

Encyclopaedia of Mathematics and Physics

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Chapter 1

Relations

Definition 1.1 (Antisymmetric). A relation R on a set A is *antisymmetric* iff, whenever xRy and yRx , then $x = y$.

Definition 1.2 (Transitive). A relation R on a type A is *transitive* iff, whenever xRy and yRz , then xRz .

Chapter 2

Order Theory

Definition 2.1 (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 2.2 (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 2.3 (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 2.4 (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 2.5 (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 2.6 (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 2.7. 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:

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

□

Corollary 2.7.1. *A linearly ordered set has the least upper bound property if and only if every nonempty set bounded below has an infimum.*

Definition 2.8 (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 2.9 (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 2.10 (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 2.11 (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 2.12. *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. □

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

Chapter 3

Field Theory

Definition 3.1 (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 3.2. *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 3.3. *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 3.4. 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 3.5. 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 3.6. In any field F , we have $-(-x) = x$.

PROOF: Since $x + (-x) = 0$. □

Proposition 3.7. 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 3.8. 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 3.9. 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 3.10. 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 3.11. In any field F , if $x \neq 0$ then $x^{-1} \neq 0$ and $(x^{-1})^{-1} = x$.

PROOF: Since $xx^{-1} = 1$. □

Proposition 3.12. 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 3.13. *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 3.14. *In any field F , we have $(-x)y = -(xy)$.*

PROOF:

$$\begin{aligned}
 xy + (-x)y &= (x + (-x))y \\
 &= 0y \\
 &= 0 \quad (\text{Proposition 3.12}) \square
 \end{aligned}$$

Corollary 3.14.1. *In any field F , we have $(-x)(-y) = xy$.*

PROOF:

$$\begin{aligned}
 (-x)(-y) &= -(x(-y)) \\
 &= -(-(xy)) \\
 &= xy \quad (\text{Proposition 3.6}) \square
 \end{aligned}$$

3.1 Ordered Fields

Definition 3.15 (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 3.16. \mathbb{Q} is an ordered field.

Proposition 3.17. *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 3.18. *In any ordered field, if $y < z$ and x is positive then $xy < xz$.*

PROOF: If $y < z$ then we have

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

Proposition 3.19. *In any ordered field, if $y < z$ and x is negative then $xy > xz$.*

PROOF:

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

□

Proposition 3.20. *In any ordered field, if $x \neq 0$ then $x^2 > 0$.*

PROOF:

- $\langle 1 \rangle 1.$ If $x > 0$ then $x^2 > 0$.

PROOF: Proposition 3.18.

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

PROOF: Proposition 3.19.

□

Corollary 3.20.1. *In any ordered field, we have $1 > 0$.*

Proposition 3.21. *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 3.20.1. □

Proposition 3.22. *In any ordered field, if $0 < x < y$ then $y^{-1} < x^{-1}$.*

PROOF:

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

PROOF: Proposition 3.21.

- $\langle 1 \rangle 3.$ $xy^{-1} < yy^{-1} = 1$
- $\langle 1 \rangle 4.$ $y^{-1} = x^{-1}xy^{-1} < x^{-1}1 = x^{-1}$

□

Lemma 3.23. *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 4

Real Analysis

4.1 Construction of the Real Numbers

Definition 4.1 (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 4.2. *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 4.3. *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 4.4 (Addition). Given cuts α and β , we define

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

Proposition 4.5. *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 4.6. *Addition is commutative and associative on R .*

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

Definition 4.7. For any $q \in \mathbb{Q}$, let $q^* = \{r \in \mathbb{Q} : r < q\}$.

Proposition 4.8. *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 4.9. *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 4.10. *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 $-q \in \beta$

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

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

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

□

Proposition 4.11. *Given $\alpha, \beta, \gamma \in R$, if $\beta < \gamma$, then $\alpha + \beta < \alpha + \gamma$.*

PROOF:

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

□

Definition 4.12. 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 4.13. 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 4.14. For any cuts α and β we have $\alpha\beta = \beta\alpha$.

