

# Mathematics

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July 22, 2023



# Chapter 1

## Sets and Classes

### 1.1 Classes

Our language is the language of first-order logic with equality over one primitive binary predicate  $\in$ . We call all the objects we reason about *sets*. When  $a \in b$ , we say  $a$  is a *member* or *element* of  $b$ , or  $b$  *contains*  $a$ . We write  $b \ni a$  for  $a \in b$ , and  $a \notin b$  for  $\neg(a \in b)$ . We write  $\forall x \in a. \phi$  as an abbreviation for  $\forall x(x \in a \rightarrow \phi)$ , and  $\exists x \in a. \phi$  as an abbreviation for  $\exists x(x \in a \wedge \phi)$ .

We shall speak informally of *classes* as an abbreviation for talking about predicates. A *class* is determined by a unary predicate  $\phi[x]$  (possibly with parameters). We write  $\{x \mid \phi[x]\}$  or  $\{x : \phi[x]\}$  for the class determined by  $\phi[x]$ . We write ' $a$  is an element of  $\{x \mid \phi[x]\}$ ' or ' $a \in \{x \mid \phi[x]\}$ ' for  $\phi[a]$ .

We say two classes  $\mathbf{A}$  and  $\mathbf{B}$  are *equal*, and write  $\mathbf{A} = \mathbf{B}$ , iff  $\forall x(x \in \mathbf{A} \leftrightarrow x \in \mathbf{B})$ .

The following are all valid formulas of first-order logic:

**Proposition Schema 1.1.1.** *For any classes  $\mathbf{A}$ ,  $\mathbf{B}$  and  $\mathbf{C}$ , the following are theorems:*

1.  $\mathbf{A} = \mathbf{A}$
2. *If  $\mathbf{A} = \mathbf{B}$  then  $\mathbf{B} = \mathbf{A}$ .*
3. *If  $\mathbf{A} = \mathbf{B}$  and  $\mathbf{B} = \mathbf{C}$  then  $\mathbf{A} = \mathbf{C}$ .*

**Definition 1.1.2** (Subclass). We say a class  $\mathbf{A}$  is a *subclass* of  $\mathbf{B}$ , or  $\mathbf{B}$  is a *superclass* of  $\mathbf{A}$ , or  $\mathbf{B}$  *includes*  $\mathbf{A}$ , and write  $\mathbf{A} \subseteq \mathbf{B}$  or  $\mathbf{B} \supseteq \mathbf{A}$ , iff every element of  $\mathbf{A}$  is an element of  $\mathbf{B}$ . Otherwise we write  $\mathbf{A} \not\subseteq \mathbf{B}$  or  $\mathbf{B} \not\supseteq \mathbf{A}$ .

We say  $\mathbf{A}$  is a *proper* subclass of  $\mathbf{B}$ ,  $\mathbf{B}$  is a *proper* superclass of  $\mathbf{A}$ , or  $\mathbf{B}$  *properly* includes  $\mathbf{A}$ , and write  $\mathbf{A} \subsetneq \mathbf{B}$  or  $\mathbf{B} \supsetneq \mathbf{A}$ , iff in addition  $\mathbf{A} \neq \mathbf{B}$ .

The following are all valid formulas of first-order logic:

**Proposition Schema 1.1.3.** *For any classes  $\mathbf{A}$ ,  $\mathbf{B}$  and  $\mathbf{C}$ , the following are theorems:*

1.  $\mathbf{A} \subseteq \mathbf{A}$
2. If  $\mathbf{A} \subseteq \mathbf{B}$  and  $\mathbf{B} \subseteq \mathbf{A}$  then  $\mathbf{A} = \mathbf{B}$ .
3. If  $\mathbf{A} \subseteq \mathbf{B}$  and  $\mathbf{B} \subseteq \mathbf{C}$  then  $\mathbf{A} \subseteq \mathbf{C}$ .

**Definition 1.1.4** (Empty Class). The *empty class*  $\emptyset$  is  $\{x \mid \perp\}$ .

**Proposition 1.1.5.** For any class  $\mathbf{A}$ , we have  $\emptyset \subseteq \mathbf{A}$ .

PROOF: Vacuously, every element of  $\emptyset$  is an element of  $\mathbf{A}$ .  $\square$

**Definition 1.1.6** (Universal Class). The *universal class*  $\mathbf{V}$  is  $\{x \mid \top\}$ .

**Proposition 1.1.7.** For any class  $\mathbf{A}$ , we have  $\mathbf{A} \subseteq \mathbf{V}$ .

PROOF: Trivially, every element of  $\mathbf{A}$  is an element of  $\mathbf{V}$ .  $\square$

**Definition 1.1.8** (Union). The *union* of two classes  $\mathbf{A}$  and  $\mathbf{B}$  is the class  $\mathbf{A} \cup \mathbf{B} = \{x \mid x \in \mathbf{A} \vee x \in \mathbf{B}\}$ .

**Proposition 1.1.9.** For any classes  $\mathbf{A}$ ,  $\mathbf{B}$ ,  $\mathbf{C}$ , we have

$$\begin{aligned}\mathbf{A} \cup \mathbf{B} &= \mathbf{B} \cup \mathbf{A} \\ \mathbf{A} \cup (\mathbf{B} \cup \mathbf{C}) &= (\mathbf{A} \cup \mathbf{B}) \cup \mathbf{C} \\ \mathbf{A} \cup \emptyset &= \mathbf{A}\end{aligned}$$

PROOF: These are valid formulas of first-order logic.  $\square$

**Definition 1.1.10** (Intersection). The *intersection* of two classes  $\mathbf{A}$  and  $\mathbf{B}$  is the class  $\{x \mid x \in \mathbf{A} \wedge x \in \mathbf{B}\}$ .

**Proposition 1.1.11.** For any classes  $\mathbf{A}$ ,  $\mathbf{B}$ ,  $\mathbf{C}$ , we have

$$\begin{aligned}\mathbf{A} \cap \mathbf{B} &= \mathbf{B} \cap \mathbf{A} \\ \mathbf{A} \cap (\mathbf{B} \cap \mathbf{C}) &= (\mathbf{A} \cap \mathbf{B}) \cap \mathbf{C} \\ \mathbf{A} \cap \emptyset &= \emptyset\end{aligned}$$

PROOF: These are valid formulas of first-order logic.  $\square$

**Proposition 1.1.12** (Distributive Laws). For any classes  $\mathbf{A}$ ,  $\mathbf{B}$ ,  $\mathbf{C}$ , we have

$$\begin{aligned}\mathbf{A} \cup (\mathbf{B} \cap \mathbf{C}) &= (\mathbf{A} \cup \mathbf{B}) \cap (\mathbf{A} \cup \mathbf{C}) \\ \mathbf{A} \cap (\mathbf{B} \cup \mathbf{C}) &= (\mathbf{A} \cap \mathbf{B}) \cup (\mathbf{A} \cap \mathbf{C})\end{aligned}$$

PROOF: These are valid formulas of first-order logic.  $\square$

**Definition 1.1.13** (Union). The *union* of a class  $\mathbf{A}$  is  $\{x \mid \exists X \in \mathbf{A}. x \in X\}$ . We write  $\bigcup_{P(x)} t(x)$  for  $\bigcup \{t(x) \mid P(x)\}$ .

**Proposition 1.1.14.** For any classes  $\mathbf{A}$  and  $\mathbf{B}$ , if  $\mathbf{A} \subseteq \mathbf{B}$  then  $\bigcup \mathbf{A} \subseteq \bigcup \mathbf{B}$ .

PROOF: First-order logic.  $\square$

**Definition 1.1.15** (Intersection). The *intersection* of a class  $\mathbf{A}$  is  $\{x \mid \forall X \in \mathbf{A}. x \in X\}$ . We write  $\bigcap_{P(x)} t(x)$  for  $\bigcap \{t(x) \mid P(x)\}$ .

**Definition 1.1.16** (Relative Complement). Let  $\mathbf{A}$  and  $\mathbf{B}$  be classes. The *relative complement* of  $\mathbf{B}$  in  $\mathbf{A}$  is the class  $\mathbf{A} - \mathbf{B} = \{x \in \mathbf{A} \mid x \notin \mathbf{B}\}$ .

**Proposition 1.1.17** (De Morgan's Laws). *For any classes  $\mathbf{A}, \mathbf{B}, \mathbf{C}$ , we have*

$$\begin{aligned}\mathbf{A} - (\mathbf{B} \cup \mathbf{C}) &= (\mathbf{A} - \mathbf{B}) \cap (\mathbf{A} - \mathbf{C}) \\ \mathbf{A} - (\mathbf{B} \cap \mathbf{C}) &= (\mathbf{A} - \mathbf{B}) \cup (\mathbf{A} - \mathbf{C})\end{aligned}$$

PROOF: First-order logic.  $\square$

**Proposition 1.1.18.** *If  $\mathbf{A} \subseteq \mathbf{B}$  then  $\mathbf{C} - \mathbf{B} \subseteq \mathbf{C} - \mathbf{A}$ .*

PROOF: First-order logic.  $\square$

**Definition 1.1.19** (Symmetric Difference). The *symmetric difference* of classes  $\mathbf{A}$  and  $\mathbf{B}$  is the class  $\mathbf{A} + \mathbf{B} := (\mathbf{A} - \mathbf{B}) \cup (\mathbf{B} - \mathbf{A})$ .

**Proposition 1.1.20.** *For any classes  $\mathbf{A}, \mathbf{B}, \mathbf{C}$ , we have*

$$\begin{aligned}\mathbf{A} \cap (\mathbf{B} + \mathbf{C}) &= (\mathbf{A} \cap \mathbf{B}) + (\mathbf{A} \cap \mathbf{C}) \\ \mathbf{A} + (\mathbf{B} + \mathbf{C}) &= (\mathbf{A} + \mathbf{B}) + \mathbf{C}\end{aligned}$$

PROOF: First-order logic.  $\square$

## 1.2 Axioms

**Axiom 1.2.1** (Extensionality). *If two sets have exactly the same members, they are equal.*

Thanks to this axiom, we may identify a set  $a$  with the class  $\{x \mid x \in a\}$ . Our use of the symbols  $\in$  and  $=$  is consistent. We say a class  $\mathbf{A}$  *is a set* iff there exists a set  $a$  such that  $a = \mathbf{A}$ ; that is,  $\{x \mid \phi[x]\}$  is a set iff  $\exists a \forall x (x \in a \leftrightarrow \phi[x])$ . Otherwise,  $\mathbf{A}$  is a *proper class*.

