$

Theorem 6.10. For all $z, w \in \mathbb{C}$ we have

$$\overline{z + w} = \bar{z} + \bar{w} .$$

PROOF:

$$\begin{aligned} \overline{(a + ib) + (c + id)} &= \overline{(a + c) + i(b + d)} \\ &= (a + c) - i(b + d) \\ &= (a - ib) + (c - id) \\ &= \overline{a + ib} + \overline{c + id} \end{aligned} \quad \square$$

Theorem 6.11. For all $z, w \in \mathbb{C}$ we have

$$\overline{zw} = \bar{z} \cdot \bar{w} .$$

PROOF:

$$\begin{aligned} \overline{(a + ib)(c + id)} &= \overline{(ac - bd) + i(ad + bc)} \\ &= (ac - bd) - i(ad + bc) \\ &= (a - ib)(c - id) \\ &= \overline{a + ib} \cdot \overline{c + id} \end{aligned} \quad \square$$

Theorem 6.12. For all $z \in \mathbb{C}$ we have

$$\text{Re}(z) = \frac{1}{2}(z + \bar{z}) .$$

PROOF:

$$\begin{aligned} (a + ib) + \overline{a + ib} &= (a + ib) + (a - ib) \\ &= 2a \\ &= 2 \text{Re}(a + ib) \end{aligned} \quad \square$$

Theorem 6.13. For all $z \in \mathbb{C}$ we have

$$\text{Im}(z) = \frac{1}{2i}(z - \bar{z}) .$$

PROOF:

$$\begin{aligned} (a + ib) - \overline{a + ib} &= (a + ib) - (a - ib) \\ &= 2ib \\ &= 2i \text{Im}(a + ib) \end{aligned} \quad \square$$

Theorem 6.14. For all $z \in \mathbb{C}$ we have $z\bar{z}$ is a non-negative real.

PROOF:

$$\begin{aligned}(a + ib)(\overline{a + ib}) &= (a + ib)(a - ib) \\ &= a^2 + b^2\end{aligned}\quad \square$$

Theorem 6.15. *For any $z \in \mathbb{C}$, if $z\bar{z} = 0$ then $z = 0$.*

PROOF: Let $z = a + ib$. Then $z\bar{z} = a^2 + b^2 = 0$ iff $a = b = 0$. \square

Definition 6.16 (Absolute Value). For $z \in \mathbb{C}$, the *absolute value* of z is

$$|z| = (z\bar{z})^{1/2}.$$

Proposition 6.17. *For x a non-negative real we have $|x| = x$.*

PROOF: Since $|x| = \sqrt{x^2} = x$. \square

Proposition 6.18. *For x a negative real we have $|x| = -x$.*

PROOF: Since $|x| = \sqrt{x^2} = -x$. \square

Theorem 6.19. *For any complex number z we have $|z| \geq 0$.*

PROOF: Immediate from definition. \square

Theorem 6.20. *For any complex number z , if $|z| = 0$ then $z = 0$.*

PROOF: From Theorem 6.15. \square

Theorem 6.21. *For any complex number z we have*

$$|\bar{z}| = |z|.$$

PROOF: Immediate from definitions. \square

Theorem 6.22. *For any complex numbers z and w we have*

$$|zw| = |z||w|.$$

PROOF:

$$\begin{aligned}|zw| &= \sqrt{zw\bar{z}\bar{w}} \\ &= \sqrt{z\bar{z}}\sqrt{w\bar{w}} && \text{(Proposition 5.26)} \\ &= |z||w|\end{aligned}\quad \square$$

Theorem 6.23. *For any complex number z we have*

$$|\operatorname{Re} z| \leq |z|$$

PROOF: Let $z = a + ib$. Then

$$|\operatorname{Re} z| = \sqrt{a^2} \leq \sqrt{a^2 + b^2}. \square$$

Theorem 6.24. *For any complex numbers z and w we have*

$$|z + w| \leq |z| + |w|.$$

PROOF:

$$\begin{aligned}
|z + w|^2 &= (z + w)(\bar{z} + \bar{w}) \\
&= z\bar{z} + z\bar{w} + \bar{z}w + w\bar{w} \\
&= |z|^2 + 2\operatorname{Re}(z\bar{w}) + |w|^2 && \text{(Theorem 6.12)} \\
&\leq |z|^2 + 2|z\bar{w}| + |w|^2 && \text{(Theorem 6.23)} \\
&= |z|^2 + 2|z||w| + |w|^2 && \text{(Theorem 6.22)} \\
&= (|z| + |w|)^2 && \square
\end{aligned}$$

Theorem 6.25 (Schwarz Inequality). *Let $a_1, \dots, a_n, b_1, \dots, b_n$ be complex numbers. Then*

$$\left| \sum_{j=1}^n a_j \bar{b}_j \right|^2 \leq \sum_{j=1}^n |a_j|^2 \sum_{j=1}^n |b_j|^2 .$$

PROOF:

$$\langle 1 \rangle 1. \text{ LET: } A = \sum_{j=1}^n |a_j|^2$$

$$\langle 1 \rangle 2. \text{ LET: } B = \sum_{j=1}^n |b_j|^2$$

$$\langle 1 \rangle 3. \text{ LET: } C = \sum_{j=1}^n a_j \bar{b}_j$$

$$\langle 1 \rangle 4. \text{ ASSUME: w.l.o.g. } B > 0$$

PROOF: If $B = 0$ then $b_1 = \dots = b_n = 0$ and both sides of the inequality are 0.

$$\langle 1 \rangle 5. \sum_{j=1}^n |Ba_j - Cb_j|^2 = B(AB - |C|^2)$$

PROOF:

$$\begin{aligned}
\sum_{j=1}^n |Ba_j - Cb_j|^2 &= \sum_{j=1}^n (Ba_j - Cb_j)(B\bar{a}_j - \bar{C}\bar{b}_j) \\
&= B^2 \sum_{j=1}^n |a_j|^2 - B\bar{C} \sum_{j=1}^n a_j \bar{b}_j - BC \sum_{j=1}^n \bar{a}_j b_j + |C|^2 \sum_{j=1}^n |b_j|^2 \\
&= B^2 A - 2B|C|^2 + B|C|^2 \\
&= B(AB - |C|^2)
\end{aligned}$$

$$\langle 1 \rangle 6. B(AB - |C|^2) \geq 0$$

$$\langle 1 \rangle 7. AB \geq |C|^2$$

\square

Proposition 6.26. *For any non-zero complex number w , there are exactly two complex numbers z such that $z^2 = w$.*

PROOF:

$$\langle 1 \rangle 1. \text{ There are at most two complex numbers } z \text{ such that } z^2 = w.$$

PROOF: Proposition 4.15.

$$\langle 1 \rangle 2. \text{ There are at least two complex numbers } z \text{ such that } z^2 = w.$$

$$\langle 2 \rangle 1. \text{ LET: } w = u + iv$$

$$\langle 2 \rangle 2. \text{ LET: } a = \sqrt{\frac{|w|+u}{2}}$$

$$\langle 2 \rangle 3. \text{ LET: } b = \sqrt{\frac{|w|-u}{2}}$$

⟨2⟩4. CASE: $v \geq 0$

⟨3⟩1. LET: $z = a + ib$

⟨3⟩2. $z^2 = w$

PROOF:

$$\begin{aligned} z^2 &= (a + ib)^2 \\ &= a^2 - b^2 + 2iab \\ &= u + i\sqrt{|w|^2 - u^2} \\ &= u + iv \\ &= w \end{aligned}$$

⟨3⟩3. $(-z)^2 = w$

⟨2⟩5. CASE: $v \leq 0$

⟨3⟩1. LET: $z = a - ib$

⟨3⟩2. $z^2 = w$

PROOF:

$$\begin{aligned} z^2 &= (a - ib)^2 \\ &= a^2 - b^2 - 2iab \\ &= u - i\sqrt{|w|^2 - u^2} \\ &= u - i|v| \\ &= w \end{aligned}$$

⟨3⟩3. $(-z)^2 = w$

□

6.1 Algebraic Numbers

Definition 6.27 (Algebraic). A complex number z is *algebraic* iff there exist integers a_0, a_1, \dots, a_n not all zero such that

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

otherwise, it is *transcendental*.

Proposition 6.28. *The set of algebraic numbers is countable.*

PROOF: There are countably many finite sequences of integers (a_0, a_1, \dots, a_n) , and for each one, there are only finitely many complex numbers z such that $a_0 z^n + a_1 z^{n-1} + \dots + a_n = 0$. □

Part I

Linear Algebra

Chapter 7

Vector Spaces

7.1 Convex Sets

Definition 7.1 (Convex). Let $E \subseteq \mathbb{R}^k$. Then E is *convex* iff, for all $\vec{x}, \vec{y} \in E$ and $\lambda \in (0, 1)$,

$$\lambda \vec{x} + (1 - \lambda) \vec{y} \in E \text{ .}$$

Proposition 7.2. *Every k -cell is convex.*

PROOF:

$\langle 1 \rangle 1$. LET: $C = \{\vec{x} \in \mathbb{R}^k : \forall i. a_i \leq x_i \leq b_i\}$ be a k -cell.

$\langle 1 \rangle 2$. LET: $\vec{x}, \vec{y} \in C$ and $\lambda \in (0, 1)$.

PROVE: $\lambda \vec{x} + (1 - \lambda) \vec{y} \in C$

$\langle 1 \rangle 3$. For each i we have $a_i \leq \lambda x_i + (1 - \lambda) y_i \leq b_i$

PROOF: Since $\lambda a_1 + (1 - \lambda) a_i \leq \lambda x_i + (1 - \lambda) y_i \leq \lambda b_i + (1 - \lambda) b_i$.

□

Chapter 8

Real Inner Product Spaces

Definition 8.1 (Inner Product). Given $\vec{x}, \vec{y} \in \mathbb{R}^k$, define the *inner product* $\vec{x} \cdot \vec{y}$ by

$$(x_1, \dots, x_k) \cdot (y_1, \dots, y_k) = x_1 y_1 + \dots + x_k y_k \ .$$

Definition 8.2 (Norm). Define the *norm* of a vector $\vec{x} \in \mathbb{R}^k$ by

$$\|\vec{x}\| = \sqrt{\vec{x} \cdot \vec{x}} \ .$$

Proposition 8.3.

$$\|\vec{x}\| \geq 0$$

PROOF: Immediate from the definition. \square

Proposition 8.4. If $\|\vec{x}\| = 0$ then $\vec{x} = \vec{0}$.

PROOF: If $\|\vec{x}\| = 0$ then $x_1^2 + \dots + x_n^2 = 0$ so $x_1 = \dots = x_n = 0$. \square

Proposition 8.5. For $\alpha \in \mathbb{R}$ and $\vec{x} \in \mathbb{R}^k$,

$$\|\alpha \vec{x}\| = |\alpha| \|\vec{x}\| \ .$$

PROOF: Easy. \square

Proposition 8.6. For $\vec{x}, \vec{y} \in \mathbb{R}^k$, we have

$$\|\vec{x} \cdot \vec{y}\| \leq \|\vec{x}\| \|\vec{y}\| \ .$$

PROOF: By the Schwarz inequality. \square

Proposition 8.7. For $\vec{x}, \vec{y} \in \mathbb{R}^k$ we have

$$\|\vec{x} + \vec{y}\| \leq \|\vec{x}\| + \|\vec{y}\| \ .$$

PROOF:

$$\begin{aligned}
 \|\vec{x} + \vec{y}\|^2 &= (\vec{x} + \vec{y}) \cdot (\vec{x} + \vec{y}) \\
 &= \vec{x} \cdot \vec{x} + 2\vec{x} \cdot \vec{y} + \vec{y} \cdot \vec{y} \\
 &\leq \|\vec{x}\|^2 + 2\|\vec{x}\|\|\vec{y}\| + \|\vec{y}\|^2 && \text{(Proposition 8.6)} \\
 &= (\|\vec{x}\| + \|\vec{y}\|)^2 && \square
 \end{aligned}$$

Corollary 8.7.1. For $\vec{x}, \vec{y}, \vec{z} \in \mathbb{R}^k$ we have

$$\|\vec{x} - \vec{z}\| \leq \|\vec{x} - \vec{y}\| + \|\vec{y} - \vec{z}\| .$$

8.1 Balls

Definition 8.8 (Closed Ball). Let $\vec{x} \in \mathbb{R}^k$ and $r > 0$. The *closed ball* with centre \vec{x} and radius r is

$$\{y \in \mathbb{R}^k : \|y - x\| \leq r\} .$$

Proposition 8.9. Every closed ball is convex.

PROOF:

(1)1. LET: B be the closed ball with center \vec{a} and radius r .