PROOF: Easy from the definitions. □

Proposition 4.15. 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 4.16. *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 4.17. *There exists an ordered field with the least upper bound property.*

Proposition 4.18. *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 4.19. *Any two complete ordered fields are isomorphic.*

Definition 4.20. Let \mathbb{R} be the complete ordered field. We call its elements *real numbers*.

4.2 Properties of the Real Numbers

Theorem 4.21. \mathbb{Q} is a subfield of \mathbb{R} .

Theorem 4.22 (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 4.23. \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 4.24. 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 4.25 (*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 4.26. 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 4.27. 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 3.23. \square

Lemma 4.28. 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:

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

Lemma 4.29. 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 4.30. 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 4.31. 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 4.32. 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 4.33. 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 4.34. 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 4.28.

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

\square

Lemma 4.35. 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: Similar. \square

Proposition 4.36. 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: $b^x \leq u$

(1)3. LET: q be a rational number with $q \leq x$.

PROVE: $b^q \leq u$

(1)4. ASSUME: for a contradiction $b^q > u$.

(1)5. PICK a positive integer n such that $b^{q-1/n} > u$.

PROOF: Lemma 4.35.

(1)6. $b^{q-1/n} \leq u$

PROOF: (1)2

(1)7. Q.E.D.

PROOF: This contradicts (1)4.

□

Lemma 4.37. *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:

(1)1. For all $x \in A$ and $y \in B$ we have $xy \leq ab$.

(1)2. If u is any upper bound for $\{xy : x \in A, y \in B\}$ then $ab \leq u$.

(2)1. LET: u be an upper bound for $\{xy : x \in A, y \in B\}$.

(2)2. For all $x \in A$ we have u/x is an upper bound for B .

(2)3. For all $x \in A$ we have $b \leq u/x$

(2)4. For all $x \in A$ we have $x \leq u/b$

(2)5. $a \leq u/b$

(2)6. $ab \leq u$

□

Proposition 4.38. *Let $b, x, y \in \mathbb{R}$ with $b > 1$. Then*

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

PROOF:

(1)1. For any rational number $q < x + y$, there exist rational numbers $r < x$ and $s < y$ such that $q = r + s$.

(2)1. $q - x < y$

(2)2. PICK a rational t such that $q - x < t < y$

(2)3. $q = t + (q - t)$ and $t < y, q - t < x$

(1)2. $b^x b^y = b^{x+y}$

PROOF:

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

□

4.3 The Extended Real Number System

Definition 4.39 (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 5

Complex Analysis

Definition 5.1 (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 5.2. *The complex numbers form a field.*

Theorem 5.3. *The function that maps a to $(a, 0)$ is an embedding of \mathbb{R} in \mathbb{C} .*

Definition 5.4.

$$i = (0, 1)$$

Lemma 5.5.

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

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

Lemma 5.6.

$$i^2 = -1$$

PROOF: Immediate from definitions. \square

Definition 5.7 (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 5.8 (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 5.9 (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 5.10. 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 5.11. 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 5.12. 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 5.13. 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 5.14. 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 5.15. *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 5.16 (Absolute Value). For $z \in \mathbb{C}$, the *absolute value* of z is

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

Proposition 5.17. *For x a non-negative real we have $|x| = x$.*

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

Proposition 5.18. *For x a negative real we have $|x| = -x$.*

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

Theorem 5.19. *For any complex number z we have $|z| \geq 0$.*

PROOF: Immediate from definition. \square

Theorem 5.20. *For any complex number z , if $|z| = 0$ then $z = 0$.*

PROOF: From Theorem 5.15. \square

Theorem 5.21. *For any complex number z we have*

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

PROOF: Immediate from definitions. \square

Theorem 5.22. *For any complex numbers z and w we have*

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

PROOF:

$$\begin{aligned}|zw| &= \sqrt{zw\bar{z}\bar{w}} \\ &= \sqrt{z\bar{z}}\sqrt{w\bar{w}} && \text{(Proposition 4.26)} \\ &= |z||w|\end{aligned}\quad \square$$

Theorem 5.23. *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 5.24. *For any complex numbers z and w we have*