**Axiom 1.2.2** (Union). *The union of a set is a set.*

**Axiom 1.2.3** (Power Set). *For any set  $A$ , the class  $\mathcal{P}A = \{x \mid x \subseteq A\}$  is a set, called the power set of  $A$ .*

**Axiom 1.2.4** (Infinity). *There exists a set  $I$  such that:*

- *There exists an element of  $I$  that has no members*
- *For every  $x \in I$ , there exists a set  $y \in I$  such that the elements of  $y$  are exactly  $x$  and the members of  $x$ .*

**Axiom 1.2.5** (Choice). *For any set  $A$  of pairwise disjoint, nonempty sets, there exists a set  $C$  such that, for all  $x \in A$ ,  $x \cap C$  has exactly one element.*

**Axiom Schema 1.2.6** (Replacement). *For any predicate  $P(x, y)$ , the following is an axiom:*

*Let  $A$  be a set. Assume that, for all  $x \in A$ , there exists at most one  $y$  such that  $P(x, y)$ . Then  $\{y \mid \exists x \in A. P(x, y)\}$  is a set.*

**Axiom 1.2.7** (Regularity). *For any nonempty set  $A$ , there exists  $m \in A$  such that  $m \cap A = \emptyset$ .*

## 1.3 Basic Constructions on Sets

### 1.3.1 Consequences of the Axioms

**Proposition 1.3.1.** *The class  $\emptyset = \{x \mid \perp\}$  is a set.*

PROOF: Immediate from the Axiom of Infinity.  $\square$

**Proposition 1.3.2** (Pairing). *For any sets  $a$  and  $b$ , the class  $\{a, b\} = \{x \mid x = a \vee x = b\}$  is a set.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $P(x, y)$  be the predicate  $(x = \emptyset \wedge y = a) \vee (x = \mathcal{P}\emptyset \wedge y = b)$ .

$\langle 1 \rangle 2$ . For all  $x \in \mathcal{P}\mathcal{P}\emptyset$ , there exists at most one  $y$  such that  $P(x, y)$ .

$\langle 2 \rangle 1$ . LET:  $x \in \mathcal{P}\mathcal{P}\emptyset$

$\langle 2 \rangle 2$ . LET:  $y$  and  $y'$  be sets.

$\langle 2 \rangle 3$ . ASSUME:  $P(x, y)$  and  $P(x, y')$

$\langle 2 \rangle 4$ .  $(x = \emptyset \wedge y = a) \vee (x = \mathcal{P}\emptyset \wedge y = b)$

PROOF: From  $\langle 2 \rangle 3$ .

$\langle 2 \rangle 5$ .  $(x = \emptyset \wedge y' = a) \vee (x = \mathcal{P}\emptyset \wedge y' = b)$

PROOF: From  $\langle 2 \rangle 3$ .

$\langle 2 \rangle 6$ .  $\emptyset \neq \mathcal{P}\emptyset$

PROOF: Since  $\emptyset \in \mathcal{P}\emptyset$  and  $\emptyset \notin \emptyset$ .

$\langle 2 \rangle 7$ .  $y = y'$

$\langle 1 \rangle 3$ . LET:  $A$  be the set  $\{y \mid \exists x \in \mathcal{P}\mathcal{P}\emptyset. P(x, y)\}$ .

$\langle 1 \rangle 4$ .  $A = \{a, b\}$

$\square$

**Proposition 1.3.3.** *The union of two sets is a set.*

PROOF: The union of two sets  $A$  and  $B$  is  $\bigcup\{A, B\}$ .  $\square$

**Proposition Schema 1.3.4.** *For any sets  $a_1, \dots, a_n$ , the class  $\{a_1, \dots, a_n\} = \{x \mid x = a_1 \vee \dots \vee x = a_n\}$  is a set.*

PROOF: The case  $n = 1$  follows from Pairing since  $\{a\} = \{a, a\}$ .

If we have proved the theorem for  $n$  we have  $\{a_1, \dots, a_n, a_{n+1}\} = \{a_1, \dots, a_n\} \cup \{a_{n+1}\}$ .  $\square$

**Proposition 1.3.5.** *For any classes  $\mathbf{A}$  and  $\mathbf{B}$ , if  $\mathbf{A} \subseteq \mathbf{B}$  then  $\bigcup \mathbf{A} \subseteq \bigcup \mathbf{B}$ .*

PROOF:

- $\langle 1 \rangle 1$ . ASSUME:  $\mathbf{A} \subseteq \mathbf{B}$
  - $\langle 1 \rangle 2$ . LET:  $x \in \bigcup \mathbf{A}$
  - $\langle 1 \rangle 3$ . PICK  $A \in \mathbf{A}$  such that  $x \in A$
  - $\langle 1 \rangle 4$ .  $A \in \mathbf{B}$
  - $\langle 1 \rangle 5$ .  $x \in \bigcup \mathbf{B}$
- 

**Proposition 1.3.6.** *For any sets  $A$  and  $B$ , if  $A \subseteq B$  then  $\mathcal{P}A \subseteq \mathcal{P}B$ .*

PROOF: From Proposition 1.1.3. □

**Proposition 1.3.7.** *For any set  $A$  we have  $\bigcup \mathcal{P}A = A$ .*

PROOF:

- $\langle 1 \rangle 1$ .  $\bigcup \mathcal{P}A \subseteq A$ 
    - $\langle 2 \rangle 1$ . LET:  $x \in \bigcup \mathcal{P}A$
    - $\langle 2 \rangle 2$ . PICK  $X \in \mathcal{P}A$  such that  $x \in X$ 
      - PROOF:  $\langle 2 \rangle 1$
    - $\langle 2 \rangle 3$ .  $X \subseteq A$ 
      - PROOF:  $\langle 2 \rangle 2$
    - $\langle 2 \rangle 4$ .  $x \in A$ 
      - PROOF:  $\langle 2 \rangle 2, \langle 2 \rangle 3$
  - $\langle 1 \rangle 2$ .  $A \subseteq \bigcup \mathcal{P}A$ 
    - PROOF: For all  $x \in A$  we have  $x \in \{x\} \in \mathcal{P}A$ .
  - $\langle 1 \rangle 3$ . Q.E.D.
- PROOF: By Proposition 1.1.3.
- 

### 1.3.2 Comprehension

**Proposition Schema 1.3.8** (Comprehension). *For any predicate  $P(x)$ , the following is a theorem:*

*For any set  $A$ , the class  $\{x \in A \mid P(x)\}$  is a set.*

PROOF:

- $\langle 1 \rangle 1$ . LET:  $A$  be a set.
- $\langle 1 \rangle 2$ . LET:  $Q(x, y)$  be the predicate  $P(x) \wedge y = x$ .
- $\langle 1 \rangle 3$ . For all  $x \in A$ , there exists at most one  $y$  such that  $Q(x, y)$ .
  - $\langle 2 \rangle 1$ . LET:  $x \in A$
  - $\langle 2 \rangle 2$ . LET:  $y$  and  $y'$  be sets.
  - $\langle 2 \rangle 3$ . ASSUME:  $Q(x, y)$  and  $Q(x, y')$
  - $\langle 2 \rangle 4$ .  $x \in A \wedge P(x) \wedge y = x \wedge y' = x$ 
    - PROOF: From  $\langle 2 \rangle 3$ .
  - $\langle 2 \rangle 5$ .  $y = y'$ 
    - PROOF: From  $\langle 2 \rangle 4$ .

$\langle 1 \rangle 4$ . LET:  $B$  be the set  $\{y \mid \exists x \in A.Q(x, y)\}$

PROOF: This is a set by an Axiom of Replacement and  $\langle 1 \rangle 3$ .

$\langle 1 \rangle 5$ .  $B = \{y \in A \mid P(y)\}$

PROOF:

$$y \in B \Leftrightarrow \exists x \in A.Q(x, y) \quad (\langle 1 \rangle 4)$$

$$\Leftrightarrow \exists x \in A(P(x) \wedge y = x) \quad (\langle 1 \rangle 2)$$

$$\Leftrightarrow P(y)$$

□

**Corollary 1.3.8.1.** *The intersection of a set and a class is a set.*

**Corollary 1.3.8.2.** *The intersection of a nonempty class is a set.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $\mathbf{A}$  be a nonempty class.

$\langle 1 \rangle 2$ . PICK  $A \in \mathbf{A}$

$\langle 1 \rangle 3$ .  $\bigcap \mathbf{A} = \{x \in A \mid \forall X \in \mathbf{A}.x \in X\}$  which is a set.

□

**Corollary 1.3.8.3.** *The relative complement of a class in a set is a set.*

**Corollary 1.3.8.4** (Russell's Paradox).  $\mathbf{V}$  is a proper class.

PROOF:

$\langle 1 \rangle 1$ . LET:  $\mathbf{R} = \{x \mid x \notin x\}$

$\langle 1 \rangle 2$ .  $\mathbf{R}$  is a proper class.

$\langle 2 \rangle 1$ . ASSUME: for a contradiction  $\mathbf{R}$  is a set

$\langle 2 \rangle 2$ .  $\mathbf{R} \in \mathbf{R}$  iff  $\mathbf{R} \notin \mathbf{R}$

$\langle 2 \rangle 3$ . This is a contradiction.

$\langle 1 \rangle 3$ .  $\mathbf{V}$  is a proper class.

PROOF: From Comprehension and  $\langle 1 \rangle 2$ .

□

**Definition 1.3.9.** For any sets  $A$  and  $B$ , the *relative complement*  $A - B$  is the set  $\{x \in A \mid x \notin B\}$ .

**Proposition 1.3.10** (Distributive Laws). *For any set  $A$  and class  $\mathbf{B}$ , we have*

$$A \cup \bigcap \mathbf{B} = \bigcap \{A \cup X \mid X \in \mathbf{B}\}$$

$$A \cap \bigcup \mathbf{B} = \bigcup \{A \cap X \mid X \in \mathbf{B}\}$$

PROOF: First-order logic. □

**Proposition 1.3.11** (De Morgan's Laws). *For any set  $C$  and class  $\mathbf{A}$ , we have*

$$C - \bigcap \mathbf{A} = \bigcup \{C - X \mid X \in \mathbf{A}\}$$

$$C - \bigcup \mathbf{A} = \bigcap \{C - X \mid X \in \mathbf{A}\}$$

PROOF: First-order logic. □



## 1.4 Transitive Classes

**Definition 1.4.1** (Transitive Class). A class  $\mathbf{A}$  is a *transitive class* iff whenever  $x \in y \in \mathbf{A}$  then  $x \in \mathbf{A}$ .

**Proposition 1.4.2.** *Let  $A$  be a set. Then the following are equivalent.*

1.  $A$  is a transitive class.
2.  $\bigcup A \subseteq A$
3. Every element of  $A$  is a subset of  $A$ .
4.  $A \subseteq \mathcal{P}A$

PROOF: Immediate from definitions.  $\square$

**Proposition 1.4.3.** *For any set  $a$ , we have  $a$  is a transitive set if and only if  $\mathcal{P}a$  is a transitive set.*

PROOF:

- $\langle 1 \rangle 1$ . If  $a$  is a transitive set then  $\mathcal{P}a$  is a transitive set.  
 $\langle 2 \rangle 1$ . ASSUME:  $a$  is a transitive set.  
 $\langle 2 \rangle 2$ .  $a \subseteq \mathcal{P}a$   
 PROOF: Proposition 1.4.2,  $\langle 2 \rangle 1$ .  
 $\langle 2 \rangle 3$ .  $\mathcal{P}a \subseteq \mathcal{P}\mathcal{P}a$   
 PROOF: Proposition 1.3.6,  $\langle 2 \rangle 2$ .  
 $\langle 2 \rangle 4$ .  $\mathcal{P}a$  is a transitive set.  
 PROOF: Proposition 1.4.2,  $\langle 2 \rangle 3$ .  
 $\langle 1 \rangle 2$ . If  $\mathcal{P}a$  is a transitive set then  $a$  is a transitive set.  
 $\langle 2 \rangle 1$ . ASSUME:  $\mathcal{P}a$  is a transitive set.  
 $\langle 2 \rangle 2$ .  $\bigcup \mathcal{P}a \subseteq \mathcal{P}a$   
 PROOF: Proposition 1.4.2,  $\langle 2 \rangle 1$ .  
 $\langle 2 \rangle 3$ .  $a \subseteq \mathcal{P}a$   
 PROOF: Proposition 1.3.7,  $\langle 2 \rangle 2$   
 $\langle 2 \rangle 4$ .  $a$  is a transitive set.  
 PROOF: Proposition 1.4.2,  $\langle 2 \rangle 3$ .