(1)2. LET: $\vec{x}, \vec{y} \in B$

(1)3. LET: $\lambda \in (0, 1)$

(1)4. $\lambda\vec{x} + (1 - \lambda)\vec{y} \in B$

PROOF:

$$\begin{aligned}
 \|\lambda\vec{x} + (1 - \lambda)\vec{y} - \vec{a}\| &= \|\lambda(\vec{x} - \vec{a}) + (1 - \lambda)(\vec{y} - \vec{a})\| \\
 &= \lambda\|\vec{x} - \vec{a}\| + (1 - \lambda)\|\vec{y} - \vec{a}\| \\
 &\leq \lambda r + (1 - \lambda)r \\
 &= r && \square
 \end{aligned}$$

\square

Chapter 9

Complex Inner Product Spaces

Definition 9.1 (Inner Product). Let V be a complex vector space. An *inner product* on V is a function $\langle \cdot, \cdot \rangle : V^2 \rightarrow \mathbb{C}$ such that, for all $x, y, z \in V$ and $\alpha \in \mathbb{C}$:

- $\langle y, x \rangle = \overline{\langle x, y \rangle}$
- $\langle x + y, z \rangle = \langle x, z \rangle + \langle y, z \rangle$
- $\langle \alpha x, y \rangle = \alpha \langle x, y \rangle$
- $\langle x, x \rangle \geq 0$
- If $\langle x, x \rangle = 0$ then $x = 0$.

An *inner product space* consists of a complex vector space V and an inner product on V .

Definition 9.2 (Norm). Let V be an inner product space and $x \in V$. The *norm* of x is

$$\|x\| = \sqrt{\langle x, x \rangle} .$$

Proposition 9.3. *An inner product space is a metric space under*

$$d(x, y) = \|x - y\| .$$

Definition 9.4 (Bounded). Let V_1 and V_2 be inner product spaces and $T : V_1 \rightarrow V_2$ a linear transformation. Then T is *bounded* iff $\{\|T(x)\| : \|x\| = 1\}$ is bounded above.

Proposition 9.5. *Every linear transformation between finite dimensional inner product spaces is bounded.*

Definition 9.6 (Outer Product). Let V be an inner product space and $|\psi\rangle, |\phi\rangle \in V$. The *outer product* of $|\psi\rangle$ and $|\phi\rangle$ is

$$|\psi\rangle \langle \phi| : V \rightarrow V .$$

9.1 Hilbert Spaces

Definition 9.7 (Hilbert Space). A *Hilbert space* is a complete inner product space.

Theorem 9.8 (Completeness Relation). Let \mathcal{H} be a Hilbert space. Let $\{|e_n\rangle\}_{n \in \mathbb{N}}$ be a countable orthonormal basis for \mathcal{H} . Then

$$\sum_{n=0}^{\infty} |e_n\rangle \langle e_n| = I \quad .$$

PROOF:

$\langle 1 \rangle 1$. LET: $|\psi\rangle \in \mathcal{H}$

$\langle 1 \rangle 2$. LET: $|\psi\rangle = \sum_{n=0}^{\infty} \alpha_n |e_n\rangle$

$\langle 1 \rangle 3$. $\sum_{n=0}^{\infty} \langle e_n | \phi \rangle |e_n\rangle = |\psi\rangle$

PROOF:

$$\begin{aligned} \sum_{n=0}^{\infty} \langle e_n | \phi \rangle |e_n\rangle &= \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} \alpha_m \langle e_n | e_m \rangle |e_n\rangle \\ &= \sum_{n=0}^{\infty} \alpha_n |e_n\rangle \\ &= |\psi\rangle \end{aligned}$$

□

□

Definition 9.9 (Separable). A Hilbert space is *separable* iff it has a countable dense orthonormal basis.

Chapter 10

Lie Algebras

Definition 10.1 (Lie Algebra). Let K be a field. A *Lie algebra* \mathcal{L} over K consists of a vector space \mathcal{L} over K and an operation

$$[\cdot, \cdot] : \mathcal{L}^2 \rightarrow \mathcal{L} ,$$

the *Lie bracket* or *commutator*, such that, for all $x, y, z \in \mathcal{L}$ and $\alpha \in K$:

$$\begin{aligned} [x + y, z] &= [x, z] + [y, z] \\ [x, y + z] &= [x, y] + [x, z] \\ [\alpha x, y] &= \alpha[x, y] \\ [x, x] &= 0 \\ [x, [y, z]] + [y, [z, x]] + [z, [x, y]] &= 0 \end{aligned} \quad \text{(Jacobi identity)}$$

Lemma 10.2. If K has characteristic 0 then the condition $[x, x] = 0$ can be replaced with $[x, y] = -[y, x]$.

Proposition 10.3. The commutator is determined by its values on any basis for \mathcal{L} .

Example 10.4. \mathbb{R}^3 with the cross product is a real Lie algebra.

Example 10.5. For any $n \geq 0$, we have $GL(n, K)$ is a Lie algebra over K under

$$[A, B] = AB - BA .$$

Definition 10.6 (Linear Lie Algebra). A *linear Lie algebra* over K is a Lie algebra over K that is a subalgebra of $GL(n, K)$ for some n .

Example 10.7 (Special Linear Algebra). The *special Linear algebra* $SL(n, \mathbb{R}) = \{A \in GL(n, \mathbb{R}) : \text{tr} = 0\}$ is a real linear Lie algebra.

Example 10.8 (Orthogonal Lie Algebra). The *orthogonal Lie algebra* $SO(n, \mathbb{R}) = \{A \in GL(n, \mathbb{R}) : A \text{ is skew-symmetric}\}$ is a real linear Lie algebra.

Example 10.9. Let $u(n)$ be the set of all skew-Hermitian $n \times n$ -matrices as a real Lie algebra.

Let $su(n) = u(n) \cap SL(n, \mathbb{R})$.

Proposition 10.10. $SU(2)$ is spanned by the Pauli matrices

$$\sigma_x = \frac{1}{2} \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}, \quad \sigma_y = \frac{1}{2} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_z = \frac{1}{2} \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}$$

which satisfy

$$\begin{aligned} [\sigma_x, \sigma_y] &= \sigma_z \\ [\sigma_y, \sigma_z] &= \sigma_x \\ [\sigma_z, \sigma_x] &= \sigma_y \end{aligned}$$

10.1 Lie Algebar Homomorphisms

Definition 10.11 (Homomorphism). Let L_1 and L_2 be Lie algebras over the same field. A *Lie algebra homomorphism* $\phi : L_1 \rightarrow L_2$ is a linear transformation such that

$$\phi([x, y]) = [\phi(x), \phi(y)]$$

for all $x, y \in L_1$.

Lemma 10.12. *Every bijective Lie algebra homomorphism is an isomorphism.*

Definition 10.13 (Representation). Let L be a real (complex) Lie algebra. A *representation* of L is a Lie algebra homomorphism $L \rightarrow GL(n, \mathbb{R})$ ($GL(n, \mathbb{C})$) for some n .

Example 10.14. The linear transformation $\mathbb{R}^3 \rightarrow su(2)$ defined by

$$i \mapsto \sigma_x, j \mapsto \sigma_y, k \mapsto \sigma_z$$

is a representation of \mathbb{R}^3 .

Part II

Topology

Chapter 11

Metric Spaces

Definition 11.1 (Metric). A *metric* on a set X is a function $d : X^2 \rightarrow \mathbb{R}$ such that, for all $x, y, z \in X$:

- $d(x, y) \geq 0$
- $d(x, y) = 0$ iff $x = y$
- $d(x, y) = d(y, x)$
- **Triangle Inequality** $d(x, z) \leq d(x, y) + d(y, z)$

A *metric space* X consists of a set X and a metric on X .

Example 11.2. \mathbb{R}^k is a metric space under $d(\vec{x}, \vec{y}) = \|\vec{x} - \vec{y}\|$. The triangle inequality is Corollary 8.7.1.

Example 11.3. For any set X , the *discrete* metric on X is defined by

$$d(x, y) = \begin{cases} 1 & \text{if } x \neq y \\ 0 & \text{if } x = y \end{cases}$$

Proposition 11.4. Let (X, d) be a metric space and Y a subset of X . Then $d \upharpoonright Y^2$ is a metric on Y .

PROOF: Easy. \square

11.1 Balls

Definition 11.5 (Open Ball). Let $\vec{x} \in \mathbb{R}^k$ and $r > 0$. The *open ball* with *centre* \vec{x} and *radius* r is

$$\{y \in \mathbb{R}^k : \|y - x\| < r\} .$$

Proposition 11.6. Every open ball in \mathbb{R}^k is convex.

PROOF:

(1)1. LET: B be the open ball with center \vec{a} and radius r .

(1)2. LET: $\vec{x}, \vec{y} \in B$

(1)3. LET: $\lambda \in (0, 1)$

(1)4. $\lambda\vec{x} + (1 - \lambda)\vec{y} \in B$

PROOF:

$$\begin{aligned} \|\lambda\vec{x} + (1 - \lambda)\vec{y} - \vec{a}\| &= \|\lambda(\vec{x} - \vec{a}) + (1 - \lambda)(\vec{y} - \vec{a})\| \\ &= \lambda\|\vec{x} - \vec{a}\| + (1 - \lambda)\|\vec{y} - \vec{a}\| \\ &< \lambda r + (1 - \lambda)r \\ &= r \end{aligned}$$

□

□

11.2 Limit Points

Definition 11.7 (Limit Point). Let X be a metric space. Let $E \subseteq X$ and $p \in X$. Then p is a *limit point* of E iff every open ball with centre p contains a point of E other than p .

Proposition 11.8. Let X be a metric space. Let $E \subseteq X$. Let p be a limit point of E . Then every neighbourhood of p contains infinitely many points of E .

PROOF:

(1)1. ASSUME: for a contradiction N is a neighbourhood of p that contains only finitely many points q_1, \dots, q_n of $E - \{p\}$.

(1)2. LET: $r = \min(q_1, \dots, q_n)$

(1)3. LET: B be the open ball with centre p and radius r .

(1)4. B is a neighbourhood of p that contains no points of E other than p .

□

Corollary 11.8.1. A finite set has no limit points.

Definition 11.9 (Isolated Point). Let X be a metric space. Let $E \subseteq X$ and $p \in X$. Then p is an *isolated point* of E iff $p \in E$ and p is not a limit point of E .

11.3 Closed Sets

Definition 11.10 (Closed Set). Let X be a metric space. Let $E \subseteq X$. Then E is *closed* iff every limit point of E is a member of E .

11.4 Interior Points

Definition 11.11 (Interior Point). Let X be a metric space. Let $E \subseteq X$ and $p \in X$. Then p is an *interior point* of E iff there exists an open ball B with centre p such that $B \subseteq E$.

Definition 11.12 (Interior). The *interior* of a set E , denoted E° , is the set of all its interior points.

Proposition 11.13. *The interior of E is the largest open set that is included in E .*

PROOF:

- (1)1. LET: I be the interior of E .
- (1)2. I is open.
 - (2)1. LET: $p \in I$
 - (2)2. PICK an open ball B with centre p such that $B \subseteq E$.
 - (2)3. $B \subseteq I$
 - (3)1. LET: $q \in B$
 - (3)2. There exists an open ball B' with centre q such that $B' \subseteq B$.
 - (3)3. There exists an open ball B' with centre q such that $B' \subseteq E$.
 - (3)4. $q \in I$
- (1)3. If J is any open set and $J \subseteq E$ then $J \subseteq I$.
 - (2)1. LET: J be an open set.
 - (2)2. ASSUME: $J \subseteq E$
 - (2)3. For all $p \in J$, there exists an open ball B with centre p such that $B \subseteq J$.
 - (2)4. For all $p \in J$, there exists an open ball B with centre p such that $B \subseteq E$.
 - (2)5. $p \in I$

□

11.5 Open Sets

Definition 11.14 (Open Sets). Let X be a metric space. Let $E \subseteq X$. Then E is *open* iff every point in E is an interior point of E .

Proposition 11.15. *Every open ball is open.*

PROOF:

- (1)1. LET: B be an open ball with centre c and radius r .
- (1)2. LET: $x \in B$
- (1)3. LET: $\epsilon = r - d(x, c)$
- (1)4. LET: B' be the open ball with centre x and radius ϵ .
 - PROVE: $B' \subseteq B$
- (1)5. LET: $y \in B'$
- (1)6. $d(y, c) < r$

PROOF:

$$\begin{aligned}
 d(y, c) &\leq d(y, x) + d(x, c) && \text{(Triangle Inequality)} \\
 &< \epsilon + d(x, c) && ((1)5) \\
 &= r && ((1)3)
 \end{aligned}$$

□

Proposition 11.16. *A set is open if and only if its complement is closed.*

PROOF:

$\langle 1 \rangle 1$. LET: $E \subseteq X$

$\langle 1 \rangle 2$. If E is open then $X - E$ is closed.

$\langle 2 \rangle 1$. ASSUME: E is open.

$\langle 2 \rangle 2$. LET: p be a limit point of $X - E$.

PROVE: $p \in X - E$

$\langle 2 \rangle 3$. ASSUME: for a contradiction $p \in E$.

$\langle 2 \rangle 4$. PICK an open ball B with centre p such that $B \subseteq E$.

$\langle 2 \rangle 5$. B contains a point of $X - E$.

PROOF: $\langle 2 \rangle 2$

$\langle 2 \rangle 6$. Q.E.D.

PROOF: This contradicts $\langle 2 \rangle 4$.

$\langle 1 \rangle 3$. If $X - E$ is closed then E is open.

$\langle 2 \rangle 1$. ASSUME: $X - E$ is closed.

$\langle 2 \rangle 2$. LET: $p \in E$

$\langle 2 \rangle 3$. ASSUME: for a contradiction no open ball with centre p is a subset of E .

