

# 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.

□

**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. □

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  $\alpha$  of  $\mathbb{Q}$  such that:

- $\emptyset \neq \alpha \neq \mathbb{Q}$
- $\alpha$  is closed downwards.
- $\alpha$  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  $\alpha$  and  $\beta$ , 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  $\alpha$  and  $\beta$ , we define

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

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

PROOF:

- ⟨1⟩1.  $\alpha + \beta$  is nonempty.  
     PROOF: Since  $\alpha$  and  $\beta$  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  $\alpha$  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  $\alpha$ , there exists a cut  $\beta$  such that  $\alpha + \beta = 0$ .*

PROOF:

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

⟨1⟩2.  $\beta$  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  $\alpha$  is closed downwards.

- $\langle 2 \rangle 3$ .  $\beta$  is closed downwards.
  - $\langle 3 \rangle 1$ . LET:  $p \in \beta$  and  $q < p$ .
  - $\langle 3 \rangle 2$ . PICK  $r > 0$  such that  $-p - r \notin \alpha$
  - $\langle 3 \rangle 3$ .  $-p - r < -q - r$
  - $\langle 3 \rangle 4$ .  $-q - r \notin \alpha$
  - $\langle 3 \rangle 5$ .  $q \in \beta$
- $\langle 2 \rangle 4$ .  $\beta$  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  $\alpha$  and  $\beta$ , 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  $\alpha$  and  $\beta$ , 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  $\alpha$  and  $\beta$  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  $\alpha$  and  $\beta$ , we have  $\alpha\beta$  is a cut.

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

□

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

PROOF: Easy from the definitions. □

**Proposition 5.15.** For any cuts  $\alpha$ ,  $\beta$  and  $\gamma$  we have

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

PROOF:

$\langle 1 \rangle 1$ . CASE:  $\alpha$ ,  $\beta$  and  $\gamma$  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  $\alpha$ ,  $\beta$  or  $\gamma$  is  $0^*$ .

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

$\langle 1 \rangle 3$ . CASE:  $\alpha$  and  $\beta$  are positive,  $\gamma$  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:  $\alpha$  is positive,  $\beta$  is negative,  $\gamma$  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:  $\alpha$  is positive,  $\beta$  and  $\gamma$  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:  $\alpha$  is negative,  $\beta$  and  $\gamma$  are positive.

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

$\langle 1 \rangle 7$ . CASE:  $\alpha$  is negative,  $\beta$  is positive,  $\gamma$  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:  $\alpha$  and  $\beta$  are negative,  $\gamma$  is positive.

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

$\langle 1 \rangle 9$ . CASE:  $\alpha$ ,  $\beta$  and  $\gamma$  are all negative.

PROOF:

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

□

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

PROOF:

$\langle 1 \rangle 1$ . CASE:  $\alpha$  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:  $\alpha$  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:

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

**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

$$\begin{aligned} [a, b) &:= \{x \in \mathbb{R} : a \leq x < b\} \\ (a, b] &:= \{x \in \mathbb{R} : a < x \leq b\} \end{aligned}$$

**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  $a_i \in \bigcap_{n=0}^{\infty} J_{ni}$ .

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

□

## 5.3 The Extended Real Number System

**Definition 5.45** (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.

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

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

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

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

$\langle 2 \rangle 4.$  CASE:  $v \geq 0$

$\langle 3 \rangle 1.$  LET:  $z = a + ib$

$\langle 3 \rangle 2.$   $z^2 = w$

PROOF:

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

$\langle 3 \rangle 3.$   $(-z)^2 = w$

$\langle 2 \rangle 5.$  CASE:  $v \leq 0$

$\langle 3 \rangle 1.$  LET:  $z = a - ib$

$\langle 3 \rangle 2.$   $z^2 = w$

PROOF:

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

$\langle 3 \rangle 3.$   $(-z)^2 = w$

□



**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.

**Proposition 11.3.** 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 11.4** (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 11.5.** 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 11.6** (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 11.7.** 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 11.7.1.** A finite set has no limit points.

**Definition 11.8** (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 11.9** (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 11.10** (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  $B \subseteq E$ .

## 11.5 Open Sets

**Definition 11.11** (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 11.12.** *Every open ball is open.*

PROOF:

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

PROOF:

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

□

**Proposition 11.13.** *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 11.13.1.** *A set is closed if and only if its complement is open.*

**Proposition 11.14.** *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 11.14.1.** *The intersection of a set of closed sets is closed.*

**Proposition 11.15.** *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 11.15.1.** *The union of two closed sets is closed.*

**Example 11.16.** 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 11.17.** *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:

- $\langle 1 \rangle 1$ . If  $E$  is open in  $Y$  then there exists an open subset  $G$  of  $X$  such that  $E = G \cap Y$ .
- $\langle 2 \rangle 1$ . ASSUME:  $E$  is open in  $Y$ .
- $\langle 2 \rangle 2$ . 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  $E$ .
- $\langle 2 \rangle 3$ . For  $p \in E$ ,  
LET:  $V_p$  be the open ball in  $X$  with centre  $p$  and radius  $r_p$ .
- $\langle 2 \rangle 4$ . LET:  $G = \bigcup_{p \in E} V_p$
- $\langle 2 \rangle 5$ .  $G$  is open in  $X$ .
- PROOF: Proposition 11.14.
- $\langle 2 \rangle 6$ .  $E = G \cap Y$
- $\langle 3 \rangle 1$ .  $E \subseteq G \cap Y$ 
  - $\langle 4 \rangle 1$ . LET:  $p \in E$
  - $\langle 4 \rangle 2$ .  $p \in V_p$
  - $\langle 4 \rangle 3$ .  $p \in G$
- $\langle 3 \rangle 2$ .  $G \cap Y \subseteq E$ 
  - $\langle 4 \rangle 1$ . LET:  $x \in G \cap Y$
  - $\langle 4 \rangle 2$ . PICK  $p \in E$  such that  $x \in V_p$
  - $\langle 4 \rangle 3$ .  $d(x, p) < r_p$

- $\langle 4 \rangle 4. x \in E$   
 $\langle 1 \rangle 2.$  For any open subset  $G$  of  $X$ , we have  $G \cap Y$  is open in  $Y$ .  
 $\langle 2 \rangle 1.$  LET:  $G$  be an open subset of  $X$ .  
 $\langle 2 \rangle 2.$  LET:  $p \in G \cap Y$   
 $\langle 2 \rangle 3.$  PICK  $r > 0$  such that the open ball in  $X$  with centre  $p$  and radius  $r$  is included in  $G$ .  
 $\langle 2 \rangle 4.$  The open ball in  $Y$  with centre  $p$  and radius  $r$  is included in  $G \cap Y$ .  
 $\square$

## 11.6 Perfect Sets

**Definition 11.18** (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 11.19** (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  $d(p, q) < M$ .

## 11.8 Dense Sets

**Definition 11.20** (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 11.21** (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 11.22.**  $\overline{E}$  is the smallest closed set that includes  $E$ .

PROOF:

- $\langle 1 \rangle 1.$   $\overline{E}$  is closed.  
 $\langle 2 \rangle 1.$  LET:  $p$  be a limit point of  $\overline{E}$ .  
 $\langle 2 \rangle 2.$  ASSUME:  $p \notin E$   
PROVE:  $p$  is a limit point of  $E$ .  
 $\langle 2 \rangle 3.$  LET:  $B$  be the open ball with centre  $p$  and radius  $r$ .  
PROVE:  $B$  intersects  $E$ .  
 $\langle 2 \rangle 4.$  PICK a point  $q \in B \cap \overline{E}$ .  
 $\langle 2 \rangle 5.$  PICK an open ball  $B'$  with centre  $q$  such that  $B' \subseteq B$ .  
 $\langle 2 \rangle 6.$  PICK a point  $r \in E \cap B'$   
 $\langle 2 \rangle 7.$   $r \in E \cap B$   
 $\langle 1 \rangle 2.$  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 11.22.1.**  $E$  is closed if and only if  $E = \overline{E}$ .

**Theorem 11.23.** 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  $p$ .

□

## 11.10 Compact Sets

**Definition 11.24** (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 11.25** (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 11.26.** Every finite set is compact.

PROOF: Easy. □

**Theorem 11.27.** 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  $X$ .
- ⟨2⟩1. ASSUME:  $K$  is compact in  $Y$ .
- ⟨2⟩2. LET:  $\mathcal{U}$  be an open cover of  $K$  in  $X$ .
- ⟨2⟩3.  $\{U \cap Y : U \in \mathcal{U}\}$  is an open cover of  $K$  in  $Y$ .
- ⟨2⟩4. PICK a finite subcover  $\{U_1 \cap Y, \dots, U_n \cap Y\}$

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

□

**Proposition 11.28.** *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 11.29.** *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 11.29.1.** *The intersection of a compact set and a closed set is compact.*

**Proposition 11.30.** *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 11.30.1.** *Let  $(K_n)$  be a sequence of nonempty compact sets such that  $K_0 \supseteq K_1 \supseteq \cdots$ . Then  $\bigcap_{n=0}^{\infty} K_n \neq \emptyset$ .*

**Theorem 11.31.** *Every infinite subset of a compact set  $K$  has a limit point in  $K$ .*

PROOF:

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

PROOF: This contradicts the fact that  $E$  is finite.

□



**Part III**

**More Algebra**



## Chapter 12

# Lie Groups

**Definition 12.1** (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 12.2.** *Every bijective Lie group homomorphism is an isomorphism.*

**Definition 12.3** (Unitary Group). The *unitary group*  $U(n)$  is the Lie group of all  $n \times n$  unitary matrices.

**Definition 12.4** (Special Unitary Group). The *special unitary group*  $SU(n)$  is the Lie group of all  $n \times n$  unitary matrices with determinant 1.

**Definition 12.5** (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 12.6.**  $U(n)$  and  $SU(n)$  are Lie subgroups of  $GL(n, \mathbb{C})$ .