$\square$

**Proposition 1.4.4.** *If  $\mathbf{A}$  is a transitive class then  $\bigcup \mathbf{A}$  is a transitive class.*

PROOF:

- $\langle 1 \rangle 1$ . ASSUME:  $\mathbf{A}$  is a transitive class.  
 $\langle 1 \rangle 2$ . LET:  $x \in y \in \bigcup \mathbf{A}$   
 $\langle 1 \rangle 3$ .  $y \in \mathbf{A}$   
 PROOF:  $\langle 1 \rangle 1$ ,  $\langle 1 \rangle 2$   
 $\langle 1 \rangle 4$ .  $x \in \mathbf{A}$   
 PROOF:  $\langle 1 \rangle 1$ ,  $\langle 1 \rangle 2$ ,  $\langle 1 \rangle 3$

$\square$

**Proposition 1.4.5.** *If every member of  $\mathbf{A}$  is a transitive set then  $\bigcup \mathbf{A}$  is a transitive class.*

PROOF:

$\langle 1 \rangle 1$ . ASSUME: Every member of  $\mathbf{A}$  is a transitive set.

$\langle 1 \rangle 2$ . LET:  $x \in y \in \bigcup \mathbf{A}$

$\langle 1 \rangle 3$ . PICK  $A \in \mathbf{A}$  such that  $y \in A$ .

$\langle 1 \rangle 4$ .  $x \in A$

$\langle 1 \rangle 5$ .  $x \in \bigcup \mathbf{A}$

□

**Proposition 1.4.6.** *If every member of  $\mathbf{A}$  is a transitive set then  $\bigcap \mathbf{A}$  is a transitive class.*

PROOF:

$\langle 1 \rangle 1$ . ASSUME: Every member of  $\mathbf{A}$  is a transitive set.

$\langle 1 \rangle 2$ . LET:  $x \in y \in \bigcap \mathbf{A}$

PROVE:  $x \in \bigcap \mathbf{A}$

$\langle 1 \rangle 3$ . LET:  $A \in \mathbf{A}$

$\langle 1 \rangle 4$ .  $y \in A$

$\langle 1 \rangle 5$ .  $x \in A$

□

## Chapter 2

# Relations

### 2.1 Ordered Pairs

**Definition 2.1.1** (Ordered Pair). For any sets  $a$  and  $b$ , the *ordered pair*  $(a, b)$  is defined to be  $\{\{a\}, \{a, b\}\}$ .

**Theorem 2.1.2.** For any sets  $a, b, c, d$ , we have  $(a, b) = (c, d)$  if and only if  $a = c$  and  $b = d$ .

PROOF:

$\langle 1 \rangle 1$ . If  $(a, b) = (c, d)$  then  $a = c$  and  $b = d$ .

$\langle 2 \rangle 1$ . ASSUME:  $\{\{a\}, \{a, b\}\} = \{\{c\}, \{c, d\}\}$

$\langle 2 \rangle 2$ .  $\bigcap \{\{a\}, \{a, b\}\} = \bigcap \{\{c\}, \{c, d\}\}$

$\langle 2 \rangle 3$ .  $\{a\} = \{c\}$

$\langle 2 \rangle 4$ .  $a = c$

$\langle 2 \rangle 5$ .  $\bigcup \{\{a\}, \{a, b\}\} = \bigcup \{\{c\}, \{c, d\}\}$

$\langle 2 \rangle 6$ .  $\{a, b\} = \{c, d\}$

$\langle 2 \rangle 7$ .  $b = c$  or  $b = d$

$\langle 2 \rangle 8$ .  $a = d$  or  $b = d$

$\langle 2 \rangle 9$ . If  $b = c$  and  $a = d$  then  $b = d$

PROOF: By  $\langle 2 \rangle 4$ .

$\langle 2 \rangle 10$ .  $b = d$

PROOF: From  $\langle 2 \rangle 7$ ,  $\langle 2 \rangle 8$ ,  $\langle 2 \rangle 9$ .

$\langle 1 \rangle 2$ . If  $a = c$  and  $b = d$  then  $(a, b) = (c, d)$ .

PROOF: First-order logic.

□

**Definition 2.1.3** (Cartesian Product). The *Cartesian product* of classes  $\mathbf{A}$  and  $\mathbf{B}$  is the class  $\mathbf{A} \times \mathbf{B} := \{(x, y) \mid x \in \mathbf{A}, y \in \mathbf{B}\}$ .

**Proposition 2.1.4.** If  $A$  and  $B$  are sets then  $A \times B$  is a set.

PROOF: It is a subset of  $\mathcal{PP}(A \cup B)$ . □

**Proposition 2.1.5.** *For any classes  $\mathbf{A}$ ,  $\mathbf{B}$  and  $\mathbf{C}$ , we have  $\mathbf{A} \times (\mathbf{B} \cup \mathbf{C}) = (\mathbf{A} \times \mathbf{B}) \cup (\mathbf{A} \times \mathbf{C})$ .*

PROOF:

$$\begin{aligned} (x, y) \in \mathbf{A} \times (\mathbf{B} \cup \mathbf{C}) &\Leftrightarrow x \in \mathbf{A} \wedge (y \in \mathbf{B} \vee y \in \mathbf{C}) \\ &\Leftrightarrow (x \in \mathbf{A} \wedge y \in \mathbf{B}) \vee (x \in \mathbf{A} \wedge y \in \mathbf{C}) \\ &\Leftrightarrow (x, y) \in (\mathbf{A} \times \mathbf{B}) \cup (\mathbf{A} \times \mathbf{C}) \quad \square \end{aligned}$$

**Proposition 2.1.6.** *If  $\mathbf{A} \times \mathbf{B} = \mathbf{A} \times \mathbf{C}$  and  $\mathbf{A}$  is nonempty then  $\mathbf{B} = \mathbf{C}$ .*

PROOF:

$\langle 1 \rangle 1.$  PICK  $a \in \mathbf{A}$

$\langle 1 \rangle 2.$  For all  $x$  we have  $x \in \mathbf{B}$  iff  $x \in \mathbf{C}$ .

PROOF:

$$\begin{aligned} x \in \mathbf{B} &\Leftrightarrow (a, x) \in \mathbf{A} \times \mathbf{B} \\ &\Leftrightarrow (a, x) \in \mathbf{A} \times \mathbf{C} \\ &\Leftrightarrow x \in \mathbf{C} \end{aligned}$$

$\square$

**Proposition 2.1.7.** *For any set  $A$  and class  $\mathbf{B}$ , we have  $A \times \bigcup \mathbf{B} = \bigcup \{A \times X \mid X \in \mathbf{B}\}$ .*

PROOF:

$$\begin{aligned} (x, y) \in A \times \bigcup \mathbf{B} &\Leftrightarrow x \in A \wedge \exists Y \in \mathbf{B}. y \in Y \\ &\Leftrightarrow \exists Y \in \mathbf{B} (x \in A \wedge y \in Y) \\ &\Leftrightarrow (x, y) \in \bigcup \{A \times X \mid X \in \mathbf{B}\} \quad \square \end{aligned}$$

## 2.2 Relations

**Definition 2.2.1** (Relation). A *relation* is a class of ordered pairs.

**Definition 2.2.2** (Domain). The *domain* of a class  $\mathbf{R}$  is the class

$$\text{dom } \mathbf{R} := \{x \mid \exists y. (x, y) \in \mathbf{R}\} .$$

**Definition 2.2.3** (Range). The *range* of a class  $\mathbf{R}$  is the class

$$\text{ran } \mathbf{R} := \{x \mid \exists y. (y, x) \in \mathbf{R}\} .$$

**Definition 2.2.4** (Field). The *field* of a class  $\mathbf{R}$  is the class

$$\text{fld } \mathbf{R} := \text{dom } \mathbf{R} \cup \text{ran } \mathbf{R} .$$

**Proposition 2.2.5.** *For any set  $R$ , the classes  $\text{dom } R$ ,  $\text{ran } R$ ,  $\text{fld } R$  are sets.*

PROOF: They are all subsets of  $\bigcup \bigcup R$ .  $\square$

**Definition 2.2.6** (Single-Rooted). A class  $\mathbf{R}$  is *single-rooted* iff, for all  $y \in \text{ran } \mathbf{R}$ , there is exactly one  $x$  such that  $(x, y) \in \mathbf{R}$ .

**Definition 2.2.7** (Inverse). The *inverse* of a class  $\mathbf{F}$  is the class

$$\mathbf{F}^{-1} := \{(x, y) \mid (y, x) \in \mathbf{F}\} .$$

**Proposition 2.2.8.** For any class  $\mathbf{F}$ , we have  $\text{dom } \mathbf{F}^{-1} = \text{ran } \mathbf{F}$

PROOF:

$$\begin{aligned} y \in \text{dom } \mathbf{F}^{-1} &\Leftrightarrow \exists x.(y, x) \in \mathbf{F}^{-1} \\ &\Leftrightarrow \exists x.(x, y) \in \mathbf{F} \\ &\Leftrightarrow y \in \text{ran } \mathbf{F} \end{aligned} \quad \square$$

**Proposition 2.2.9.** For any class  $\mathbf{F}$ , we have  $\text{ran } \mathbf{F}^{-1} = \text{dom } \mathbf{F}$ .

PROOF:

$$\begin{aligned} y \in \text{ran } \mathbf{F}^{-1} &\Leftrightarrow \exists x.(x, y) \in \mathbf{F}^{-1} \\ &\Leftrightarrow \exists x.(y, x) \in \mathbf{F} \\ &\Leftrightarrow y \in \text{dom } \mathbf{F} \end{aligned} \quad \square$$

**Proposition 2.2.10.** For any relation  $\mathbf{F}$ , we have  $(\mathbf{F}^{-1})^{-1} = \mathbf{F}$ .

PROOF:

$$\begin{aligned} (x, y) \in (\mathbf{F}^{-1})^{-1} &\Leftrightarrow (y, x) \in \mathbf{F}^{-1} \\ &\Leftrightarrow (x, y) \in \mathbf{F} \end{aligned} \quad \square$$

**Definition 2.2.11** (Composition). The *composition* of classes  $\mathbf{F}$  and  $\mathbf{G}$  is the class

$$\mathbf{F} \circ \mathbf{G} := \{(x, z) \mid \exists y.(x, y) \in \mathbf{G} \wedge (y, z) \in \mathbf{F}\} .$$

**Proposition 2.2.12.** For any classes  $\mathbf{F}$  and  $\mathbf{G}$ ,

$$(\mathbf{F} \circ \mathbf{G})^{-1} = \mathbf{G}^{-1} \circ \mathbf{F}^{-1} .$$

PROOF:

$$\begin{aligned} (z, x) \in (\mathbf{F} \circ \mathbf{G})^{-1} &\Leftrightarrow (x, z) \in \mathbf{F} \circ \mathbf{G} \\ &\Leftrightarrow \exists y.(x, y) \in \mathbf{G} \wedge (y, z) \in \mathbf{F} \\ &\Leftrightarrow \exists y.(y, x) \in \mathbf{G}^{-1} \wedge (z, y) \in \mathbf{F}^{-1} \\ &\Leftrightarrow (z, x) \in \mathbf{G}^{-1} \circ \mathbf{F}^{-1} \end{aligned} \quad \square$$

**Definition 2.2.13** (Restriction). The *restriction* of the class  $\mathbf{F}$  to the class  $\mathbf{A}$  is the class  $\mathbf{F} \upharpoonright \mathbf{A} := \{(x, y) \mid x \in \mathbf{A}, (x, y) \in \mathbf{F}\}$ .