$\langle 2 \rangle 4$. Every open ball with centre p intersects $X - E$.

$\langle 2 \rangle 5$. p is a limit point of $X - E$.

$\langle 2 \rangle 6$. $p \in X - E$

PROOF: $\langle 2 \rangle 1$

$\langle 2 \rangle 7$. Q.E.D.

PROOF: This contradicts $\langle 2 \rangle 2$.

□

Corollary 11.16.1. *A set is closed if and only if its complement is open.*

Proposition 11.17. *The union of a set of open sets is open.*

PROOF:

$\langle 1 \rangle 1$. LET: \mathcal{U} be a set of open sets.

$\langle 1 \rangle 2$. LET: $p \in \bigcup \mathcal{U}$

$\langle 1 \rangle 3$. PICK $U \in \mathcal{U}$ such that $p \in U$.

$\langle 1 \rangle 4$. PICK an open ball B with centre p such that $B \subseteq U$.

$\langle 1 \rangle 5$. $B \subseteq \bigcup \mathcal{U}$

□

Corollary 11.17.1. *The intersection of a set of closed sets is closed.*

Proposition 11.18. *The intersection of two open sets is open.*

PROOF:

$\langle 1 \rangle 1$. LET: U and V be open.

$\langle 1 \rangle 2$. LET: $p \in U \cap V$

$\langle 1 \rangle 3$. PICK open balls B_1 and B_2 with centre p such that $B_1 \subseteq U$ and $B_2 \subseteq V$.

$\langle 1 \rangle 4$. ASSUME: w.l.o.g. the radius of B_1 is \leq the radius of B_2 .

$\langle 1 \rangle 5$. $B_1 \subseteq U \cap V$

□

Corollary 11.18.1. *The union of two closed sets is closed.*

Example 11.19. The intersection of a set of open sets is not necessarily open.

For every positive integer n , we have $(-1/n, 1/n)$ is open in \mathbb{R} , but $\bigcap_{n=1}^{\infty} (-1/n, 1/n) = \{0\}$ is not open.

Theorem 11.20. *Let X be a metric space. Let $Y \subseteq X$ and $E \subseteq Y$. Then E is open in Y if and only if there exists an open subset G of X such that $E = G \cap Y$.*

PROOF:

(1)1. If E is open in Y then there exists an open subset G of X such that $E = G \cap Y$.

(2)1. ASSUME: E is open in Y .

(2)2. For $p \in E$, PICK $r_p > 0$ such that the open ball in Y with centre p and radius r_p is included in E .

(2)3. For $p \in E$,

LET: V_p be the open ball in X with centre p and radius r_p .

(2)4. LET: $G = \bigcup_{p \in E} V_p$

(2)5. G is open in X .

PROOF: Proposition 11.17.

(2)6. $E = G \cap Y$

(3)1. $E \subseteq G \cap Y$

(4)1. LET: $p \in E$

(4)2. $p \in V_p$

(4)3. $p \in G$

(3)2. $G \cap Y \subseteq E$

(4)1. LET: $x \in G \cap Y$

(4)2. PICK $p \in E$ such that $x \in V_p$

(4)3. $d(x, p) < r_p$

(4)4. $x \in E$

(1)2. For any open subset G of X , we have $G \cap Y$ is open in Y .

(2)1. LET: G be an open subset of X .

(2)2. LET: $p \in G \cap Y$

(2)3. PICK $r > 0$ such that the open ball in X with centre p and radius r is included in G .

(2)4. The open ball in Y with centre p and radius r is included in $G \cap Y$.

□

11.6 Perfect Sets

Definition 11.21 (Perfect Set). Let X be a metric space. Let $E \subseteq X$. Then E is *perfect* iff E is closed and every point in E is a limit point of E .

11.7 Bounded Sets

Definition 11.22 (Bounded Set). Let X be a metric space. Let $E \subseteq X$. Then E is *bounded* iff there exists a real number M and $q \in X$ such that, for all $p \in E$, we have $d(p, q) < M$.

Definition 11.23 (Diameter). Let X be a metric space and $E \subseteq X$ be bounded. Then the *diameter* of E is $\sup\{d(x, y) : x, y \in E\}$.

Proposition 11.24. Let X be a metric space. Let $E \subseteq X$ be bounded. Then \overline{E} is bounded and

$$\text{diam } \overline{E} = \text{diam } E .$$

PROOF:

(1)1. $\text{diam } E$ is an upper bound for $\{d(x, y) : x, y \in \overline{E}\}$.

⟨2⟩1. LET: $x, y \in \overline{E}$

⟨2⟩2. For all $\epsilon > 0$ we have $d(x, y) < \text{diam } E + \epsilon$.

⟨3⟩1. LET: $\epsilon > 0$

⟨3⟩2. PICK $x', y' \in E$ such that $d(x', x) < \epsilon/2$ and $d(y', y) < \epsilon/2$

⟨3⟩3. $d(x', y') < \text{diam } E$

⟨3⟩4. $d(x, y) < \text{diam } E + \epsilon$

⟨2⟩3. $d(x, y) \leq \text{diam } E$

(1)2. $\text{diam } \overline{E}$ is an upper bound for $\{d(x, y) : x, y \in E\}$.

PROOF: This follows since $E \subseteq \overline{E}$.

□

11.8 Dense Sets

Definition 11.25 (Dense Set). Let X be a metric space. Let $E \subseteq X$. Then E is *dense* iff every point of X is either a limit point of E or a point of E , or both.

11.9 Closure

Definition 11.26 (Closure). Let X be a metric space. Let $E \subseteq X$. Then the *closure* of E , denoted \overline{E} , is the union of E and the set of limit points of E .

Proposition 11.27. \overline{E} is the smallest closed set that includes E .

PROOF:

(1)1. \overline{E} is closed.

⟨2⟩1. LET: p be a limit point of \overline{E} .

⟨2⟩2. ASSUME: $p \notin E$

PROVE: p is a limit point of E .

⟨2⟩3. LET: B be the open ball with centre p and radius r .

PROVE: B intersects E .

⟨2⟩4. PICK a point $q \in B \cap \overline{E}$.

⟨2⟩5. PICK an open ball B' with centre q such that $B' \subseteq B$.

- ⟨2⟩6. PICK a point $r \in E \cap B'$
- ⟨2⟩7. $r \in E \cap B$
- ⟨1⟩2. If C is closed and $E \subseteq C$ then $\overline{E} \subseteq C$.
 - ⟨2⟩1. ASSUME: C is closed.
 - ⟨2⟩2. ASSUME: $E \subseteq C$
 - ⟨2⟩3. LET: $p \in \overline{E}$
 - ⟨2⟩4. ASSUME: for a contradiction $p \notin C$
 - ⟨2⟩5. p is a limit point of C .
 - ⟨3⟩1. LET: B be an open ball with centre p .
 - ⟨3⟩2. B intersects E .
 - ⟨3⟩3. B intersects C .
 - ⟨3⟩4. B intersects C in a point other than p .
 - PROOF: ⟨2⟩3
- ⟨2⟩6. Q.E.D.
- PROOF: This contradicts ⟨2⟩1.

□

Corollary 11.27.1. E is closed if and only if $E = \overline{E}$.

Theorem 11.28. Let E be a nonempty set of real numbers bounded above. Then $\sup E \in \overline{E}$.

PROOF:

- ⟨1⟩1. ASSUME: $\sup E \notin E$
PROVE: $\sup E$ is a limit point of E .
- ⟨1⟩2. LET: B be an open ball with centre $\sup E$ and radius r .
- ⟨1⟩3. There exists $x \in E$ such that $x > \sup E - r$.
- ⟨1⟩4. E intersects B in a point other than p .

□

Proposition 11.29.

$$\overline{A \cup B} = \overline{A} \cup \overline{B}$$

PROOF:

- ⟨1⟩1. $\overline{A \cup B}$ is a closed set that includes $A \cup B$.
- ⟨1⟩2. If C is a closed set that includes $A \cup B$ then $\overline{A \cup B} \subseteq C$.

□

Example 11.30. It is not true in general. that $\overline{\bigcup \mathcal{A}} = \bigcup_{A \in \mathcal{A}} \overline{A}$.

In \mathbb{R} , let $\mathcal{A} = \{\{1/n\} : n \in \mathbb{Z}^+\}$. Then

$$\begin{aligned} \overline{\bigcup \mathcal{A}} &= \{1/n : n \in \mathbb{Z}^+\} \cup \{0\} \\ \bigcup_{A \in \mathcal{A}} \overline{A} &= \{1/n : n \in \mathbb{Z}^+\} \end{aligned}$$

Proposition 11.31.

$$X - E^\circ = \overline{X - E}$$

PROOF:

$$\begin{aligned}
 p \in X - E^\circ &\Leftrightarrow p \notin E^\circ \\
 &\Leftrightarrow \forall B \text{ an open ball with centre } p, B \not\subseteq E \\
 &\Leftrightarrow \forall B \text{ an open ball with centre } p, B \text{ intersects } X - E \\
 &\Leftrightarrow p \in \overline{X - E} \quad \square
 \end{aligned}$$

11.10 Compact Sets

Definition 11.32 (Open Cover). Let X be a metric space. Let $E \subseteq X$. An *open cover* of E is a set \mathcal{U} of open sets such that $E \subseteq \bigcup \mathcal{U}$.

Definition 11.33 (Compact Set). Let X be a metric space. Let $K \subseteq X$. Then K is *compact* iff every open cover of K includes a finite subcover.

Proposition 11.34. *Every finite set is compact.*

PROOF: Easy. \square

Theorem 11.35. *Let X be a metric space. Let $Y \subseteq X$ and $K \subseteq Y$. Then K is compact in Y if and only if K is compact in X .*

PROOF:

- (1) 1. If K is compact in Y then K is compact in X .
 - $\langle 2 \rangle$ 1. ASSUME: K is compact in Y .
 - $\langle 2 \rangle$ 2. LET: \mathcal{U} be an open cover of K in X .
 - $\langle 2 \rangle$ 3. $\{U \cap Y : U \in \mathcal{U}\}$ is an open cover of K in Y .
 - $\langle 2 \rangle$ 4. PICK a finite subcover $\{U_1 \cap Y, \dots, U_n \cap Y\}$
 - $\langle 2 \rangle$ 5. $\{U_1, \dots, U_n\}$ is a finite subset of \mathcal{U} that is an open cover of K in X .
- (1) 2. If K is compact in X then K is compact in Y .
 - $\langle 2 \rangle$ 1. ASSUME: K is compact in X .
 - $\langle 2 \rangle$ 2. LET: \mathcal{U} be an open cover of K in Y .
 - $\langle 2 \rangle$ 3. $\{U \text{ open in } X : U \cap Y \in \mathcal{U}\}$ is an open cover of K in X .
 - $\langle 2 \rangle$ 4. PICK a finite subcover $\{U_1, \dots, U_n\}$.
 - $\langle 2 \rangle$ 5. $\{U_1 \cap Y, \dots, U_n \cap Y\}$ is a subset of \mathcal{U} that is an open cover of E in Y .

\square

Proposition 11.36. *Every compact set is closed.*

PROOF:

- (1) 1. LET: E be compact.
- (1) 2. LET: $p \in X - E$
 - PROVE: There exists an open ball with centre p that is a subset of $X - E$.
- (1) 3. For all $q \in E$, there exist disjoint open balls B with centre q and B' with centre p .
- (1) 4. The set of open balls B such that there exists a disjoint open ball B' with centre p is an open cover of E .
- (1) 5. PICK a finite subcover $\{B_1, \dots, B_n\}$.

- (1)6. For $i = 1, \dots, n$, PICK an open ball B'_i with centre p such that $B_i \cap B'_i = \emptyset$.
 (1)7. $B'_1 \cap \dots \cap B'_n$ is an open ball with centre p that is a subset of $X - E$.

□

Proposition 11.37. *Every closed subset of a compact set is compact.*

PROOF:

- (1)1. LET: E be compact and $C \subseteq E$ be closed.
 (1)2. LET: \mathcal{U} be an open cover of C .
 (1)3. $\mathcal{U} \cup \{X - C\}$ is an open cover of E .
 (1)4. PICK a finite subcover $\{U_1, \dots, U_n\}$ or $\{U_1, \dots, U_n, X - C\}$.
 (1)5. $\{U_1, \dots, U_n\}$ covers C .

□

Corollary 11.37.1. *The intersection of a compact set and a closed set is compact.*

Proposition 11.38. *Let \mathcal{K} be a nonempty set of compact sets. If every nonempty finite subset of \mathcal{K} has nonempty intersection, then $\bigcap \mathcal{K}$ is nonempty.*

PROOF:

- (1)1. PICK $K \in \mathcal{K}$
 (1)2. ASSUME: $\bigcap \mathcal{K} = \emptyset$
 (1)3. $\{X - K' : K' \in \mathcal{K}\}$ is an open cover of K .
 (1)4. PICK a finite subcover $\{X - K_1, \dots, X - K_n\}$.
 (1)5. There exists $p \in K \cap K_1 \cap \dots \cap K_n$
 (1)6. Q.E.D.

PROOF: (1)4 and (1)5 form a contradiction.