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

PROOF:

$$\begin{aligned}
 |z + w|^2 &= (z + w)(\bar{z} + \bar{w}) \\
 &= z\bar{z} + z\bar{w} + \bar{z}w + w\bar{w} \\
 &= |z|^2 + 2\operatorname{Re}(z\bar{w}) + |w|^2 && \text{(Theorem 5.12)} \\
 &\leq |z|^2 + 2|z\bar{w}| + |w|^2 && \text{(Theorem 5.23)} \\
 &= |z|^2 + 2|z||w| + |w|^2 && \text{(Theorem 5.22)} \\
 &= (|z| + |w|)^2 \quad \square
 \end{aligned}$$

Theorem 5.25 (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

Part I

Linear Algebra

Chapter 6

Vector Spaces

Chapter 7

Real Inner Product Spaces

Definition 7.1 (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 7.2 (Norm). Define the *norm* of a vector $\vec{x} \in \mathbb{R}^k$ by

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

Proposition 7.3.

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

PROOF: Immediate from the definition. \square

Proposition 7.4. 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 7.5. For $\alpha \in \mathbb{R}$ and $\vec{x} \in \mathbb{R}^k$,

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

PROOF: Easy. \square

Proposition 7.6. 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 7.7. For $\vec{x}, \vec{y} \in \mathbb{R}^k$ we have

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

PROOF:

$$\begin{aligned}
 \|\vec{x} + \vec{y}\|^2 &= (\vec{x} + \vec{y}) \cdot (\vec{x} + \vec{y}) \\
 &= \vec{x} \cdot \vec{x} + 2\vec{x} \cdot \vec{y} + \vec{y} \cdot \vec{y} \\
 &\leq \|\vec{x}\|^2 + 2\|\vec{x}\|\|\vec{y}\| + \|\vec{y}\|^2 && \text{(Proposition 7.6)} \\
 &= (\|\vec{x}\| + \|\vec{y}\|)^2 && \square
 \end{aligned}$$

Corollary 7.7.1. *For $\vec{x}, \vec{y}, \vec{z} \in \mathbb{R}^k$ we have*

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

Chapter 8

Complex Inner Product Spaces

Definition 8.1 (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 8.2 (Norm). Let V be an inner product space and $x \in V$. The *norm* of x is

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

Proposition 8.3. *An inner product space is a metric space under*

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

Definition 8.4 (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 8.5. *Every linear transformation between finite dimensional inner product spaces is bounded.*

Definition 8.6 (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

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

8.1 Hilbert Spaces

Definition 8.7 (Hilbert Space). A *Hilbert space* is a complete inner product space.

Theorem 8.8 (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:

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

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

(1)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 8.9 (Separable). A Hilbert space is *separable* iff it has a countable dense orthonormal basis.

Chapter 9

Lie Algebras

Definition 9.1 (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 9.2. If K has characteristic 0 then the condition $[x, x] = 0$ can be replaced with $[x, y] = -[y, x]$.

Proposition 9.3. The commutator is determined by its values on any basis for \mathcal{L} .

Example 9.4. \mathbb{R}^3 with the cross product is a real Lie algebra.

Example 9.5. For any $n \geq 0$, we have $GL(n, K)$ is a Lie algebra over K under

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

Definition 9.6 (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 9.7 (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 9.8 (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 9.9. 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 9.10. $SU(2)$ 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

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

9.1 Lie Algebra Homomorphisms

Definition 9.11 (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 9.12. Every bijective Lie algebra homomorphism is an isomorphism.

Definition 9.13 (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 9.14. 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

More Algebra

Chapter 10

Lie Groups

Definition 10.1 (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 10.2. *Every bijective Lie group homomorphism is an isomorphism.*

Definition 10.3 (Unitary Group). The *unitary group* $U(n)$ is the Lie group of all $n \times n$ unitary matrices.

Definition 10.4 (Special Unitary Group). The *special unitary group* $SU(n)$ is the Lie group of all $n \times n$ unitary matrices with determinant 1.

Definition 10.5 (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 10.6. $U(n)$ and $SU(n)$ are Lie subgroups of $GL(n, \mathbb{C})$.