**Definition 2.2.14** (Image). The *image* of the class  $\mathbf{A}$  under the class  $\mathbf{F}$  is the set  $F(\mathbf{A}) := \text{ran}(\mathbf{F} \upharpoonright \mathbf{A}) = \{y \mid \exists x \in \mathbf{A}.(x, y) \in \mathbf{F}\}$ .

**Proposition 2.2.15.** *For any classes  $\mathbf{F}$ ,  $\mathbf{A}$  and  $\mathbf{B}$ , we have*

$$\mathbf{F}(\mathbf{A} \cup \mathbf{B}) = \mathbf{F}(\mathbf{A}) \cup \mathbf{F}(\mathbf{B}) .$$

PROOF:

$$\begin{aligned} y \in \mathbf{F}(\mathbf{A} \cup \mathbf{B}) &\Leftrightarrow \exists x \in \mathbf{A} \cup \mathbf{B}. (x, y) \in \mathbf{F} \\ &\Leftrightarrow \exists x \in \mathbf{A}. (x, y) \in \mathbf{F} \vee \exists x \in \mathbf{B}. (x, y) \in \mathbf{F} \\ &\Leftrightarrow y \in \mathbf{F}(\mathbf{A}) \cup \mathbf{F}(\mathbf{B}) \quad \square \end{aligned}$$

**Proposition 2.2.16.** *For any classes  $\mathbf{F}$  and  $\mathbf{A}$  we have  $\mathbf{F}(\bigcup \mathbf{A}) = \bigcup \{\mathbf{F}(X) \mid X \in \mathbf{A}\}$ .*

PROOF:

$$\begin{aligned} y \in \mathbf{F}(\bigcup \mathbf{A}) &\Leftrightarrow \exists x \in \bigcup \mathbf{A}. (x, y) \in \mathbf{F} \\ &\Leftrightarrow \exists x. \exists X. X \in \mathbf{A} \wedge x \in X \wedge (x, y) \in \mathbf{F} \\ &\Leftrightarrow \exists X \in \mathbf{F}. y \in \mathbf{F}(X) \quad \square \end{aligned}$$

**Proposition 2.2.17.** *For any classes  $\mathbf{F}$ ,  $\mathbf{A}$  and  $\mathbf{B}$ , we have  $\mathbf{F}(\mathbf{A} \cap \mathbf{B}) \subseteq \mathbf{F}(\mathbf{A}) \cap \mathbf{F}(\mathbf{B})$ . Equality holds if  $\mathbf{F}$  is single-rooted.*

PROOF:

- (1)1.  $\mathbf{F}(\mathbf{A} \cap \mathbf{B}) \subseteq \mathbf{F}(\mathbf{A}) \cap \mathbf{F}(\mathbf{B})$ 
  - (2)1. LET:  $y \in \mathbf{F}(\mathbf{A} \cap \mathbf{B})$
  - (2)2. PICK  $x \in \mathbf{A} \cap \mathbf{B}$  such that  $(x, y) \in \mathbf{F}$
  - (2)3.  $y \in \mathbf{F}(\mathbf{A})$
  - PROOF: Since  $x \in \mathbf{A}$ .
  - (2)4.  $y \in \mathbf{F}(\mathbf{B})$
  - PROOF: Since  $x \in \mathbf{B}$ .
- (1)2. If  $\mathbf{F}$  is single-rooted then  $\mathbf{F}(\mathbf{A} \cap \mathbf{B}) = \mathbf{F}(\mathbf{A}) \cap \mathbf{F}(\mathbf{B})$ .
  - (2)1. ASSUME:  $\mathbf{F}$  is single-rooted.
  - (2)2. LET:  $y \in \mathbf{F}(\mathbf{A}) \cap \mathbf{F}(\mathbf{B})$
  - (2)3. PICK  $x \in \mathbf{A}$  such that  $(x, y) \in \mathbf{F}$
  - (2)4. PICK  $x' \in \mathbf{B}$  such that  $(x', y) \in \mathbf{F}$
  - (2)5.  $x = x'$
  - PROOF: (2)1
  - (2)6.  $x \in \mathbf{A} \cap \mathbf{B}$
  - (2)7.  $y \in \mathbf{F}(\mathbf{A} \cap \mathbf{B})$

□

**Proposition 2.2.18.** *For any classes  $\mathbf{F}$  and  $\mathbf{A}$  we have*

$$\mathbf{F}\left(\bigcap \mathbf{A}\right) \subseteq \bigcap \{\mathbf{F}(X) \mid X \in \mathbf{A}\} .$$

*Equality holds if  $\mathbf{F}$  is single-rooted and  $\mathbf{A}$  is nonempty.*

PROOF:

- (1)1.  $\mathbf{F}(\bigcap \mathbf{A}) \subseteq \bigcap \{\mathbf{F}(X) \mid X \in \mathbf{A}\}$

- ⟨2⟩1. LET:  $y \in \mathbf{F}(\bigcap \mathbf{A})$
- ⟨2⟩2. PICK  $x \in \bigcap \mathbf{A}$  such that  $(x, y) \in \mathbf{F}$
- ⟨2⟩3. LET:  $X \in \mathbf{A}$   
PROVE:  $y \in \mathbf{F}(X)$
- ⟨2⟩4.  $x \in X$
- ⟨2⟩5.  $y \in \mathbf{F}(X)$
- ⟨1⟩2. If  $\mathbf{F}$  is single-rooted then  $\mathbf{F}(\bigcap \mathbf{A}) = \bigcap \{\mathbf{F}(X) \mid X \in \mathbf{A}\}$ 
  - ⟨2⟩1. ASSUME:  $\mathbf{F}$  is single-rooted.
  - ⟨2⟩2. ASSUME:  $\mathbf{A}$  is nonempty.
  - ⟨2⟩3. LET:  $y \in \bigcap \{\mathbf{F}(X) \mid X \in \mathbf{A}\}$
  - ⟨2⟩4. PICK  $X_0 \in \mathbf{A}$
  - ⟨2⟩5. PICK  $x \in X_0$  such that  $(x, y) \in \mathbf{F}$
  - ⟨2⟩6.  $x \in \bigcap \mathbf{A}$ 
    - ⟨3⟩1. LET:  $X \in \mathbf{A}$
    - ⟨3⟩2. PICK  $x' \in X$  such that  $(x', y) \in \mathbf{F}$ .
    - ⟨3⟩3.  $x = x'$   
PROOF: ⟨2⟩1
    - ⟨3⟩4.  $x \in X$
  - ⟨2⟩7.  $y \in \mathbf{F}(\bigcap \mathbf{A})$

□

**Proposition 2.2.19.** *For any classes  $\mathbf{F}$ ,  $\mathbf{A}$  and  $\mathbf{B}$ , we have*

$$\mathbf{F}(\mathbf{A}) - \mathbf{F}(\mathbf{B}) \subseteq \mathbf{F}(\mathbf{A} - \mathbf{B}) .$$

*Equality holds if  $\mathbf{F}$  is single-rooted.*

PROOF:

- ⟨1⟩1.  $\mathbf{F}(\mathbf{A}) - \mathbf{F}(\mathbf{B}) \subseteq \mathbf{F}(\mathbf{A} - \mathbf{B})$ 
  - ⟨2⟩1. LET:  $y \in \mathbf{F}(\mathbf{A}) - \mathbf{F}(\mathbf{B})$
  - ⟨2⟩2. PICK  $x \in \mathbf{A}$  such that  $(x, y) \in \mathbf{F}$
  - ⟨2⟩3.  $x \notin \mathbf{B}$
  - ⟨2⟩4.  $x \in \mathbf{A} - \mathbf{B}$
  - ⟨2⟩5.  $y \in \mathbf{F}(\mathbf{A} - \mathbf{B})$
- ⟨1⟩2. If  $\mathbf{F}$  is single-rooted then  $\mathbf{F}(\mathbf{A}) - \mathbf{F}(\mathbf{B}) = \mathbf{F}(\mathbf{A} - \mathbf{B})$ 
  - ⟨2⟩1. ASSUME:  $\mathbf{F}$  is single-rooted.
  - ⟨2⟩2. LET:  $y \in \mathbf{F}(\mathbf{A} - \mathbf{B})$
  - ⟨2⟩3. PICK  $x \in \mathbf{A} - \mathbf{B}$  such that  $(x, y) \in \mathbf{F}$
  - ⟨2⟩4.  $y \in \mathbf{F}(\mathbf{A})$
  - ⟨2⟩5.  $y \notin \mathbf{F}(\mathbf{B})$ 
    - ⟨3⟩1. ASSUME: for a contradiction  $y \in \mathbf{F}(\mathbf{B})$
    - ⟨3⟩2. PICK  $x' \in \mathbf{B}$  such that  $(x', y) \in \mathbf{F}$
    - ⟨3⟩3.  $x = x'$   
PROOF: ⟨2⟩1
    - ⟨3⟩4.  $x \in \mathbf{B}$
    - ⟨3⟩5. Q.E.D.  
PROOF: This contradicts ⟨2⟩3.

□

**Definition 2.2.20** (Reflexive). Let  $\mathbf{R}$  be a binary relation on  $\mathbf{A}$ . Then  $\mathbf{R}$  is *reflexive* on  $\mathbf{A}$  iff  $\forall x \in \mathbf{A}. (x, x) \in \mathbf{R}$ .

**Definition 2.2.21** (Irreflexive). A relation  $\mathbf{R}$  is *irreflexive* iff there is no  $x$  such that  $(x, x) \in \mathbf{R}$ .

**Definition 2.2.22** (Symmetric). A relation  $\mathbf{R}$  is *symmetric* iff, whenever  $(x, y) \in \mathbf{R}$ , then  $(y, x) \in \mathbf{R}$ .

**Definition 2.2.23** (Transitive). A relation  $\mathbf{R}$  is *transitive* iff, whenever  $(x, y), (y, z) \in \mathbf{R}$ , then  $(x, z) \in \mathbf{R}$ .

**Proposition 2.2.24.** *If  $\mathbf{R}$  is transitive then  $\mathbf{R}^{-1}$  is transitive.*

PROOF:

- $\langle 1 \rangle 1$ . ASSUME:  $(x, y), (y, z) \in \mathbf{R}^{-1}$
- $\langle 1 \rangle 2$ .  $(y, x), (z, y) \in \mathbf{R}$
- $\langle 1 \rangle 3$ .  $(z, x) \in \mathbf{R}$
- $\langle 1 \rangle 4$ .  $(x, z) \in \mathbf{R}^{-1}$

□

## 2.3 $n$ -ary Relations

**Definition Schema 2.3.1.** For any sets  $a_1, \dots, a_n$ , define the *ordered  $n$ -tuple*  $(a_1, \dots, a_n)$  by

$$(a_1) := a_1$$

$$(a_1, \dots, a_n, a_{n+1}) = ((a_1, \dots, a_n), a_{n+1})$$

**Definition Schema 2.3.2.** An  *$n$ -ary relation on  $\mathbf{A}$*  is a class of ordered  $n$ -tuples all of whose components are in  $\mathbf{A}$ .