□

Corollary 11.38.1. *Let (K_n) be a sequence of nonempty compact sets such that $K_0 \supseteq K_1 \supseteq \dots$. Then $\bigcap_{n=0}^{\infty} K_n \neq \emptyset$.*

Theorem 11.39. *Let X be a metric space and $E \subseteq X$. Then E is compact if and only if every infinite subset of E has a limit point in E .*

PROOF:

- (1)1. If E is compact then every infinite subset of E has a limit point in E .
 (2)1. ASSUME: E is compact.
 (2)2. LET: $A \subseteq E$ be infinite.
 (2)3. ASSUME: for a contradiction E has no limit point in K .
 (2)4. For all $p \in K$, there exists an open ball B with centre p such that B does not intersect E outside p .
 (2)5. The set of open balls that intersect E in at most one point is an open cover for K .
 (2)6. PICK a finite subcover B_1, \dots, B_n .
 (2)7. E has at most n points.
 (2)8. Q.E.D.

PROOF: This contradicts the fact that E is finite.

- (1)2. If every infinite subset of K has a limit point in K then K is compact.
- (2)1. ASSUME: Every infinite subset of K has a limit point in K .
- (2)2. LET: \mathcal{U} be an open cover of K .
- (2)3. ASSUME: w.l.o.g. \mathcal{U} is countable.
- PROOF: We may replace \mathcal{U} with the set of all open balls B with centres in \mathbb{Q}^2 and rational radius such that there exists $U \in \mathcal{U}$ such that $B \subseteq U$.
- (2)4. PICK an enumeration $\mathcal{U} = \{G_n : n \in \mathbb{N}\}$.
- (2)5. For $n \in \mathbb{N}$,
- LET: $F_n = \bigcup_{i=0}^n G_i$.
- (2)6. For all $n \in \mathbb{N}$, we have $K - F_n \neq \emptyset$.
- PROOF: Since $\{G_0, \dots, G_n\}$ does not cover K .
- (2)7. $\bigcap_{n=0}^{\infty} F_n = \emptyset$
- PROOF: Since $\{G_n : n \in \mathbb{N}\}$ covers K .
- (2)8. For $n \in \mathbb{N}$, PICK $a_n \in K - F_n$
- (2)9. LET: $E = \{a_n : n \in \mathbb{N}\}$
- (2)10. E is infinite.
- (3)1. LET: $n \in \mathbb{N}$
- PROVE: there exists m such that $a_m \notin \{a_0, a_1, \dots, a_n\}$.
- (3)2. For $i = 0, \dots, n$, PICK k_i such that $a_i \in G_{k_i}$.
- (3)3. LET: $m = \max(k_0, \dots, k_n)$
- (3)4. ASSUME: for a contradiction $a_m = a_i$ for some $i = 0, \dots, n$
- (3)5. $a_i \in G_{k_i}$
- (3)6. $a_i \notin F_m$
- (3)7. Q.E.D.
- PROOF: This is a contradiction since $k_i \leq m$.
- (2)11. PICK a limit point l for E in K .
- PROOF: From (2)1.
- (2)12. PICK n such that $l \in G_n$.
- (2)13. PICK an open ball B with centre l such that $B \subseteq G_n$
- (2)14. $B \cap E$ is infinite.
- PROOF: Proposition 11.8.
- (2)15. PICK $m \geq n$ such that $a_m \in B$.
- (2)16. $a_m \in G_n$
- (2)17. Q.E.D.
- PROOF: This is a contradiction since $a_m \notin F_m$.

□

Theorem 11.40 (Heine-Borel). *Let $E \subseteq \mathbb{R}^k$. Then E is compact if and only if it is closed and bounded.*

PROOF:

- (1)1. If E is compact then E is closed.
- PROOF: Proposition 11.36.
- (1)2. If E is compact then E is bounded.
- PROOF: Otherwise $\{(-N, N)^k : N \in \mathbb{Z}^+\}$ would be an open cover of E with no finite subcover.
- (1)3. If E is closed and bounded then E is compact.

- $\langle 2 \rangle 1$. ASSUME: E is closed and bounded.
- $\langle 2 \rangle 2$. PICK \vec{c} and M such that $\forall \vec{x} \in E, \|\vec{x} - \vec{c}\| < M$.
- $\langle 2 \rangle 3$. $E \subseteq \prod_{i=1}^k [c_i - M, c_i + M]$
- $\langle 2 \rangle 4$. E is compact.

PROOF: Proposition 11.37.

□

Corollary 11.40.1 (Weierstrass's Theorem). *Every bounded infinite subset of \mathbb{R}^k has a limit point.*

PROOF: It is a bounded infinite subset of some k -cell and therefore has a limit point in that k -cell. □

Example 11.41. It is not true that, in any metric space, a set is compact if and only if it is closed and bounded.

In \mathbb{Q} , the set $\{p \in \mathbb{Q} : 2 < p^2 < 3\}$ is closed and bounded but not compact.

Theorem 11.42. *Every nonempty perfect set in \mathbb{R}^k is uncountable.*

PROOF:

- $\langle 1 \rangle 1$. LET: P be a nonempty perfect set in \mathbb{R}^k .
- $\langle 1 \rangle 2$. P is infinite.

PROOF: Corollary 11.8.1.

- $\langle 1 \rangle 3$. ASSUME: for a contradiction P is countable.
- $\langle 1 \rangle 4$. PICK an enumeration $P = \{x_n : n \in \mathbb{N}\}$.
- $\langle 1 \rangle 5$. PICK a sequence (V_n) of open balls such that, for all n , we have $\overline{V_{n+1}} \subseteq V_n$ and $x_n \notin \overline{V_{n+1}}$ and $V_n \cap P \neq \emptyset$
 - $\langle 2 \rangle 1$. ASSUME: as induction hypothesis we have picked V_0, \dots, V_{n-1} that satisfy these conditions.
 - $\langle 2 \rangle 2$. PICK $p \in P \cap V_n$ such that $p \neq x_n$

PROOF: We cannot have $P \cap V_n = \{x_n\}$ because then V_n would be a neighbourhood of x_n that only intersects P at x_n .
 - $\langle 2 \rangle 3$. PICK an open ball B with centre p such that $B \subseteq V_n \cap P - \{x_n\}$
 - $\langle 2 \rangle 4$. LET: V_{n+1} be the open ball with centre p and half the radius of B .
 - $\langle 2 \rangle 5$. $\overline{V_{n+1}} \subseteq V_n$

PROOF: Since $\overline{V_{n+1}} \subseteq B \subseteq V_n$.
 - $\langle 2 \rangle 6$. $x_n \notin \overline{V_{n+1}}$

PROOF: Since $\overline{V_{n+1}} \subseteq B \subseteq P - \{x_n\}$.
 - $\langle 2 \rangle 7$. $V_{n+1} \cap P \neq \emptyset$

PROOF: Since $p \in V_{n+1} \cap P$.
- $\langle 1 \rangle 6$. For $n \in \mathbb{N}$,

LET: $K_n = \overline{V_n} \cap P$.
- $\langle 1 \rangle 7$. For all $n \in \mathbb{N}$, K_n is compact.

PROOF: By the Heine-Borel Theorem.
- $\langle 1 \rangle 8$. $\bigcap_{n=0}^{\infty} K_n \cap P = \emptyset$

PROOF: Since for each n we have $x_n \notin K_{n+1}$.
- $\langle 1 \rangle 9$. $\bigcap_{n=0}^{\infty} K_n = \emptyset$

PROOF: Since $\bigcap_{n=0}^{\infty} K_n \subseteq P$.

(1)10. Q.E.D.

PROOF: This contradicts Proposition 11.38.

□

Corollary 11.42.1. *For any $a, b \in \mathbb{R}$ with $a < b$, the closed interval $[a, b]$ is uncountable.*

Corollary 11.42.2. *\mathbb{R} is uncountable.*

Corollary 11.42.3. *The set of transcendental numbers is uncountable.*

PROOF: Since the set of algebraic numbers is countable. □

Example 11.43. The Cantor set is a perfect set in \mathbb{R} that does not include any open interval.

PROOF:

(1)1. LET: (E_n) be the sequence of unions of closed intervals from the definition of the Cantor set, and C be the Cantor set.

(1)2. $C \neq \emptyset$

PROOF: Since $0 \in C$.

(1)3. C is closed.

PROOF: Each E_n is closed and C is their intersection.

(1)4. Every point of C is a limit point of C .

(2)1. LET: $p \in C$

(2)2. LET: B be an open ball with centre p and radius r .

(2)3. PICK n such that each of the intervals that make up E_n has length $< r/2$.

(2)4. LET: I be the interval in E_n that contains p .

(2)5. $I \subseteq B$

(2)6. The endpoint of I that is not p is in $P \cap B$.

(1)5. C does not include any open interval.

(2)1. LET: (α, β) be any open interval.

(2)2. PICK m such that $3^{-m} < (\beta - \alpha)/6$

(2)3. PICK k such that $(\frac{3k+1}{3^m}, \frac{3k+2}{3^m}) \subseteq (\alpha, \beta)$

(2)4. $(\frac{3k+1}{3^m}, \frac{3k+2}{3^m}) \subseteq P$

(2)5. $(\frac{3k+1}{3^m}, \frac{3k+2}{3^m}) \cap E_m = \emptyset$

(2)6. Q.E.D.

PROOF: This is a contradiction.

□

Corollary 11.43.1. *The Cantor set is uncountable.*

Proposition 11.44. *Let X be a metric space. Let (K_n) be a sequence of compact sets in X such that $K_0 \supseteq K_1 \supseteq K_2 \supseteq \dots$. Assume $\text{diam } K_n \rightarrow 0$ as $n \rightarrow \infty$. Then $\bigcap_{n=0}^{\infty} K_n$ is a singleton.*

PROOF:

(1)1. $\bigcap_n K_n \neq \emptyset$

PROOF: Corollary 11.38.1.

- (1)2. $\bigcap_n K_n$ has no more than one point.
- (2)1. ASSUME: for a contradiction $a, b \in \bigcap_n K_n$ with $a \neq b$.
- (2)2. LET: $\epsilon = d(a, b)$
- (2)3. PICK n such that $\text{diam } K_n < \epsilon$
- (2)4. $a, b \in K_n$
- (2)5. Q.E.D.

PROOF: This is a contradiction.

□

11.11 Connected Sets

Definition 11.45 (Separated). Let X be a metric space. Let $A, B \subseteq X$. Then A and B are *separated* iff $\overline{A} \cap B = A \cap \overline{B} = \emptyset$.

Proposition 11.46. *Any two disjoint open sets are separated.*

PROOF:

- (1)1. LET: A and B be disjoint open sets.
- (1)2. ASSUME: for a contradiction $p \in \overline{A} \cap B$.
- (1)3. B is a neighbourhood of p .
- (1)4. B intersects A .

□

Definition 11.47 (Connected). Let X be a metric space. Let $E \subseteq X$. Then E is *connected* iff E is not the union of two nonempty separated sets.

Theorem 11.48. *A subset E of the real line is connected if and only if it is convex.*

PROOF:

- (1)1. If E is connected then E is convex.
 - (2)1. ASSUME: E is connected.
 - (2)2. LET: $x, y \in E$
 - (2)3. LET: $z \in (x, y)$
 - (2)4. $z \in E$

PROOF: Otherwise $E \cap (-\infty, z)$ and $E \cap (z, +\infty)$ would be a separation of E .
- (1)2. If E is convex then E is connected.
 - (2)1. ASSUME: E is convex.
 - (2)2. ASSUME: for a contradiction $E = A \cup B$ where A and B are nonempty and separated.
 - (2)3. PICK $a \in A$ and $b \in B$.
 - (2)4. ASSUME: w.l.o.g. $a < b$
 - (2)5. LET: $z = \sup(A \cap [a, b])$
 - (2)6. $z \in \overline{A}$
 - (2)7. $z \notin B$

$\langle 2 \rangle 8. z < b$

$\langle 2 \rangle 9. \text{ CASE: } z \in A$

$\langle 3 \rangle 1. z \notin \overline{B}$

$\langle 3 \rangle 2. \text{ PICK } z_1 \in (z, b) \text{ such that } z_1 \notin B$

$\langle 3 \rangle 3. a < z_1 < b$

$\langle 3 \rangle 4. z_1 \notin E$

PROOF: We have $z_1 \notin A$ from $\langle 2 \rangle 5$ since $z_1 \in [a, b]$ and $z_1 > z$, and $z_1 \notin B$ from $\langle 3 \rangle 2$.

$\langle 3 \rangle 5. \text{ Q.E.D.}$

PROOF: This contradicts $\langle 2 \rangle 1$.

$\langle 2 \rangle 10. \text{ CASE: } z \notin A$

PROOF: Then $a < z < b$ and $z \notin E$ contradicting $\langle 2 \rangle 1$.

□

Proposition 11.49. *Every connected metric space with more than one point is uncountable.*

PROOF:

$\langle 1 \rangle 1. \text{ LET: } X \text{ be a connected metric space with more than one points.}$

$\langle 1 \rangle 2. \text{ PICK distinct points } p, q \in X.$

$\langle 1 \rangle 3. \text{ LET: } \epsilon = d(p, q)$

$\langle 1 \rangle 4. \text{ For every } r \in (0, \epsilon), \text{ there exists a point } x \in X \text{ such that } d(p, x) = r.$

PROOF: Otherwise $\{x \in X : d(p, x) < r\}$ and $\{x \in X : d(p, x) > r\}$ would form a separation of X .

□

Proposition 11.50. *The closure of a connected set is connected.*

PROOF:

$\langle 1 \rangle 1. \text{ LET: } X \text{ be a metric space.}$

$\langle 1 \rangle 2. \text{ LET: } E \text{ be a connected subspace of } X.$

$\langle 1 \rangle 3. \text{ ASSUME: for a contradiction } A \text{ and } B \text{ form a separation of } \overline{E}$

PROVE: $A \cap E$ and $B \cap E$ form a separation of E .

$\langle 1 \rangle 4. A \cap E \neq \emptyset$

$\langle 2 \rangle 1. \text{ ASSUME: for a contradiction } A \cap E = \emptyset$

$\langle 2 \rangle 2. E \subseteq B$

$\langle 2 \rangle 3. \overline{E} \subseteq \overline{B}$

$\langle 2 \rangle 4. A \subseteq \overline{B}$

$\langle 2 \rangle 5. A \cap \overline{B} = A \neq \emptyset$

$\langle 2 \rangle 6. \text{ Q.E.D.}$

PROOF: This contradicts $\langle 1 \rangle 3$.

$\langle 1 \rangle 5. B \cap E \neq \emptyset$

PROOF: Similar.

$\langle 1 \rangle 6. \overline{A \cap E} \cap B \cap E = \emptyset$

PROOF: Since $\overline{A \cap E} \cap B \cap E \subseteq \overline{A} \cap B$.

$\langle 1 \rangle 7. A \cap E \cap \overline{B \cap E} = \emptyset$

PROOF: Similar.

□

Example 11.51. The interior of a connected set is not necessarily connected.

Two touching discs in \mathbb{R}^2 form a connected set but the interior is disconnected.

Proposition 11.52. *Every convex set in \mathbb{R}^k is connected.*

PROOF:

⟨1⟩1. LET: E be a convex set in \mathbb{R}^k .

⟨1⟩2. ASSUME: for a contradiction A and B form a separation of E .

⟨1⟩3. PICK $\vec{a} \in A$ and $\vec{b} \in B$.

⟨1⟩4. Define $p : [0, 1] \rightarrow \mathbb{R}^k$ by $p(t) = (1 - t)\vec{a} + t\vec{b}$.

⟨1⟩5. $p^{-1}(A)$ and $p^{-1}(B)$ are separated sets in \mathbb{R} .

⟨1⟩6. PICK $x \in [0, 1]$ such that $x \notin p^{-1}(A)$ and $x \notin p^{-1}(B)$.

PROOF: There exists such an x since $[0, 1]$ is connected.

⟨1⟩7. $p(x) \in E$

PROOF: Since E is convex.

⟨1⟩8. $p(x) \notin A \cup B$

⟨1⟩9. Q.E.D.

PROOF: This contradicts ⟨1⟩2.

□

11.12 Separable Spaces

Definition 11.53 (Separable). A metric space is *separable* iff it has a countable dense subset.

Example 11.54. \mathbb{R}^k is separable since \mathbb{Q}^k is dense.

Proposition 11.55. *Every compact metric space is separable.*

PROOF:

⟨1⟩1. LET: X be a compact metric space.

⟨1⟩2. For $n \in \mathbb{Z}^+$, pick finitely many points a_{n1}, \dots, a_{nr_n} such that $\{B(a_{ni}, 1/n) : 1 \leq i \leq r_n\}$ covers X .

PROOF: Since $\{B(x, 1/n) : x \in X\}$ covers X .

⟨1⟩3. $\{a_{ni} : n \in \mathbb{Z}^+, 1 \leq i \leq r_n\}$ is dense.

⟨2⟩1. LET: U be an open set and $p \in U$.

⟨2⟩2. PICK $\epsilon > 0$ such that $B(p, \epsilon) \subseteq U$.

⟨2⟩3. PICK n such that $1/n < \epsilon$.

⟨2⟩4. PICK i such that $p \in B(a_{ni}, 1/n)$

⟨2⟩5. $a_{ni} \in U$

□

11.13 Bases

Definition 11.56 (Basis). A *basis* for a metric space X is a set \mathcal{B} of open sets such that, for every open set U and point $p \in U$, there exists $B \in \mathcal{B}$ such that $p \in B \subseteq U$.

Proposition 11.57. *Every separable metric space has a countable basis.*

PROOF:

- (1)1. LET: X be a separable metric space.
- (1)2. PICK a countable dense set D in X .
- (1)3. LET: $\mathcal{B} = \{B(p, \epsilon) : p \in D, \epsilon \in \mathbb{Q}^+\}$
- PROVE: \mathcal{B} is a basis.
- (1)4. LET: U be an open set in X and $p \in U$
- (1)5. PICK $\epsilon > 0$ such that $B(p, \epsilon) \subseteq U$
- (1)6. PICK $q \in B(p, \epsilon) \cap D$
- (1)7. PICK a rational δ such that $d(p, q) < \delta < \epsilon$.
- (1)8. $B(q, \delta) \in \mathcal{B}$ and $B(q, \delta) \subseteq U$.

□

11.14 Condensation Points

Definition 11.58 (Condensation Point). Let X be a metric space, $p \in X$ and $E \subseteq X$. Then p is a *condensation point* of E iff every neighbourhood of p contains uncountably many points in E .

Proposition 11.59. *Let X be a metric space. Let $E \subseteq X$. Let P be the set of condensation points of E . Then P is perfect.*

PROOF:

- (1)1. P is closed.
- (2)1. LET: $p \in X - P$
- (2)2. PICK a neighbourhood U of p that contains only countably many points of E .
- (2)3. For every $x \in U$, we have that U is a neighbourhood of x that contains only countably many points of E .
- (2)4. $p \in U \subseteq X - P$
- (1)2. Every point in P is a limit point of P .

PROOF: Immediate from definitions.

□

Proposition 11.60. *Let X be a metric space with a countable basis. Let $E \subseteq X$ be uncountable. Let P be the set of condensation points of E . Then $E - P$ is countable.*

PROOF:

- (1)1. PICK a countable basis \mathcal{B} for X .
- (1)2. LET: $W = \bigcup \{B \in \mathcal{B} : E \cap B \text{ is countable}\}$

- ⟨1⟩3. $P = X - W$
- ⟨2⟩1. $P \subseteq X - W$
 - ⟨3⟩1. ASSUME: for a contradiction $p \in P \cap W$
 - ⟨3⟩2. PICK $B \in \mathcal{B}$ such that $p \in B$ and $E \cap B$ is countable.
 - ⟨3⟩3. $E \cap B$ is uncountable.
 - ⟨3⟩4. Q.E.D.
- PROOF: This is a contradiction.
- ⟨2⟩2. $X - W \subseteq P$
 - ⟨3⟩1. LET: $p \in X - W$
 - ⟨3⟩2. LET: U be a neighbourhood of p .
 - ⟨3⟩3. PICK $B \in \mathcal{B}$ such that $p \in B \subseteq U$.
 - ⟨3⟩4. $E \cap B$ is uncountable.
 - PROOF: Since $p \notin W$.
 - ⟨3⟩5. $E \cap W$ is uncountable.
- ⟨1⟩4. $E - P = E \cap W$
- ⟨1⟩5. $E - P$ is countable.

□

Corollary 11.60.1. *Every closed subset of a metric space with a countable basis is the union of a perfect set and a countable set.*

PROOF:

- ⟨1⟩1. LET: X be a metric space with a countable basis.
- ⟨1⟩2. LET: E be a closed subset of X .
- ⟨1⟩3. LET: P be the set of condensation points of E .
- ⟨1⟩4. $E - P$ is countable.

PROOF: Proposition 11.60.

- ⟨1⟩5. $P \cap E$ is perfect.

- ⟨2⟩1. $P \cap E$ is closed.

PROOF: Proposition 11.59.

- ⟨2⟩2. Every point in $P \cap E$ is a limit point of $P \cap E$.

- ⟨3⟩1. LET: $l \in P \cap E$
- ⟨3⟩2. LET: U be a neighbourhood of l .
- ⟨3⟩3. PICK $x \in P \cap U$
- ⟨3⟩4. U is a neighbourhood of x .
- ⟨3⟩5. U contains uncountably many points of E .
- ⟨3⟩6. U intersects $P \cap E$

PROOF: It cannot be that every point in U and E is not in P since $E - P$ is countable.

□

Corollary 11.60.2. *Let X be a metric space with a countable basis. Then every countable set in X has an isolated point.*

Chapter 12

Convergence

Definition 12.1 (Converge). Let X be a metric space. Let (p_n) be a sequence in X and $l \in X$. Then we say (p_n) *converges* to the *limit* l , and write

$$p_n \rightarrow l \text{ as } n \rightarrow \infty ,$$

iff for every $\epsilon > 0$, there exists an integer N such that, for all $n \geq N$, we have $d(p_n, l) < \epsilon$.

We say (p_n) *diverges* iff it does not converge to any limit.

Proposition 12.2. *A sequence has at most one limit.*

PROOF:

- (1)1. ASSUME: $p_n \rightarrow l$ and $p_n \rightarrow m$ as $n \rightarrow \infty$.
- (1)2. ASSUME: for a contradiction $l \neq m$.
- (1)3. LET: $\epsilon = d(l, m)/2$
- (1)4. There exists N such that $\forall n \geq N. d(p_n, l) < \epsilon$ and $d(p_n, m) < \epsilon$
- (1)5. $d(l, m) < 2\epsilon$
- (1)6. Q.E.D.

PROOF: This is a contradiction.

□

Proposition 12.3. *Every convergent sequence is bounded.*

PROOF:

- (1)1. LET: $p_n \rightarrow l$ as $n \rightarrow \infty$
- (1)2. PICK N such that $\forall n \geq N. d(p_n, l) < 1$
- (1)3. LET: $M = \max(d(p_0, l), \dots, d(p_{N-1}, l), 1)$
- (1)4. For all n , we have $d(p_n, l) \leq M$.

□

Proposition 12.4. *If l is a limit point of E , then there exists a sequence in E that converges to l .*

PROOF:

$\langle 1 \rangle 1$. For $n \in \mathbb{Z}^+$, PICK a point $a_n \in E$ such that $d(a_n, l) < 1/n$.

PROOF: Since $B(l, 1/n)$ intersects E .

$\langle 1 \rangle 2$. $a_n \rightarrow l$ as $n \rightarrow \infty$.

□

Corollary 12.4.1. *Every sequence in a compact metric space has a convergent subsequence.*

PROOF: By Theorem 11.39. □

Proposition 12.5. *Assume $s_n \rightarrow s$ and $t_n \rightarrow t$ in \mathbb{C} . Then $s_n + t_n \rightarrow s + t$.*

PROOF:

$\langle 1 \rangle 1$. LET: $\epsilon > 0$

$\langle 1 \rangle 2$. PICK N such that, for all $n \geq N$, we have $d(s_n, s) < \epsilon/2$ and $d(t_n, t) < \epsilon/2$.

$\langle 1 \rangle 3$. For all $n \geq N$ we have $d(s_n + t_n, s + t) < \epsilon$.

□

Lemma 12.6. *If $s_n \rightarrow s$ as $n \rightarrow \infty$ in \mathbb{C} , and $c \in \mathbb{C}$, then $cs_n \rightarrow cs$ as $n \rightarrow \infty$.*

PROOF:

$\langle 1 \rangle 1$. LET: $\epsilon > 0$

$\langle 1 \rangle 2$. ASSUME: w.l.o.g. $c \neq 0$

$\langle 1 \rangle 3$. PICK N such that $\forall n \geq N, |s_n - s| < \epsilon/|c|$.

$\langle 1 \rangle 4$. $\forall n \geq N, |cs_n - cs| < \epsilon$

□

Proposition 12.7. *If $s_n \rightarrow s$ and $t_n \rightarrow t$ in \mathbb{C} then $s_n t_n \rightarrow st$.*

PROOF:

$\langle 1 \rangle 1$. $(s_n - s)(t_n - t) \rightarrow 0$ as $n \rightarrow \infty$

$\langle 2 \rangle 1$. LET: $\epsilon > 0$

$\langle 2 \rangle 2$. PICK N such that, for all $n \geq N$, we have $|s_n - s| < \sqrt{\epsilon}$ and $|t_n - t| < \sqrt{\epsilon}$.

$\langle 2 \rangle 3$. For all $n \geq N$ we have $|(s_n - s)(t_n - t)| < \epsilon$

$\langle 1 \rangle 2$. $s_n t_n - st \rightarrow 0$ as $n \rightarrow \infty$

PROOF:

$$s_n t_n - st = (s_n - s)(t_n - t) + s(t_n - t) + t(s_n - s)$$

$$\rightarrow 0$$

$$\text{as } n \rightarrow \infty$$

□

Proposition 12.8. *If $s_n \rightarrow s$ as $n \rightarrow \infty$ in \mathbb{C} , and every s_n and s is nonzero, then $1/s_n \rightarrow 1/s$ as $n \rightarrow \infty$.*

PROOF:

$\langle 1 \rangle 1$. PICK m such that, for all $n \geq m$, we have $|s_n - s| < \frac{1}{2}|s|$.