## 2.4 Equivalence Relations

**Definition 2.4.1** (Equivalence Relation). An *equivalence relation* on a class  $\mathbf{A}$  is a relation on  $\mathbf{A}$  that is reflexive on  $\mathbf{A}$ , symmetric and transitive.

**Proposition 2.4.2.** *If  $\mathbf{R}$  is a symmetric and transitive relation, then  $\mathbf{R}$  is an equivalence relation on  $\text{fld } \mathbf{R}$ .*

PROOF:

- $\langle 1 \rangle 1$ . LET:  $x \in \text{fld } \mathbf{R}$   
           PROVE:  $(x, x) \in \mathbf{R}$
- $\langle 1 \rangle 2$ . PICK  $y$  such that either  $(x, y) \in \mathbf{R}$  or  $(y, x) \in \mathbf{R}$
- $\langle 1 \rangle 3$ .  $(x, y) \in \mathbf{R}$  and  $(y, x) \in \mathbf{R}$   
           PROOF: Symmetry.



(1)4.  $(x, x) \in \mathbf{R}$

PROOF: Transitivity.

□

**Definition 2.4.3** (Equivalence Class). Let  $\mathbf{R}$  be an equivalence relation on  $\mathbf{A}$  and  $a \in \mathbf{A}$ . The *equivalence class* of  $a$  modulo  $\mathbf{R}$  is

$$[a]_{\mathbf{R}} := \{x \mid (a, x) \in \mathbf{R}\} .$$

**Proposition 2.4.4.** Let  $\mathbf{R}$  be an equivalence relation on  $\mathbf{A}$  and  $a, b \in \mathbf{A}$ . Then  $[a]_{\mathbf{R}} = [b]_{\mathbf{R}}$  if and only if  $(a, b) \in \mathbf{R}$ .

PROOF:

(1)1. If  $[a]_{\mathbf{R}} = [b]_{\mathbf{R}}$  then  $(a, b) \in \mathbf{R}$ .

(2)1. ASSUME:  $[a]_{\mathbf{R}} = [b]_{\mathbf{R}}$

(2)2.  $(b, b) \in \mathbf{R}$

PROOF: Reflexivity

(2)3.  $b \in [b]_{\mathbf{R}}$

(2)4.  $b \in [a]_{\mathbf{R}}$

(2)5.  $(a, b) \in \mathbf{R}$

(1)2. If  $(a, b) \in \mathbf{R}$  then  $[a]_{\mathbf{R}} = [b]_{\mathbf{R}}$ .

(2)1. For all  $x, y \in \mathbf{A}$ , if  $(x, y) \in \mathbf{R}$  then  $[y]_{\mathbf{R}} \subseteq [x]_{\mathbf{R}}$

(3)1. LET:  $x, y \in \mathbf{A}$

(3)2. ASSUME:  $(x, y) \in \mathbf{R}$

(3)3. LET:  $t \in [y]_{\mathbf{R}}$

(3)4.  $(y, t) \in \mathbf{R}$

PROOF: (3)3

(3)5.  $(x, t) \in \mathbf{R}$

PROOF: Transitivity, (3)2, (3)4.

(3)6.  $t \in [x]_{\mathbf{R}}$

PROOF: (3)5

(2)2. ASSUME:  $(a, b) \in \mathbf{R}$

(2)3.  $[b]_{\mathbf{R}} \subseteq [a]_{\mathbf{R}}$

PROOF: (2)1, (2)2.

(2)4.  $(b, a) \in \mathbf{R}$

PROOF: Symmetry, (2)2.

(2)5.  $[a]_{\mathbf{R}} \subseteq [b]_{\mathbf{R}}$

PROOF: (2)1, (2)4.

(2)6.  $[a]_{\mathbf{R}} = [b]_{\mathbf{R}}$

PROOF: (2)3, (2)5.

□

**Definition 2.4.5** (Partition). A *partition*  $\Pi$  of a set  $A$  is a set of nonempty subsets of  $A$  that is disjoint and exhaustive, i.e.

1. no two different sets in  $\Pi$  have any common elements, and
2. each element of  $A$  is in some set in  $\Pi$ .

**Definition 2.4.6.** Let  $R$  be an equivalence relation on a set  $A$ . The *quotient set*  $A/R$  is the set of all equivalence classes.

**Proposition 2.4.7.** Let  $R$  be an equivalence relation on a set  $A$ . Then  $A/R$  is a partition of  $A$ .

PROOF:

$\langle 1 \rangle 1$ . Every member of  $A/R$  is nonempty.

PROOF: Since  $a \in [a]_R$  by reflexivity.

$\langle 1 \rangle 2$ . No two different sets in  $A/R$  have any common elements.

$\langle 2 \rangle 1$ . LET:  $[a]_R, [b]_R \in A/R$

$\langle 2 \rangle 2$ . LET:  $c \in [a]_R \cap [b]_R$

PROVE:  $[a]_R = [b]_R$

$\langle 2 \rangle 3$ .  $(a, c) \in R$

PROOF:  $\langle 2 \rangle 2$

$\langle 2 \rangle 4$ .  $(b, c) \in R$

PROOF:  $\langle 2 \rangle 2$

$\langle 2 \rangle 5$ .  $(c, b) \in R$

PROOF: Symmetry,  $\langle 2 \rangle 4$

$\langle 2 \rangle 6$ .  $(a, b) \in R$

PROOF: Transitivity,  $\langle 2 \rangle 3$ ,  $\langle 2 \rangle 5$

$\langle 2 \rangle 7$ .  $[a]_R = [b]_R$

PROOF: Proposition 2.4.4,  $\langle 2 \rangle 6$

$\langle 1 \rangle 3$ . Each element of  $A$  is in some set in  $A/R$ .

PROOF: Since  $a \in [a]_R$  by reflexivity.

□

## 2.5 Ordering Relations

**Definition 2.5.1** (Linear Ordering). Let  $\mathbf{A}$  be a class. A *linear ordering* or *total ordering* on  $\mathbf{A}$  is a relation  $\mathbf{R}$  on  $\mathbf{A}$  such that:

1.  $\mathbf{R}$  is transitive.

2. *Trichotomy*. For all  $x, y \in \mathbf{A}$ , exactly one of the following holds:

$$(x, y) \in \mathbf{R}, \quad (y, x) \in \mathbf{R}, \quad x = y .$$

We often use the symbol  $<$  for a linear ordering, and then write  $x < y$  for  $(x, y) \in <$ .

**Theorem 2.5.2.** Any linear ordering on a class is *irreflexive*.

PROOF: Immediate from trichotomy. □

**Proposition 2.5.3.** If  $\mathbf{R}$  is a linear ordering on  $\mathbf{A}$  then  $\mathbf{R}^{-1}$  is also a linear ordering on  $\mathbf{A}$ .

PROOF:

$\langle 1 \rangle 1.$   $\mathbf{R}^{-1}$  is transitive.

PROOF: Proposition 2.2.24.

$\langle 1 \rangle 2.$   $\mathbf{R}^{-1}$  satisfies trichotomy.

$\langle 2 \rangle 1.$  LET:  $x, y \in \mathbf{A}$

$\langle 2 \rangle 2.$  Exactly one of  $(x, y) \in \mathbf{R}$ ,  $(y, x) \in \mathbf{R}$ ,  $x = y$  holds.

$\langle 2 \rangle 3.$  Exactly one of  $(y, x) \in \mathbf{R}^{-1}$ ,  $(x, y) \in \mathbf{R}^{-1}$ ,  $x = y$  holds.

□

**Definition 2.5.4** (Lexicographic Ordering). Let  $A$  and  $B$  be linearly ordered sets. The *lexicographic ordering*  $<$  on  $A \times B$  is defined by:

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

**Proposition 2.5.5.** Let  $A$  and  $B$  be linearly ordered sets. Then the lexicographic ordering on  $A \times B$  is a linear ordering.

PROOF:

$\langle 1 \rangle 1.$   $<$  is transitive.

$\langle 2 \rangle 1.$  LET:  $(a_1, b_1) < (a_2, b_2) < (a_3, b_3)$

PROVE:  $(a_1, b_1) < (a_3, b_3)$

$\langle 2 \rangle 2.$  CASE:  $a_1 < a_2$

$\langle 3 \rangle 1.$   $a_2 < a_3$  or  $a_2 = a_3$

PROOF:  $\langle 2 \rangle 1$

$\langle 3 \rangle 2.$   $a_1 < a_3$

PROOF: Transitivity

$\langle 3 \rangle 3.$   $(a_1, b_1) < (a_3, b_3)$

$\langle 2 \rangle 3.$  CASE:  $a_1 = a_2$  and  $b_1 < b_2$  and  $a_2 < a_3$

PROOF: We have  $a_1 < a_3$  so  $(a_1, b_1) < (a_3, b_3)$ .

$\langle 2 \rangle 4.$  CASE:  $a_1 = a_2$  and  $b_1 < b_2$  and  $a_2 = a_3$  and  $b_2 < b_3$

PROOF: We have  $a_1 = a_3$  and  $b_1 < b_3$  so  $(a_1, b_1) < (a_3, b_3)$ .

$\langle 1 \rangle 2.$   $<$  satisfies trichotomy.

$\langle 2 \rangle 1.$  LET:  $(a_1, b_1), (a_2, b_2) \in A \times B$

$\langle 2 \rangle 2.$  Exactly one of  $a_1 < a_2$ ,  $a_1 = a_2$ ,  $a_2 < a_1$  holds.

$\langle 2 \rangle 3.$  CASE:  $a_1 < a_2$

PROOF: We have  $(a_1, b_1) < (a_2, b_2)$ ,  $(a_1, b_1) \neq (a_2, b_2)$ , and  $(a_2, b_2) \not< (a_1, b_1)$ .

$\langle 2 \rangle 4.$  CASE:  $a_1 = a_2$

$\langle 3 \rangle 1.$  Exactly one of  $b_1 < b_2$ ,  $b_1 = b_2$ ,  $b_2 < b_1$  holds.

$\langle 3 \rangle 2.$  Exactly one of  $(a_1, b_1) < (a_2, b_2)$ ,  $(a_1, b_1) = (a_2, b_2)$ ,  $(a_2, b_2) < (a_1, b_1)$  holds.

$\langle 2 \rangle 5.$  CASE:  $a_2 < a_1$

PROOF: We have  $(a_2, b_2) < (a_1, b_1)$ ,  $(a_2, b_2) \neq (a_1, b_1)$ , and  $(a_1, b_1) \not< (a_2, b_2)$ .



## Chapter 3

# Functions

### 3.1 Functions

**Definition 3.1.1** (Function). A *function* is a relation  $\mathbf{F}$  such that, for all  $x \in \text{dom } \mathbf{F}$ , there is only one  $y$  such that  $(x, y) \in \mathbf{F}$ . We denote this  $y$  by  $\mathbf{F}(x)$ .

We say that  $\mathbf{F}$  is a function *from*  $\mathbf{A}$  *into*  $\mathbf{B}$ , or that  $\mathbf{F}$  *maps*  $\mathbf{A}$  *into*  $\mathbf{B}$ , and write  $\mathbf{F} : \mathbf{A} \rightarrow \mathbf{B}$ , iff  $\mathbf{F}$  is a function,  $\text{dom } \mathbf{F} = \mathbf{A}$  and  $\text{ran } \mathbf{F} \subseteq \mathbf{B}$ .

**Proposition 3.1.2.** *For any class  $\mathbf{F}$ ,  $\mathbf{F}^{-1}$  is a function if and only if  $\mathbf{F}$  is single-rooted.*

PROOF: Immediate from definitions.  $\square$

**Proposition 3.1.3.** *For any relation  $\mathbf{F}$ ,  $\mathbf{F}$  is a function if and only if  $\mathbf{F}^{-1}$  is single-rooted.*

PROOF: Immediate from definitions.  $\square$

**Proposition 3.1.4.** *Let  $\mathbf{F}$  and  $\mathbf{G}$  be functions. Then  $\mathbf{F} \circ \mathbf{G}$  is a function, its domain is*

$$\{x \in \text{dom } \mathbf{G} \mid \mathbf{G}(x) \in \text{dom } \mathbf{F}\} ,$$

*and for  $x$  in this domain,  $(\mathbf{F} \circ \mathbf{G})(x) = \mathbf{F}(\mathbf{G}(x))$ .*

PROOF:

$\langle 1 \rangle 1.$   $\mathbf{F} \circ \mathbf{G}$  is a function.

$\langle 2 \rangle 1.$  LET:  $(x, z), (x, z') \in \mathbf{F} \circ \mathbf{G}$

$\langle 2 \rangle 2.$  PICK  $y, y'$  such that  $(x, y) \in \mathbf{G}, (y, z) \in \mathbf{F}, (x, y') \in \mathbf{G}, (y', z') \in \mathbf{F}$

$\langle 2 \rangle 3.$   $y = y'$

PROOF:  $\mathbf{G}$  is a function.

$\langle 2 \rangle 4.$   $z = z'$

PROOF:  $\mathbf{F}$  is a function.

$\langle 1 \rangle 2.$   $\text{dom}(\mathbf{F} \circ \mathbf{G}) = \{x \in \text{dom } \mathbf{G} \mid \mathbf{G}(x) \in \text{dom } \mathbf{F}\}$

PROOF:

$$\begin{aligned}
 x \in \text{dom}(\mathbf{F} \circ \mathbf{G}) &\Leftrightarrow \exists z. (x, z) \in \mathbf{F} \circ \mathbf{G} \\
 &\Leftrightarrow \exists y, z. ((x, y) \in \mathbf{G} \wedge (y, z) \in \mathbf{F}) \\
 &\Leftrightarrow \exists y. ((x, y) \in \mathbf{G} \wedge y \in \text{dom } \mathbf{F}) \\
 &\Leftrightarrow x \in \text{dom } \mathbf{G} \wedge \mathbf{G}(x) \in \text{dom } \mathbf{F}
 \end{aligned}$$

$$\langle 1 \rangle 3. \forall x \in \text{dom}(\mathbf{F} \circ \mathbf{G}). (\mathbf{F} \circ \mathbf{G})(x) = \mathbf{F}(\mathbf{G}(x))$$

PROOF:

- $\langle 2 \rangle 1.$  LET:  $x \in \text{dom}(\mathbf{F} \circ \mathbf{G})$
- $\langle 2 \rangle 2.$   $(x, (\mathbf{F} \circ \mathbf{G})(x)) \in \mathbf{F} \circ \mathbf{G}$
- $\langle 2 \rangle 3.$  PICK  $y$  such that  $(x, y) \in \mathbf{G}$  and  $(y, (\mathbf{F} \circ \mathbf{G})(x)) \in \mathbf{F}$
- $\langle 2 \rangle 4.$   $y = \mathbf{G}(x)$
- $\langle 2 \rangle 5.$   $\mathbf{F}(\mathbf{G}(x)) = (\mathbf{F} \circ \mathbf{G})(x)$

□

**Proposition 3.1.5.** *For any set  $A$  there exists a function  $F : \mathcal{P}A - \{\emptyset\} \rightarrow A$  (a choice function for  $A$ ) such that, for every nonempty  $B \subseteq A$ , we have  $F(B) \in B$ .*

PROOF:

- $\langle 1 \rangle 1.$  LET:  $A$  be a set.
- $\langle 1 \rangle 2.$  LET:  $\mathcal{A} = \{\{B\} \times B \mid B \in \mathcal{P}A - \{\emptyset\}\}$
- $\langle 1 \rangle 3.$  Every member of  $\mathcal{A}$  is nonempty.
- $\langle 1 \rangle 4.$  Any two distinct members of  $\mathcal{A}$  are disjoint.
- $\langle 1 \rangle 5.$  PICK a set  $C$  such that, for all  $X \in \mathcal{A}$ , we have  $C \cap X$  is a singleton.

PROOF: Axiom of Choice.

- $\langle 1 \rangle 6.$  LET:  $F = C \cap \bigcup \mathcal{A}$
- $\langle 1 \rangle 7.$   $F : \mathcal{P}A - \{\emptyset\} \rightarrow A$ 
  - $\langle 2 \rangle 1.$   $F$  is a function.
    - $\langle 3 \rangle 1.$  LET:  $(B, b), (B, b') \in F$
    - $\langle 3 \rangle 2.$   $(B, b), (B, b') \in \{B\} \times B$
    - PROOF: Since  $(B, b), (B, b') \in \bigcup \mathcal{A}$ .
    - $\langle 3 \rangle 3.$   $(B, b), (B, b') \in C \cap (\{B\} \times B)$
    - $\langle 3 \rangle 4.$   $(B, b) = (B, b')$
    - PROOF: From  $\langle 1 \rangle 5$ .
    - $\langle 3 \rangle 5.$   $b = b'$

$$\langle 2 \rangle 2. \text{dom } F = \mathcal{P}A - \{\emptyset\}$$

PROOF:

$$\begin{aligned}
 B \in \text{dom } F &\Leftrightarrow \exists b. (B, b) \in F \\
 &\Leftrightarrow \exists b. ((B, b) \in \bigcup \mathcal{A} \wedge (B, b) \in C) \\
 &\Leftrightarrow \exists b. \exists B' \in \mathcal{P}A - \{\emptyset\}. ((B, b) \in \{B'\} \times B' \wedge (B, b) \in C) \\
 &\Leftrightarrow B \in \mathcal{P}A - \{\emptyset\} \wedge \exists b \in B. (B, b) \in C \\
 &\Leftrightarrow B \in \mathcal{P}A - \{\emptyset\} \tag{⟨1⟩5}
 \end{aligned}$$

$$\langle 2 \rangle 3. \text{ran } F \subseteq A$$

$$\langle 1 \rangle 8. \text{For every nonempty } B \subseteq A \text{ we have } F(B) \in B$$

□

**Proposition 3.1.6.** *For any relation  $R$  there exists a function  $H \subseteq R$  with  $\text{dom } H = \text{dom } R$ .*

PROOF:

- $\langle 1 \rangle 1$ . LET:  $R$  be a relation.
- $\langle 1 \rangle 2$ . PICK a choice function  $G$  for  $\text{ran } R$ .
- $\langle 1 \rangle 3$ . Define  $H : \text{dom } R \rightarrow \text{ran } R$  by  $H(x) = G(\{y \mid xRy\})$
- $\langle 1 \rangle 4$ .  $H \subseteq R$

□

**Proposition 3.1.7.** *For any function  $G$  and nonempty class  $A$ , we have*

$$G^{-1} \left( \bigcap A \right) = \bigcap \{ G^{-1}(X) \mid X \in A \} .$$

PROOF: Propositions 2.2.18 and 3.1.3. □

**Proposition 3.1.8.** *For any function  $G$  and classes  $A$  and  $B$ , we have*

$$G^{-1}(A - B) = G^{-1}(A) - G^{-1}(B) .$$

PROOF: Proposition 2.2.19 and 3.1.3. □

**Definition 3.1.9** (Identity Function). For any class  $A$ , the *identity function* on  $A$  is  $I_A = \{(x, x) \mid x \in A\}$ .

**Definition 3.1.10** (Injective). A function is *one-to-one*, *injective* or an *injection* iff it is single-rooted.

**Proposition 3.1.11.** *Let  $F$  be a one-to-one function. Let  $x \in \text{dom } F$ . Then  $F^{-1}(F(x)) = x$ .*

PROOF:

- $\langle 1 \rangle 1$ .  $F^{-1}$  is a function.

PROOF: Proposition 3.1.2.

- $\langle 1 \rangle 2$ .  $(x, F(x)) \in F$
- $\langle 1 \rangle 3$ .  $(F(x), x) \in F^{-1}$

□

**Proposition 3.1.12.** *Let  $F$  be a one-to-one function. Let  $y \in \text{ran } F$ . Then  $F(F^{-1}(y)) = y$ .*

PROOF:

- $\langle 1 \rangle 1$ .  $F^{-1}$  is a function.

PROOF: Proposition 3.1.2.

- $\langle 1 \rangle 2$ .  $y \in \text{dom } F^{-1}$

PROOF: Proposition 2.2.8.

- $\langle 1 \rangle 3$ .  $(y, F^{-1}(y)) \in F^{-1}$
- $\langle 1 \rangle 4$ .  $(F^{-1}(y), y) \in F$

□

**Proposition 3.1.13.** *Let  $F : A \rightarrow B$  where  $A$  is nonempty. There exists  $G : B \rightarrow A$  (a left inverse) such that  $G \circ F = I_A$  if and only if  $F$  is one-to-one.*

PROOF:

- $\langle 1 \rangle 1$ . If there exists  $G : B \rightarrow A$  such that  $G \circ F = I_A$  then  $F$  is one-to-one.
  - $\langle 2 \rangle 1$ . ASSUME:  $G : B \rightarrow A$  and  $G \circ F = I_A$
  - $\langle 2 \rangle 2$ . LET:  $x, y \in A$
  - $\langle 2 \rangle 3$ . ASSUME:  $F(x) = F(y)$
  - $\langle 2 \rangle 4$ .  $x = y$
  - PROOF:  $x = G(F(x)) = G(F(y)) = y$
- $\langle 1 \rangle 2$ . If  $F$  is one-to-one then there exists  $G : B \rightarrow A$  such that  $G \circ F = I_A$ .
  - $\langle 2 \rangle 1$ . ASSUME:  $F$  is one-to-one.
  - $\langle 2 \rangle 2$ . PICK  $a \in A$
  - $\langle 2 \rangle 3$ . LET:  $G : B \rightarrow A$  be the function defined by:  $G(b) = F^{-1}(b)$  if  $b \in \text{ran } F$ ,  $G(b) = a$  otherwise.
  - PROVE:  $G \circ F = I_A$
  - $\langle 2 \rangle 4$ . LET:  $x \in A$
  - $\langle 2 \rangle 5$ .  $G(F(x)) = x$

□

**Definition 3.1.14** (Surjective). Let  $F : A \rightarrow B$ . We say that  $F$  is *surjective*, or maps  $A$  *onto*  $B$ , and write  $F : A \twoheadrightarrow B$ , iff for all  $y \in B$  there exists  $x \in A$  such that  $F(x) = y$ .