$\langle 1 \rangle 2$. $\forall n \geq m, |s_n| > \frac{1}{2}|s|$

$\langle 1 \rangle 3$. LET: $\epsilon > 0$

$\langle 1 \rangle 4$. PICK $N > m$ such that, for all $n \geq N$, we have

$$|s_n - s| < \frac{1}{2}|s|^2\epsilon .$$

(1)5. For all $n \geq N$, we have

$$\left| \frac{1}{s_n} - \frac{1}{s} \right| < \epsilon .$$

PROOF:

$$\begin{aligned} \left| \frac{1}{s_n} - \frac{1}{s} \right| &= \frac{|s_n - s|}{|s_n||s|} \\ &< \frac{|s|^2 \epsilon}{2|s_n||s|} \\ &= \frac{|s| \epsilon}{2|s_n|} \\ &< \epsilon \end{aligned}$$

□

Theorem 12.9. Let (\vec{x}_n) be a sequence in \mathbb{R}^k and $\vec{l} \in \mathbb{R}^k$. Then $\vec{x}_n \rightarrow \vec{l}$ as $n \rightarrow \infty$ iff, for $i = 1, \dots, k$, we have $\pi_i(\vec{x}_n) \rightarrow \pi_i(\vec{l})$ as $n \rightarrow \infty$.

PROOF:

(1)1. If $\vec{x}_n \rightarrow \vec{l}$ then $\pi_i(\vec{x}_n) \rightarrow \pi_i(l)$.

(2)1. $\|\vec{x}_n - \vec{l}\| \rightarrow 0$ as $n \rightarrow \infty$.

(2)2. $\sqrt{\sum_{i=1}^k (\pi_i(\vec{x}_n) - \pi_i(l))^2} \rightarrow 0$ as $n \rightarrow \infty$.

(2)3. $\sum_{i=1}^k (\pi_i(\vec{x}_n) - \pi_i(l))^2 \rightarrow 0$ as $n \rightarrow \infty$.

(2)4. $(\pi_i(\vec{x}_n) - \pi_i(l))^2 \rightarrow 0$ as $n \rightarrow \infty$

(2)5. $\pi_i(\vec{x}_n) - \pi_i(l) \rightarrow 0$ as $n \rightarrow \infty$.

(1)2. If $\pi_i(\vec{x}_n) \rightarrow \pi_i(\vec{l})$ for every i then $\vec{x}_n \rightarrow l$.

(2)1. ASSUME: $\pi_i(\vec{x}_n) \rightarrow \pi_i(\vec{l})$ for every i .

(2)2. $\vec{x}_n \rightarrow \vec{l}$

PROOF:

$$\begin{aligned} \|\vec{x}_n - \vec{l}\|^2 &= \sum_{i=1}^k (\pi_i(\vec{x}_n) - \pi_i(\vec{l}))^2 \\ &\rightarrow 0 \end{aligned}$$

□

Corollary 12.9.1. If $\vec{x}_n \rightarrow \vec{x}$ and $\vec{y}_n \rightarrow \vec{y}$ in \mathbb{R}^k , then $\vec{x}_n + \vec{y}_n \rightarrow \vec{x} + \vec{y}$.

Corollary 12.9.2. If $\beta_n \rightarrow \beta$ in \mathbb{R} and $\vec{x}_n \rightarrow \vec{l}$ in \mathbb{R}^k , then $\beta_n \vec{x}_n \rightarrow \beta \vec{l}$.

Proposition 12.10. If $\vec{x}_n \rightarrow \vec{x}$ and $\vec{y}_n \rightarrow \vec{y}$ in \mathbb{R}^k , then $\vec{x}_n \cdot \vec{y}_n \rightarrow \vec{x} \cdot \vec{y}$.

PROOF:

$$\begin{aligned} \vec{x}_n \cdot \vec{y}_n &= \sum_{i=1}^k \pi_i(\vec{x}_n) \pi_i(\vec{y}_n) \\ &\rightarrow \sum_{i=1}^k \pi_i(\vec{x}) \pi_i(\vec{y}) \\ &= \vec{x} \cdot \vec{y} \end{aligned}$$

□

Proposition 12.11. *Let (p_n) be a sequence in the metric space X . The set E^* of all limits of convergent subsequences is a closed set.*

PROOF:

- $\langle 1 \rangle 1$. ASSUME: w.l.o.g. $\{p_n : n \in \mathbb{N}\}$ is infinite.
- $\langle 1 \rangle 2$. LET: q be a limit point of E^* .
 PROVE: $q \in E^*$
- $\langle 1 \rangle 3$. PICK an integer n_0 such that $q \neq p_{n_0}$.
- $\langle 1 \rangle 4$. Extend a strictly increasing sequence of integers (n_i) such that, for all i , we have $d(q, p_{n_i}) \leq 2^i d(q, p_{n_0})$.
 $\langle 2 \rangle 1$. ASSUME: as induction hypothesis we have picked $n_0 < n_1 < \cdots < n_i$ such that, for $0 \leq j \leq i$, we have $d(q, p_{n_j}) \leq 2^j d(q, p_{n_0})$.
 $\langle 2 \rangle 2$. PICK $x \in E^*$ such that $d(x, q) < 2^{-(i+2)} \delta$
 $\langle 2 \rangle 3$. There exists a subsequence of (p_n) that converges to x .
 $\langle 2 \rangle 4$. There exists $n_{i+1} > n_i$ such that $d(p_{n_{i+1}}, x) < 2^{-(i+2)} \delta$.
 $\langle 2 \rangle 5$. $d(p_{n_{i+1}}, q) < 2^{-(i+1)} \delta$
- $\langle 1 \rangle 5$. $p_{n_i} \rightarrow q$ as $i \rightarrow \infty$.
- $\langle 1 \rangle 6$. $q \in E^*$

□

Theorem 12.12. *Every monotonically increasing sequence in \mathbb{R} that is bounded above converges to its supremum.*

PROOF:

- $\langle 1 \rangle 1$. LET: (s_n) be a monotonically increasing sequence with supremum s .
- $\langle 1 \rangle 2$. LET: $\epsilon > 0$
- $\langle 1 \rangle 3$. PICK N such that $|s_N - s| < \epsilon$
- $\langle 1 \rangle 4$. For all $n \geq N$, we have $s - \epsilon < s - s_N \leq s - s_n \leq s$.
- $\langle 1 \rangle 5$. $\forall n \geq N, |s_n - s| < \epsilon$

□

Theorem 12.13. *Every monotonically decreasing sequence in \mathbb{R} that is bounded below converges to its infimum.*

PROOF: Similar. □

Proposition 12.14 (Sandwich Theorem). *Let (a_n) , (b_n) and (c_n) be sequences of real numbers and $l \in \mathbb{R}$. Assume $\forall n, a_n \leq b_n \leq c_n$ and $a_n \rightarrow l$ and $c_n \rightarrow l$. Then $b_n \rightarrow l$.*

PROOF:

- $\langle 1 \rangle 1$. LET: $\epsilon > 0$
- $\langle 1 \rangle 2$. PICK N such that, for all $n \geq N$, we have $|a_n - l| < \epsilon$ and $|c_n - l| < \epsilon$.
- $\langle 1 \rangle 3$. $\forall n \geq N, |b_n - l| < \epsilon$

□

Theorem 12.15. *For any real $p > 0$ we have*

$$\frac{1}{(n+1)^p} \rightarrow 0$$

as $n \rightarrow \infty$.

PROOF:

- (1)1. LET: $\epsilon > 0$
 (1)2. PICK N such that $N > (1/\epsilon)^{1/p}$.
 (1)3. LET: $n \geq N$
 (1)4. $1/n^p < \epsilon$
 \square

Theorem 12.16. *For any real $p > 0$ we have*

$$p^{\frac{1}{n+1}} \rightarrow 1$$

as $n \rightarrow \infty$.

PROOF:

- (1)1. CASE: $p > 1$

- (2)1. For $n \in \mathbb{N}$

LET: $x_n = p^{\frac{1}{n+1}} - 1$.

- (2)2. $\forall n \in \mathbb{N}. x_n > 0$

- (2)3. $\forall n \in \mathbb{N}$.

$$1 + (n+1)x_n \leq p.$$

PROOF: Since $1 + (n+1)x_n \leq (1+x_n)^{n+1}$ by the Binomial Theorem.

- (2)4. $\forall n \in \mathbb{N}$.

$$0 < x_n \leq \frac{p-1}{n+1}.$$

- (2)5. $x_n \rightarrow 0$ as $n \rightarrow \infty$.

PROOF: Sandwich Theorem.

- (1)2. CASE: $p = 1$

PROOF: Trivial.

- (1)3. CASE: $p < 1$

PROOF: Then $p^{1/(n+1)} = 1/((1/p)^{1/(n+1)}) \rightarrow 1/1 = 1$ by (1)1.

\square

Theorem 12.17.

$$(n+1)^{1/(n+1)} \rightarrow 1 \text{ as } n \rightarrow \infty$$

PROOF:

- (1)1. For $n \in \mathbb{N}$,

LET: $x_n = (n+1)^{1/(n+1)} - 1$.

- (1)2. $\forall n \in \mathbb{N}. x_n \geq 0$

- (1)3. $\forall n \in \mathbb{N}$

$$n+1 \geq \frac{n(n+1)}{2} x_n^2.$$

PROOF: Since $(1+x_n)^{n+1} \geq \frac{n(n+1)}{2} x_n^2$ by the Binomial Theorem.

- (1)4. $\forall n \geq 1$

$$0 \leq x_n \leq \sqrt{\frac{2}{n}}$$

- (1)5. $x_n \rightarrow 0$ as $n \rightarrow \infty$.

PROOF: Sandwich Theorem.

□

Theorem 12.18. *Let p and α be real numbers with $p > 0$. Then*

$$\frac{n^\alpha}{(1+p)^n} \rightarrow 0 \text{ as } n \rightarrow \infty .$$

PROOF:

(1)1. PICK a positive integer k such that $k > \alpha$.

PROOF: Archimedean Property.

(1)2. $\forall n > 2k$

$$(1+p)^n > \frac{n^k p^k}{2^k k!} .$$

$$\begin{aligned} (1+p)^n &> \binom{n}{k} p^k && \text{(Binomial Theorem)} \\ &= \frac{n(n-1)\cdots(n-k+1)}{k!} p^k \\ &> \frac{n^k p^k}{2^k k!} && (n > 2k \text{ so if } n-k < i \leq n \text{ then } i > n/2) \end{aligned}$$

(1)3. $\forall n > 2k$

$$0 < \frac{n^\alpha}{(1+p)^n} < \frac{2^k k!}{p^k} n^{\alpha-k} .$$

(1)4. $n^{\alpha-k} \rightarrow 0$ as $n \rightarrow \infty$

PROOF: Theorem 12.15.

(1)5. $\frac{n^\alpha}{(1+p)^n} \rightarrow 0$ as $n \rightarrow \infty$.

PROOF: Sandwich Theorem.

□

Corollary 12.18.1. *For any real number x with $|x| < 1$ we have $x^n \rightarrow 0$ as $n \rightarrow \infty$.*

PROOF: Taking $\alpha = 0$. □

12.1 Cauchy Sequences

Definition 12.19 (Cauchy Sequence). Let (p_n) be a sequence in the metric space X . Then (p_n) is a *Cauchy sequence* iff, for every $\epsilon > 0$, there exists N such that, for all $m, n \geq N$, we have $d(p_m, p_n) < \epsilon$.

Proposition 12.20. *Let (p_n) be a sequence in the metric space X and let $E_N = \{p_n : n \geq N\}$ for all N . Then (p_n) is a Cauchy sequence if and only if $\text{diam } E_N \rightarrow 0$ as $N \rightarrow \infty$.*

PROOF: Immediate from definitions. □

Theorem 12.21. *Every convergent sequence is Cauchy.*

PROOF:

- (1)1. LET: (p_n) be a convergent sequence with limit l .
 - (1)2. LET: $\epsilon > 0$
 - (1)3. PICK N such that, for all $n \geq N$, we have $d(p_n, l) < \epsilon/2$
 - (1)4. $\forall m, n \geq N. d(p_m, p_n) < \epsilon$
-

12.2 Complete Metric Spaces

Definition 12.22 (Complete Metric Space). A metric space is *complete* iff every Cauchy sequence converges.