**Proposition 3.1.15.** *Let  $F : A \rightarrow B$ . There exists  $H : B \rightarrow A$  (a right inverse) such that  $F \circ H = I_B$  if and only if  $F$  maps  $A$  onto  $B$ .*

PROOF:

- $\langle 1 \rangle 1$ . If  $F$  has a right inverse then  $F$  is surjective.
  - $\langle 2 \rangle 1$ . ASSUME:  $F$  has a right inverse  $H : B \rightarrow A$ .
  - $\langle 2 \rangle 2$ . LET:  $y \in B$
  - $\langle 2 \rangle 3$ .  $F(H(y)) = y$
  - $\langle 2 \rangle 4$ . There exists  $x \in A$  such that  $F(x) = y$
- $\langle 1 \rangle 2$ . If  $F$  is surjective then  $F$  has a right inverse.
  - $\langle 2 \rangle 1$ . ASSUME:  $F$  is surjective.
  - $\langle 2 \rangle 2$ . PICK a function  $H$  such that  $H \subseteq F^{-1}$  and  $\text{dom } H = \text{dom } F^{-1} = B$
  - $\langle 2 \rangle 3$ .  $H : B \rightarrow A$
  - $\langle 2 \rangle 4$ .  $F \circ H = I_B$
  - $\langle 3 \rangle 1$ . LET:  $y \in B$
  - $\langle 3 \rangle 2$ .  $(y, H(y)) \in F^{-1}$
  - $\langle 3 \rangle 3$ .  $F(H(y)) = y$

□

**Definition 3.1.16** (Function Set). Given a set  $A$  and a class  $\mathbf{B}$ , we write  $\mathbf{B}^A$  for the class of all functions  $A \rightarrow \mathbf{B}$ .

**Proposition 3.1.17.** *If  $A$  and  $B$  are sets then  $A^B$  is a set.*

PROOF: It is a subset of  $\mathcal{P}(A \times B)$ . □



**Definition 3.1.18** (Natural Map). Let  $A$  be a set and  $R$  an equivalence relation on  $A$ . The *natural map*  $A \rightarrow A/R$  is the function that maps  $a \in A$  to  $[a]_R$ .

**Definition 3.1.19** (Respects). Let  $\mathbf{R}$  be an equivalence relation on  $\mathbf{A}$  and  $\mathbf{F} : \mathbf{A} \rightarrow \mathbf{B}$ . Then  $\mathbf{F}$  *respects*  $\mathbf{A}$  iff, whenever  $(x, y) \in \mathbf{R}$ , then  $\mathbf{F}(x) = \mathbf{F}(y)$ .

**Theorem 3.1.20.** Let  $A$  be a set and  $\mathbf{B}$  a class. Let  $R$  be an equivalence relation on  $A$  and  $F : A \rightarrow \mathbf{B}$ . Then  $F$  respects  $R$  if and only if there exists  $\hat{F} : A/R \rightarrow \mathbf{B}$  such that

$$\forall a \in A. \hat{F}([a]_R) = F(a) .$$

In this case,  $\hat{F}$  is unique.

PROOF:

- $\langle 1 \rangle 1$ . If  $F$  respects  $R$  then there exists  $\hat{F} : A/R \rightarrow \mathbf{B}$  such that  $\forall a \in A. \hat{F}([a]_R) = F(a)$ .
  - $\langle 2 \rangle 1$ . ASSUME:  $F$  respects  $R$ .
  - $\langle 2 \rangle 2$ . LET:  $\hat{F} = \{([a]_R, F(a)) \mid a \in A\}$
  - $\langle 2 \rangle 3$ .  $\hat{F}$  is a function.
    - $\langle 3 \rangle 1$ . ASSUME:  $a, a' \in A$  and  $[a]_R = [a']_R$   
PROVE:  $F(a) = F(a')$
    - $\langle 3 \rangle 2$ .  $(a, a') \in R$   
PROOF: Proposition 2.4.4.
    - $\langle 3 \rangle 3$ .  $F(a) = F(a')$   
PROOF:  $\langle 2 \rangle 1$
  - $\langle 2 \rangle 4$ .  $\text{dom } \hat{F} = A/R$
  - $\langle 2 \rangle 5$ .  $\text{ran } \hat{F} \subseteq \mathbf{B}$
  - $\langle 2 \rangle 6$ .  $\forall a \in A. \hat{F}([a]_R) = F(a)$
- $\langle 1 \rangle 2$ . If there exists  $\hat{F} : A/R \rightarrow \mathbf{B}$  such that  $\forall a \in A. \hat{F}([a]_R) = F(a)$  then  $F$  respects  $R$ .
  - $\langle 2 \rangle 1$ . ASSUME:  $\hat{F} : A/R \rightarrow \mathbf{B}$  and  $\forall a \in A. \hat{F}([a]_R) = F(a)$
  - $\langle 2 \rangle 2$ . LET:  $a, a' \in A$
  - $\langle 2 \rangle 3$ . ASSUME:  $(a, a') \in R$
  - $\langle 2 \rangle 4$ .  $[a]_R = [a']_R$   
PROOF: Proposition 2.4.4.
  - $\langle 2 \rangle 5$ .  $F(a) = F(a')$   
PROOF:  $\langle 2 \rangle 1$
- $\langle 1 \rangle 3$ . If  $G, H : A/R \rightarrow \mathbf{B}$  and  $\forall a \in A. G([a]_R) = H([a]_R)$  then  $G = H$ .  
 $\square$

**Definition 3.1.21** (Strictly Monotone). Let  $(A, <_A)$  and  $(B, <_B)$  be linearly ordered sets. A function  $f : A \rightarrow B$  is *strictly monotone* iff, whenever  $x <_A y$ , then  $f(x) <_B f(y)$ .

**Proposition 3.1.22.** A strictly monotone function is injective.

PROOF:

- $\langle 1 \rangle 1$ . LET:  $(A, <_A)$  and  $(B, <_B)$  be linearly ordered sets.

$\langle 1 \rangle 2$ . LET:  $f : A \rightarrow B$  be strictly monotone.

$\langle 1 \rangle 3$ . LET:  $x, y \in A$

$\langle 1 \rangle 4$ . ASSUME:  $f(x) = f(y)$

$\langle 1 \rangle 5$ .  $f(x) \not< f(y)$  and  $f(y) \not< f(x)$

PROOF: Trichotomy.

$\langle 1 \rangle 6$ .  $x \not< y$  and  $y \not< x$

$\langle 1 \rangle 7$ .  $x = y$

PROOF: Trichotomy.

□

**Proposition 3.1.23.** *Let  $A$  and  $B$  be linearly ordered sets. Let  $f : A \rightarrow B$ . Let  $x, y \in A$ . If  $f$  is strictly monotone and  $f(x) < f(y)$  then  $x < y$ .*

PROOF:

$\langle 1 \rangle 1$ .  $f(x) \neq f(y)$  and  $f(y) \not< f(x)$

PROOF: Trichotomy.

$\langle 1 \rangle 2$ .  $x \neq y$  and  $y \not< x$

$\langle 1 \rangle 3$ .  $x < y$

PROOF: Trichotomy.

□

**Definition 3.1.24** (Closed). Let  $\mathbf{F}$  be a function and  $\mathbf{A} \subseteq \text{dom } \mathbf{F}$ . Then  $\mathbf{A}$  is *closed* under  $\mathbf{F}$  iff  $\forall x \in \mathbf{A}. \mathbf{F}(x) \in \mathbf{A}$ .

**Definition 3.1.25** (Binary Operation). A *binary operation* on a set  $A$  is a function from  $A \times A$  into  $A$ .

## 3.2 Dependent Product Sets

**Definition 3.2.1.** Let  $I$  be a set and let  $\mathbf{H}(i)$  be a class for all  $i \in I$ . We write  $\prod_{i \in I} \mathbf{H}(i)$  for the class of all functions  $f$  with  $\text{dom } f = I$  and  $\forall i \in I. f(i) \in \mathbf{H}(i)$ .

**Proposition 3.2.2.** *If  $I$  is a set and  $H(i)$  is a set for all  $i \in I$ , then  $\prod_{i \in I} H(i)$  is a set.*

PROOF:

$\langle 1 \rangle 1$ .  $\{H(i) \mid i \in I\}$  is a set.

PROOF: Axiom of Replacement.

$\langle 1 \rangle 2$ .  $\prod_{i \in I} H(i) \subseteq \bigcup \{H(i) \mid i \in I\}^I$

□

**Proposition 3.2.3.** *Let  $I$  be a set. Let  $H(i)$  be a set for all  $i \in I$ . If  $\forall i \in I. H(i) \neq \emptyset$  then  $\prod_{i \in I} H(i) \neq \emptyset$ .*

PROOF:

$\langle 1 \rangle 1$ . ASSUME:  $\forall i \in I. H(i) \neq \emptyset$

$\langle 1 \rangle 2$ . LET:  $R = \{(i, x) \mid i \in I, x \in H(i)\}$

$\langle 1 \rangle 3$ . PICK a function  $f \subseteq R$  such that  $\text{dom } f = \text{dom } R$

$\langle 1 \rangle 4$ .  $f \in \prod_{i \in I} H(i)$

□

## Chapter 4

# Natural Numbers

### 4.1 Inductive Sets

**Definition 4.1.1** (Successor). The *successor* of a set  $a$  is the set  $a^+ := a \cup \{a\}$ .

**Proposition 4.1.2.** *A set  $a$  is a transitive set if and only if*

$$\bigcup(a^+) = a \text{ .}$$

PROOF:

$\langle 1 \rangle 1$ . If  $a$  is a transitive set then  $\bigcup(a^+) = a$ .

$\langle 2 \rangle 1$ . ASSUME:  $a$  is a transitive set.

$\langle 2 \rangle 2$ .  $\bigcup(a^+) \subseteq a$

$\langle 3 \rangle 1$ . LET:  $x \in \bigcup(a^+)$

PROVE:  $x \in a$

$\langle 3 \rangle 2$ . PICK  $y \in a^+$  such that  $x \in y$ .

$\langle 3 \rangle 3$ .  $y \in a$  or  $y = a$ .

$\langle 3 \rangle 4$ . CASE:  $y \in a$

PROOF: Then  $x \in a$  because  $a$  is a transitive set.

$\langle 3 \rangle 5$ . CASE:  $y = a$

PROOF: Then  $x \in a$  immediately.

$\langle 2 \rangle 3$ .  $a \subseteq \bigcup(a^+)$

PROOF: Since  $a \in a^+$ .

$\langle 1 \rangle 2$ . If  $\bigcup(a^+) = a$  then  $a$  is a transitive set.

$\langle 2 \rangle 1$ . ASSUME:  $\bigcup(a^+) = a$

$\langle 2 \rangle 2$ .  $\bigcup a \subseteq a$

PROOF:

$$\bigcup a \subseteq \bigcup(a^+) \quad (\text{Proposition 1.3.5})$$

$$= a$$

$(\langle 2 \rangle 1)$

$\langle 2 \rangle 3$ .  $a$  is a transitive set.

PROOF: Proposition 1.4.2.

□

**Proposition 4.1.3.** *For any set  $a$ , we have  $a$  is a transitive set if and only if  $a^+$  is a transitive set.*

PROOF:

$\langle 1 \rangle 1$ . If  $a$  is a transitive set then  $a^+$  is a transitive set.