Theorem 12.23. *Every compact metric space is complete.*

PROOF:

- (1)1. LET: X be a compact metric space.
 - (1)2. LET: (p_n) be a Cauchy sequence in X .
 - (1)3. For $N \in \mathbb{N}$,
LET: $E_N = \{p_n : n \geq N\}$.
 - (1)4. $\text{diam } \overline{E_N} \rightarrow 0$ as $N \rightarrow \infty$.
 - (1)5. For all N , every $\overline{E_N}$ is compact.
PROOF: Proposition 11.37.
 - (1)6. For all N we have $\overline{E_N} \supseteq \overline{E_{N+1}}$.
 - (1)7. LET: l be the unique point in $\bigcap_{N=0}^{\infty} \overline{E_N}$
PROVE: $p_n \rightarrow l$ as $n \rightarrow \infty$.
PROOF: Proposition 11.44.
 - (1)8. LET: $\epsilon > 0$
 - (1)9. PICK N_0 such that $\forall N \geq N_0. \text{diam } \overline{E_N} < \epsilon$.
 - (1)10. $\forall q \in E_N. d(l, q) < \epsilon$
 - (1)11. $\forall n \geq N. d(l, p_n) < \epsilon$
-

Corollary 12.23.1. *Let X be a metric space. If every closed bounded set in X is compact, then X is complete.*

PROOF:

- (1)1. LET: S be a Cauchy sequence in X .
 - (1)2. S is bounded.
 - (1)3. \overline{S} is closed and bounded.
 - (1)4. \overline{S} is compact.
 - (1)5. S is a Cauchy sequence in \overline{S} .
 - (1)6. S converges.
-

Corollary 12.23.2. *For every natural number k , we have \mathbb{R}^k is complete.*

Corollary 12.23.3. *Every closed subspace of a complete metric space is complete.*

12.3 Divergent Sequences

Definition 12.24. Let (s_n) be a sequence in \mathbb{R} . Then we say s_n *diverges to* $+\infty$, and write

$$s_n \rightarrow +\infty \text{ as } n \rightarrow \infty ,$$

iff for every real number M , there exists an integer N such that

$$\forall n \geq N. s_n \geq M .$$

We say s_n *diverges to* $-\infty$, and write

$$s_n \rightarrow -\infty \text{ as } n \rightarrow \infty ,$$

iff for every real number M , there exists an integer N such that

$$\forall n \geq N. s_n \leq M .$$

Definition 12.25 (Limit Supremum, Limit Infimum). Let (s_n) be a sequence in \mathbb{R} . Let E be the set of all $l \in \mathbb{R} \cup \{+\infty, -\infty\}$ such that there exists a subsequence of (s_n) that converges to l .

The *limit supremum* of (s_n) , denoted

$$\limsup_{n \rightarrow \infty} s_n ,$$

is the supremum of E in the extended reals.

The *limit infimum* of (s_n) , denoted

$$\liminf_{n \rightarrow \infty} s_n ,$$

is the infimum of E in the extended reals.

PROOF: The set E is always nonempty because: if (s_n) is unbounded above then $+\infty \in E$; if it is unbounded below then $-\infty \in E$; and if it is bounded above and below then there is a real number in E by Corollary 12.4.1. \square

Theorem 12.26. Let (s_n) be a sequence in \mathbb{R} . Then there exists a subsequence of (s_n) that converges or diverges to $\limsup_{n \rightarrow \infty} s_n$

PROOF:

(1)1. CASE: $\limsup_n s_n = +\infty$

PROOF: (s_n) is unbounded above and so has a subsequence that diverges to $+\infty$.

(1)2. CASE: $\limsup_n s_n \in \mathbb{R}$

PROOF: Then $\limsup s_n$ is in the set of limits of subsequences of (s_n) by Proposition 12.11.

(1)3. CASE: $\limsup_n s_n = -\infty$

PROOF: (s_n) is unbounded below and so has a subsequence that diverges to $-\infty$.

□

Theorem 12.27. *Let (s_n) be a sequence in \mathbb{R} . Then there exists a subsequence of (s_n) that converges or diverges to $\liminf_{n \rightarrow \infty} s_n$*

PROOF: Similar. □

Theorem 12.28. *Let (s_n) be a sequence in \mathbb{R} . If $x > \limsup_n s_n$, then there exists N such that $\forall n \geq N, s_n < x$.*

PROOF: If not, we could choose a subsequence of (s_n) that converges to a value $\geq x$, contradicting the definition of $\limsup_n s_n$. □

Theorem 12.29. *Let (s_n) be a sequence in \mathbb{R} . If $x < \liminf_n s_n$, then there exists N such that $\forall n \geq N, s_n > x$.*

PROOF: Similar. □

Theorem 12.30. *Let (s_n) be a sequence in \mathbb{R} . Let s^* be an extended real such that:*

- *There exists a subsequence of (s_n) that converges or diverges to s^* .*
- *For any $x > s^*$, there exists N such that $\forall n \geq N, s_n < x$.*

Then $s^ = \limsup_n s_n$.*

PROOF:

⟨1⟩1. LET: E be the set of subsequential limits of (s_n) .

⟨1⟩2. s^* is an upper bound for E .

⟨2⟩1. LET: $x \in E$

⟨2⟩2. ASSUME: for a contradiction $x > s^*$.

⟨2⟩3. $s^* \in \mathbb{R}$

⟨2⟩4. LET: $y = x$ if $x \in \mathbb{R}$, or $s^* + 1$ if $x = +\infty$

⟨2⟩5. There exists N such that $\forall n \geq N, s_n < y$.

⟨2⟩6. Q.E.D.

PROOF: This contradicts the fact that some subsequence of (s_n) converges or diverges to x .

⟨1⟩3. If u is an upper bound for E then $s^* \leq u$.

□

Theorem 12.31. *Let (s_n) be a sequence in \mathbb{R} . Let s^* be an extended real such that:*

- *There exists a subsequence of (s_n) that converges or diverges to s^* .*
- *For any $x < s^*$, there exists N such that $\forall n \geq N, s_n > x$.*

Then $s^ = \liminf_n s_n$.*

PROOF: Similar. □

Proposition 12.32. *Let (s_n) be a sequence of real numbers and $l \in \mathbb{R}$. Then (s_n) converges to l iff $\limsup_n s_n = \liminf_n s_n = l$.*

PROOF:

$\langle 1 \rangle 1$. If (s_n) converges to l then $\limsup_n s_n = \liminf_n s_n = l$.

PROOF: If (s_n) converges to l then every subsequence of (s_n) converges to l .

$\langle 1 \rangle 2$. If $\limsup_n s_n = \liminf_n s_n = l$ then (s_n) converges to l .

$\langle 2 \rangle 1$. ASSUME: $\limsup_n s_n = \liminf_n s_n = l$

$\langle 2 \rangle 2$. For all $\epsilon > 0$, there exists N such that $\forall n \geq N. l - \epsilon < s_n < l + \epsilon$.

PROOF: Theorem 12.30 and 12.31.

$\langle 2 \rangle 3$. $s_n \rightarrow l$ as $n \rightarrow \infty$.

□

Theorem 12.33. *Let (s_n) and (t_n) be sequences of real numbers and $N \in \mathbb{N}$. Assume $\forall n \geq N. s_n \leq t_n$. Then*

$$\liminf_{n \rightarrow \infty} s_n \leq \liminf_{n \rightarrow \infty} t_n .$$

PROOF:

$\langle 1 \rangle 1$. For any subsequence (t_{n_r}) of (t_n) that converges or diverges to $\pm\infty$, we have $\liminf_n s_n \leq \lim_r t_{n_r}$

$\langle 2 \rangle 1$. LET: (t_{n_r}) be a subsequence of (t_n) with limit l .

$\langle 2 \rangle 2$. PICK m such that a subsequence of (s_{n_r}) has limit m .

$\langle 2 \rangle 3$. $\forall r. s_{n_r} \leq t_{n_r}$

$\langle 2 \rangle 4$. $m \leq l$

$\langle 2 \rangle 5$. $\liminf_n s_n \leq l$

$\langle 1 \rangle 2$. $\liminf_n s_n \leq \liminf_n t_n$

□

Theorem 12.34. *Let (s_n) and (t_n) be sequences of real numbers and $N \in \mathbb{N}$. Assume $\forall n \geq N. s_n \leq t_n$. Then*

$$\limsup_{n \rightarrow \infty} s_n \leq \limsup_{n \rightarrow \infty} t_n .$$

PROOF: Similar. □

Theorem 12.35. *For any sequence (c_n) of positive real numbers, we have*

$$\limsup_{n \rightarrow \infty} c_n^{1/n} \leq \limsup_{n \rightarrow \infty} \frac{c_{n+1}}{c_n} .$$

PROOF:

$\langle 1 \rangle 1$. LET: $\alpha = \limsup_n c_{n+1}/c_n$

$\langle 1 \rangle 2$. ASSUME: w.l.o.g. $\alpha < +\infty$

$\langle 1 \rangle 3$. For all $\beta > \alpha$ we have $\limsup_{n \rightarrow \infty} c_n^{1/n} \leq \beta$.

$\langle 2 \rangle 1$. LET: $\beta > \alpha$

$\langle 2 \rangle 2$. PICK N such that, for all $n \geq N$, we have

$$\frac{c_{n+1}}{c_n} \leq \beta .$$

PROOF: Theorem 12.28.

⟨2⟩3. For all $k \geq 0$ we have

$$c_{N+k+1} \leq \beta c_{N+k} .$$

⟨2⟩4. For all $n \geq N$ we have

$$c_n \leq c_N \beta^{-N} \beta^n .$$

PROOF: Induction on n .

⟨2⟩5. For all $n \geq N$ we have

$$c_n^{1/n} \leq (c_N \beta^{-N})^{1/n} \beta .$$

⟨2⟩6.

$$\limsup_{n \rightarrow \infty} c_n^{1/n} \leq \beta$$

PROOF:

$$\limsup_{n \rightarrow \infty} c_n^{1/n} \leq \limsup_{n \rightarrow \infty} (c_N \beta^{-N})^{1/n} \beta \quad (\text{Theorem 12.34})$$

$$= \beta \quad (\text{Theorem 12.16})$$

⟨1⟩4.

$$\limsup_{n \rightarrow \infty} c_n^{1/n} \leq \alpha$$

□

Theorem 12.36. For any sequence (c_n) of positive real numbers, we have

$$\liminf_{n \rightarrow \infty} \frac{c_{n+1}}{c_n} \leq \liminf_{n \rightarrow \infty} c_n^{1/n} .$$

PROOF: Similar. □

12.4 Infinite Series

Definition 12.37. Let (a_n) be a sequence of complex numbers and $s \in \mathbb{C}$. We say the *infinite series* $\sum_{n=0}^{\infty} a_n$ *converges* to s , and write

$$\sum_{n=0}^{\infty} a_n = s$$

iff

$$\sum_{n=0}^N a_n \rightarrow s \text{ as } N \rightarrow \infty .$$

If $(\sum_{n=0}^N a_n)$ diverges, we say the infinite series $\sum_{n=0}^{\infty} a_n$ diverges.

Theorem 12.38. Let (a_n) be a sequence of complex numbers. Then $\sum_{n=0}^{\infty} a_n$ converges if and only if, for all $\epsilon > 0$, there exists N such that, for all $m, n \geq N$,

$$\left| \sum_{k=m}^n a_k \right| \leq \epsilon .$$

PROOF: This is what it means for $(\sum_{k=0}^n a_k)$ to be a Cauchy sequence. □

Corollary 12.38.1. *If $\sum_{n=0}^{\infty} a_n$ converges then $a_n \rightarrow 0$ as $n \rightarrow \infty$.*

Theorem 12.39. *A series of nonnegative reals converges if and only if its partial sums form a bounded sequence.*

PROOF: Its partial sums are a monotonically increasing sequence, and so converge if and only if they are bounded above. \square

Theorem 12.40 (Comparison Test). *Let (a_n) be a sequence of complex numbers and (c_n) a sequence of real numbers. If there exists N such that $\forall n \geq N, |a_n| \leq c_n$, and if $\sum_n c_n$ converges, then $\sum_n a_n$ converges.*

PROOF:

$\langle 1 \rangle 1.$ LET: $\epsilon > 0$

$\langle 1 \rangle 2.$ PICK N such that $\forall n \geq N, |a_n| \leq c_n$ and $\forall m, n \geq N, \sum_{k=m}^n c_k < \epsilon$.

$\langle 1 \rangle 3.$ $\forall m, n \geq N, |\sum_{k=m}^n a_k| \leq \epsilon$

\square

Corollary 12.40.1. *Let (a_n) and (d_n) be sequences of real numbers. If there exists N such that $\forall n \geq N, a_n \geq d_n \geq 0$, and if $\sum_n d_n$ diverges, then $\sum_n a_n$ diverges.*

Theorem 12.41 (Geometric Series). *For x a real number with $0 \leq x < 1$ we have*

$$\sum_{n=0}^{\infty} x^n = \frac{1}{1-x}.$$

PROOF: Since $\sum_{n=0}^N x^n = \frac{1-x^{N+1}}{1-x} \rightarrow \frac{1}{1-x}$ as $n \rightarrow \infty$. \square

Theorem 12.42. *For x a real number with $x \geq 1$ we have $\sum_{n=0}^{\infty} x^n$ diverges.*

PROOF: If $x = 1$ then $\sum_{n=0}^N x^n = N + 1$. If $x > 1$ then $\sum_{n=0}^N x^n = \frac{1-x^{N+1}}{1-x}$. Both of these sequences diverge. \square

Theorem 12.43. *Let (a_n) be a monotonically decreasing sequence of nonnegative real numbers. Then $\sum_n a_n$ converges if and only if $\sum_n 2^n a_{2^n}$ converges.*

PROOF:

$\langle 1 \rangle 1.$ For $N \in \mathbb{N}$,

LET: $s_N = \sum_{n=0}^N a_n$.

$\langle 1 \rangle 2.$ For $N \in \mathbb{N}$,

LET: $t_N = \sum_{n=0}^N 2^n a_{2^n}$.

$\langle 1 \rangle 3.$ For natural number N and k with $N < 2^k$ we have $s_N \leq a_0 + t_{k-1}$.

PROOF:

$$\begin{aligned}
 s_N &\leq \sum_{n=0}^{2^k-1} a_n \\
 &= a_0 + \sum_{i=0}^{k-1} \sum_{n=2^i}^{2^{i+1}-1} a_n \\
 &\leq a_0 + \sum_{i=0}^{k-1} 2^i a_{2^i} \\
 &= a_0 + t_{k-1}
 \end{aligned}$$

(1)4. For natural number N and k with $N > 2^k$ we have $t_k < 2s_N$.

PROOF:

$$\begin{aligned}
 s_N &\geq \sum_{n=1}^{2^k} a_n \\
 &\geq \sum_{i=0}^k \sum_{n=2^i}^{2^{i+1}-1} a_n \\
 &\geq \sum_{i=0}^k 2^i a_{2^{i+1}} \\
 &= (1/2)t_k
 \end{aligned}$$

(1)5. (s_N) converges if and only if (t_k) converges.

□

Theorem 12.44. *If p is a real number with $p > 1$ then $\sum_n 1/n^p$ converges.*

PROOF: Since

$$\sum_{n=0}^{\infty} 2^n \frac{1}{2^{np}} = \sum_{n=0}^{\infty} 2^{(1-p)n}$$

which converges since $2^{1-p} < 1$. □

Theorem 12.45. *If p is a real number with $p \leq 1$ then $\sum_n 1/n^p$ diverges.*

PROOF: If $p \leq 0$ then $1/n^p$ does not converge to 0.

If $0 < p \leq 1$ we have

$$\sum_{n=0}^{\infty} 2^n \frac{1}{2^{np}} = \sum_{n=0}^{\infty} 2^{(1-p)n}$$

which diverges since $2^{1-p} \geq 1$. □

Theorem 12.46. *Let p be a real number. The series*

$$\sum_{n=2}^{\infty} \frac{1}{n(\ln n)^p}$$

converges if and only if $p > 1$.

PROOF:

$$\begin{aligned} 2^k \frac{1}{2^k (\ln 2^k)^p} &= \frac{1}{(k \ln 2)^p} \\ &= \frac{1}{(\ln 2)^p} \cdot \frac{1}{k^p} \end{aligned}$$

and this series converges iff $\sum_k \frac{1}{k^p}$ converges iff $p > 1$. \square

Theorem 12.47 (Root Test). *Let $(a_n)_{n \geq 1}$ be a sequence of complex numbers. Let $\alpha = \limsup_{n \rightarrow \infty} |a_n|^{1/n}$.*

1. *If $\alpha < 1$ then $\sum_{n=1}^{\infty} a_n$ converges.*
2. *If $\alpha > 1$ then $\sum_{n=1}^{\infty} a_n$ diverges.*

PROOF:

(1)1. If $\alpha < 1$ then $\sum_{n=1}^{\infty} a_n$ converges.

$\langle 2 \rangle 1$. ASSUME: $\alpha < 1$

$\langle 2 \rangle 2$. PICK β such that $\alpha < \beta < 1$

$\langle 2 \rangle 3$. PICK N such that $\forall n \geq N, |a_n|^{1/n} < \beta$

PROOF: Theorem 12.28.

$\langle 2 \rangle 4$. $\forall n \geq N, |a_n| < \beta^n$

$\langle 2 \rangle 5$. $\sum_{n=1}^{\infty} \beta^n$ converges.

PROOF: Theorem 12.41.

$\langle 2 \rangle 6$. $\sum_{n=1}^{\infty} a_n$ converges.

PROOF: Comparison Test.

(1)2. If $\alpha > 1$ then $\sum_{n=1}^{\infty} a_n$ diverges.

$\langle 2 \rangle 1$. ASSUME: $\alpha > 1$

$\langle 2 \rangle 2$. There exists a sequence of positive integers (n_k) such that $|a_{n_k}|^{1/n_k} \rightarrow \alpha$ as $k \rightarrow \infty$.

PROOF: Theorem 12.26.

$\langle 2 \rangle 3$. There are infinitely many n such that $|a_n| > 1$.

$\langle 2 \rangle 4$. $a_n \not\rightarrow 0$ as $n \rightarrow \infty$.

$\langle 2 \rangle 5$. $\sum_{n=1}^{\infty} a_n$ diverges.

PROOF: Corollary 12.38.1.

\square

Example 12.48. If $a_n = 1/n$ then $|a_n|^{1/n} \rightarrow 1$ and $\sum_n a_n$ diverges.

If $a_n = 1/n^2$ then $|a_n|^{1/n} \rightarrow 1$ and $\sum_n a_n$ converges.

Theorem 12.49 (Ratio Test). *Let $(a_n)_{n \geq 0}$ be a sequence of complex numbers.*

1. *If*

$$\limsup_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| < 1$$

then $\sum_{n=0}^{\infty} a_n$ converges.

2. *If there exists N such that $\forall n \geq N, \left| \frac{a_{n+1}}{a_n} \right| > 1$ then $\sum_{n=0}^{\infty} a_n$ diverges.*

PROOF:

(1)1. If $\limsup_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| < 1$ then $\sum_{n=0}^{\infty} a_n$ converges.

(2)1. ASSUME: $\limsup_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| < 1$

(2)2. $\limsup_{n \rightarrow \infty} |a_n|^{1/n} < 1$

PROOF: Theorem 12.35.

(2)3. $\sum_{n=0}^{\infty} a_n$ converges.

PROOF: Root Test

(1)2. If there exists N such that $\forall n \geq N, \left| \frac{a_{n+1}}{a_n} \right| > 1$ then $\sum_{n=0}^{\infty} a_n$ diverges.

PROOF: Since $a_n \not\rightarrow 0$ as $n \rightarrow \infty$.

□

Example 12.50. If $a_n = 1/n$ then $a_{n+1}/a_n \rightarrow 1$ and $\sum_n a_n$ diverges.

If $a_n = 1/n^2$ then $a_{n+1}/a_n \rightarrow 1$ and $\sum_n a_n$ converges.

12.5 The Number e

Lemma 12.51. The series $\sum_{n=0}^{\infty} \frac{1}{n!}$ converges.

PROOF:

$$\sum_{n=0}^N \frac{1}{n!} \leq 1 + \sum_{n=1}^N \frac{1}{2^{n-1}} < 3$$

□

Definition 12.52. The number e is

$$e = \sum_{n=0}^{\infty} \frac{1}{n!} .$$

Theorem 12.53.

$$\left(1 + \frac{1}{n}\right)^n \rightarrow e \text{ as } n \rightarrow \infty$$

PROOF:

(1)1. For $n \in \mathbb{N}$,

LET: $s_n = \sum_{k=0}^n \frac{1}{k!}$

(1)2. For $n \in \mathbb{Z}^+$,

LET: $t_n = \left(1 + \frac{1}{n}\right)^n$

(1)3. For $n \in \mathbb{Z}^+$ we have

$$t_n = \sum_{k=0}^n \frac{1}{k!} \prod_{i=1}^{k-1} \left(1 + \frac{i}{n}\right) .$$

PROOF:

$$\begin{aligned}
 t_n &= \sum_{k=0}^n \binom{n}{k} \frac{1}{n^k} && \text{(Binomial Theorem)} \\
 &= \sum_{k=0}^n \frac{\prod_{i=0}^{k-1} (n-i)}{k!} \frac{1}{n^k} \\
 &= \sum_{k=0}^n \frac{1}{k!} \prod_{i=0}^{k-1} \frac{n-i}{n} \\
 &= \sum_{k=0}^n \frac{1}{k!} \prod_{i=0}^{k-1} \left(1 - \frac{i}{n}\right) \\
 &= \sum_{k=0}^n \frac{1}{k!} \prod_{i=1}^{k-1} \left(1 - \frac{i}{n}\right)
 \end{aligned}$$

(1)4. For $n \in \mathbb{Z}^+$ we have $t_n \leq s_n$.

(1)5. $\limsup_{n \rightarrow \infty} t_n \leq e$

(1)6. For $m, n \in \mathbb{Z}^+$ with $n \geq m$ we have

$$t_n \geq \sum_{k=0}^m \frac{1}{k!} \prod_{i=1}^{k-1} \left(1 - \frac{i}{n}\right) .$$

(1)7. For $m \in \mathbb{Z}^+$ we have

$$\liminf_{n \rightarrow \infty} t_n \geq \sum_{k=0}^m \frac{1}{k!} .$$

(1)8. For $m \in \mathbb{Z}^+$ we have

$$s_m \leq \liminf_{n \rightarrow \infty} t_n .$$

(1)9.

$$e \leq \liminf_{n \rightarrow \infty} t_n$$

(1)10. $t_n \rightarrow e$ as $n \rightarrow \infty$.

PROOF: From (1)5 and (1)9.

□

Theorem 12.54. *e is irrational.*

PROOF:

(1)1. ASSUME: for a contradiction $e = p/q$ where p and q are positive integers.

(1)2. For $n \in \mathbb{N}$,

LET: $s_n = \sum_{k=0}^n \frac{1}{k!}$.

(1)3. For $n \in \mathbb{Z}^+$ we have

$$0 < e - s_n < \frac{1}{n!n} .$$

PROOF:

$$\begin{aligned} e - s_n &= \sum_{k=n+1}^{\infty} \frac{1}{k!} \\ &< \frac{1}{(n+1)!} \sum_{k=0}^{\infty} \frac{1}{(n+1)^k} \\ &= \frac{1}{n!n} \end{aligned}$$

(1)4.

$$0 < q!(e - s_q) < \frac{1}{q}$$

(1)5. $q!e$ is an integer.

(1)6. $q!(e - s_q)$ is an integer.

(1)7. There exists an integer between 0 and 1.

(1)8. Q.E.D.

PROOF: This is a contradiction.

□

Theorem 12.55. e is transcendental.

PROOF: See I. M. Niven. *Irrational Numbers* p. 25. □

12.6 Power Series

Definition 12.56 (Power Series). Let (c_n) be a sequence of complex numbers. The *power series* with *coefficients* (c_n) is the function that maps a complex number z to the series

$$\sum_{n=0}^{\infty} c_n z^n .$$

Definition 12.57 (Radius of Convergence). Let (c_n) be a sequence of complex numbers. Let

$$\begin{aligned} \alpha &:= \limsup_{n \rightarrow \infty} |c_n|^{1/n} \\ R &:= \frac{1}{\alpha} \end{aligned}$$

where $R = +\infty$ if $\alpha = 0$ and $R = 0$ if $\alpha = +\infty$. Then R is called the *radius of convergence* of the power series $\sum_n c_n z^n$.

Theorem 12.58. Let R be the radius of convergence of $\sum_n c_n z^n$.

1. If $|z| < R$ then $\sum_{n=0}^{\infty} c_n z^n$ converges.
2. If $|z| > R$ then $\sum_{n=0}^{\infty} c_n z^n$ diverges.

PROOF:

(1)1. For $z \in \mathbb{C}$ and $n \in \mathbb{N}$,

LET: $a_n(z) = c_n z^n$

(1)2.

$$\limsup_{n \rightarrow \infty} |a_n(z)|^{1/n} = |z|/R$$

(1)3. If $|z| < R$ then $\sum_{n=0}^{\infty} a_n(z)$ converges.

PROOF: Root Test.

(1)4. If $|z| > R$ then $\sum_{n=0}^{\infty} a_n(z)$ diverges.

PROOF: Root Test.

□

12.7 Summation by Parts

Theorem 12.59. Let $(a_n), (b_n)$ be two sequences of complex numbers. Let

$$A_n = \sum_{k=0}^n a_k \quad (n \geq -1) .$$

Let p and q be integers with $0 \leq p \leq q$. Then

$$\sum_{n=p}^q a_n b_n = \sum_{n=p}^{q-1} A_n (b_n - b_{n+1}) + A_q b_q - A_{p-1} b_p .$$

PROOF:

$$\begin{aligned} \sum_{n=p}^q a_n b_n &= \sum_{n=p}^q (A_n - A_{n-1}) b_n \\ &= \sum_{n=p}^q A_n b_n - \sum_{n=p-1}^{q-1} A_n b_{n+1} \\ &= \sum_{n=p}^{q-1} A_n (b_n - b_{n+1}) + A_q b_q - A_{p-1} b_p \end{aligned} \quad \square$$

Part III

More Algebra

Chapter 13

Lie Groups

Definition 13.1 (Lie Group). A *Lie group* G is a group G that is also an analytic differentiable manifold such that the group operation and inverse operation are analytic.

A *homomorphism of Lie groups* is a group homomorphism that is an analytic function.

Lemma 13.2. *Every bijective Lie group homomorphism is an isomorphism.*

Definition 13.3 (Unitary Group). The *unitary group* $U(n)$ is the Lie group of all $n \times n$ unitary matrices.

Definition 13.4 (Special Unitary Group). The *special unitary group* $SU(n)$ is the Lie group of all $n \times n$ unitary matrices with determinant 1.

Definition 13.5 (Lie Subgroup). Let G be a Lie group. A *Lie subgroup* of G is a subgroup that is also an analytic submanifold of G .

Example 13.6. $U(n)$ and $SU(n)$ are Lie subgroups of $GL(n, \mathbb{C})$.