PROOF: If  $a$  is a transitive set then  $\bigcup(a^+) = a \subseteq a^+$  by Proposition 4.1.2 and so  $a^+$  is a transitive set.

$\langle 1 \rangle 2$ . If  $a^+$  is a transitive set then  $a$  is a transitive set.

$\langle 2 \rangle 1$ . ASSUME:  $a^+$  is a transitive set.

$\langle 2 \rangle 2$ . LET:  $x \in y \in a$

$\langle 2 \rangle 3$ .  $x \in y \in a^+$

$\langle 2 \rangle 4$ .  $x \in a^+$

PROOF:  $\langle 2 \rangle 1$

$\langle 2 \rangle 5$ .  $x \neq a$

PROOF: From  $\langle 2 \rangle 2$  and the Axiom of Regularity.

$\langle 2 \rangle 6$ .  $x \in a$

□

**Definition 4.1.4.** We write 0 for  $\emptyset$ , 1 for  $\emptyset^+$ , 2 for  $\emptyset^{++}$ , etc.

**Definition 4.1.5** (Inductive). A set  $I$  is *inductive* iff  $\emptyset \in I$  and  $\forall x \in I. x^+ \in I$ .

**Definition 4.1.6** (Natural Number). A *natural number* is a set that belongs to every inductive set.

**Theorem 4.1.7.** *The class  $\mathbb{N}$  of natural numbers is a set.*

PROOF:

$\langle 1 \rangle 1$ . PICK an inductive set  $I$ .

PROOF: Axiom of Infinity.

$\langle 1 \rangle 2$ .  $\mathbb{N} \subseteq I$

□

**Theorem 4.1.8.**  *$\mathbb{N}$  is inductive, and is a subset of every other inductive set.*

PROOF:

$\langle 1 \rangle 1$ .  $\mathbb{N}$  is inductive.

$\langle 2 \rangle 1$ .  $0 \in \mathbb{N}$

PROOF: Since 0 is a member of every inductive set.

$\langle 2 \rangle 2$ .  $\forall n \in \mathbb{N}. n^+ \in \mathbb{N}$

$\langle 3 \rangle 1$ . LET:  $n \in \mathbb{N}$

$\langle 3 \rangle 2$ . LET:  $I$  be any inductive set.

PROVE:  $n^+ \in I$

$\langle 3 \rangle 3$ .  $n \in I$

PROOF:  $\langle 3 \rangle 1$ ,  $\langle 3 \rangle 2$

$\langle 3 \rangle 4$ .  $n^+ \in I$

PROOF:  $\langle 3 \rangle 2$ ,  $\langle 3 \rangle 3$

$\langle 1 \rangle 2$ .  $\mathbb{N}$  is a subset of every inductive set.

PROOF: Immediate from definitions.

□

**Corollary 4.1.8.1** (Induction Principle for  $\mathbb{N}$ ). *Any inductive subset of  $\mathbb{N}$  coincides with  $\mathbb{N}$ .*

**Theorem 4.1.9.** *Every natural number except 0 is the successor of some natural number.*

PROOF: Trivially by induction. □

**Proposition 4.1.10.** *Every natural number is a transitive set.*

PROOF:

⟨1⟩1. 0 is a transitive set.

PROOF: Vacuously, if  $x \in y \in 0$  then  $x \in 0$ .

⟨1⟩2. For every natural number  $n$ , if  $n$  is a transitive set then  $n^+$  is a transitive set.

PROOF: Proposition 4.1.3.

□

**Proposition 4.1.11.** *For natural numbers  $m$  and  $n$ , if  $m^+ = n^+$  then  $m = n$ .*

PROOF: If  $m^+ = n^+$  then

$$m = \bigcup (m^+) \quad (\text{Proposition 4.1.2})$$

$$= \bigcup (n^+)$$

$$= n \quad (\text{Proposition 4.1.2})$$

**Proposition 4.1.12.**  *$\mathbb{N}$  is a transitive set.*

PROOF:

⟨1⟩1.  $0 \subseteq \mathbb{N}$

⟨1⟩2.  $\forall n \in \mathbb{N}. n \subseteq \mathbb{N} \Rightarrow n^+ \subseteq \mathbb{N}$

⟨1⟩3.  $\forall n \in \mathbb{N}. n \subseteq \mathbb{N}$

PROOF: From ⟨1⟩1 and ⟨1⟩2 by induction.

□

## 4.2 Recursion

**Theorem 4.2.1** (Recursion Theorem on  $\mathbb{N}$ ). *Let  $A$  be a set,  $a \in A$ , and  $F : A \rightarrow A$ . Then there exists a unique function  $h : \mathbb{N} \rightarrow A$  such that*

$$h(0) = a ,$$

and for every  $n \in \mathbb{N}$ ,

$$h(n^+) = F(h(n)) .$$

PROOF:

⟨1⟩1. Define a function  $v$  to be *acceptable* iff  $\text{dom } v \subseteq \mathbb{N}$ ,  $\text{ran } v \subseteq A$ , and:

1. If  $0 \in \text{dom } v$  then  $v(0) = a$
  2. For all  $n \in \mathbb{N}$ , if  $n^+ \in \text{dom } v$ , then  $n \in \text{dom } v$  and  $v(n^+) = F(v(n))$ .
- $\langle 1 \rangle 2$ . LET:  $\mathcal{K}$  be the set of all acceptable functions.  
 PROOF: This is a set because it is a subset of  $\mathcal{P}(\mathbb{N} \times A)$ .
- $\langle 1 \rangle 3$ . LET:  $h = \bigcup \mathcal{K}$
- $\langle 1 \rangle 4$ . For all  $n$  and  $y$  we have  $(n, y) \in h$  iff there exists an acceptable  $v$  such that  $v(n) = y$ .
- $\langle 1 \rangle 5$ .  $h$  is a function.
- $\langle 2 \rangle 1$ . LET:  $P(n)$  be the predicate: there is at most one  $y$  such that  $(n, y) \in h$ .
- $\langle 2 \rangle 2$ .  $P(0)$   
 PROOF: If  $(0, y) \in h$  then  $y = a$ .
- $\langle 2 \rangle 3$ .  $\forall n \in \mathbb{N}. P(n) \Rightarrow P(n^+)$
- $\langle 3 \rangle 1$ . LET:  $n \in \mathbb{N}$
- $\langle 3 \rangle 2$ . ASSUME:  $P(n)$
- $\langle 3 \rangle 3$ . LET:  $(n^+, x), (n^+, y) \in h$
- $\langle 3 \rangle 4$ . PICK acceptable  $v_1, v_2$  such that  $v_1(n^+) = x$  and  $v_2(n^+) = y$
- $\langle 3 \rangle 5$ .  $F(v_1(n)) = x$  and  $F(v_2(n)) = y$
- $\langle 3 \rangle 6$ .  $v_1(n) = v_2(n)$   
 PROOF:  $\langle 3 \rangle 2$
- $\langle 3 \rangle 7$ .  $x = y$
- $\langle 2 \rangle 4$ .  $\forall n \in \mathbb{N}. P(n)$
- $\langle 1 \rangle 6$ .  $h$  is acceptable.
- $\langle 2 \rangle 1$ . If  $0 \in \text{dom } h$  then  $h(0) = a$
- $\langle 2 \rangle 2$ . For all  $n \in \mathbb{N}$ , if  $n^+ \in \text{dom } h$  then  $n \in \text{dom } h$  and  $h(n^+) = F(h(n))$
- $\langle 1 \rangle 7$ .  $\text{dom } h = \mathbb{N}$
- $\langle 2 \rangle 1$ .  $0 \in \text{dom } h$   
 PROOF: Since  $\{(0, a)\}$  is an acceptable function.
- $\langle 2 \rangle 2$ .  $\forall n \in \text{dom } h. n^+ \in \text{dom } h$
- $\langle 3 \rangle 1$ . LET:  $n \in \text{dom } h$
- $\langle 3 \rangle 2$ . PICK an acceptable  $v$  with  $n \in \text{dom } v$
- $\langle 3 \rangle 3$ . ASSUME: w.l.o.g.  $n^+ \notin \text{dom } v$
- $\langle 3 \rangle 4$ .  $v \cup \{(n^+, F(v(n)))\}$  is acceptable.
- $\langle 3 \rangle 5$ .  $n^+ \in \text{dom } h$
- $\langle 1 \rangle 8$ . For any function  $k : \mathbb{N} \rightarrow A$ , if  $k(0) = a$  and  $\forall n \in \mathbb{N}. k(n^+) = F(k(n))$  then  $k = h$ .  
 PROOF: Prove  $\forall n \in \mathbb{N}. k(n) = h(n)$  by induction on  $n$ .  
 $\square$

### 4.3 Arithmetic

**Definition 4.3.1** (Addition). *Addition*  $+$  is the binary operation on  $\mathbb{N}$  defined recursively by:

$$m + 0 = m$$

$$m + n^+ = (m + n)^+$$

**Theorem 4.3.2** (Associative Law for Addition). *For all  $m, n, p \in \mathbb{N}$ ,*

$$m + (n + p) = (m + n) + p$$

PROOF:

$\langle 1 \rangle 1.$   $\forall m, n \in \mathbb{N}. m + (n + 0) = (m + n) + 0$

PROOF:

$$\begin{aligned} m + (n + 0) &= m + n \\ &= (m + n) + 0 \end{aligned}$$

$\langle 1 \rangle 2.$  For any  $p \in \mathbb{N}$ , if  $\forall m, n \in \mathbb{N}. m + (n + p) = (m + n) + p$ , then  $\forall m, n \in \mathbb{N}. m + (n + p^+) = (m + n) + p^+$

PROOF:

$$\begin{aligned} m + (n + p^+) &= m + (n + p)^+ \\ &= (m + (n + p))^+ \\ &= ((m + n) + p)^+ \quad (\text{induction hypothesis}) \\ &= (m + n) + p^+ \end{aligned}$$

□

**Theorem 4.3.3** (Commutative Law for Addition). *For all  $m, n \in \mathbb{N}$ ,*

$$m + n = n + m$$

PROOF:

$\langle 1 \rangle 1.$   $\forall m \in \mathbb{N}. m + 0 = 0 + m$

$\langle 2 \rangle 1.$   $0 + 0 = 0 + 0$

$\langle 2 \rangle 2.$  For all  $m \in \mathbb{N}$ , if  $m + 0 = 0 + m$  then  $m^+ + 0 = 0 + m^+$

PROOF:

$$\begin{aligned} m^+ + 0 &= m^+ \\ &= (m + 0)^+ \\ &= (0 + m)^+ \quad (\text{induction hypothesis}) \\ &= 0 + m^+ \end{aligned}$$

$\langle 1 \rangle 2.$  For all  $m \in \mathbb{N}$ , if  $\forall n. m + n = n + m$  then  $\forall n. m^+ + n = n + m^+$

$\langle 2 \rangle 1.$  LET:  $m \in \mathbb{N}$

$\langle 2 \rangle 2.$  ASSUME:  $\forall n. m + n = n + m$

$\langle 2 \rangle 3.$   $m^+ + 0 = 0 + m^+$

PROOF:  $\langle 1 \rangle 1$

$\langle 2 \rangle 4.$  For all  $n \in \mathbb{N}$ , if  $m^+ + n = n + m^+$  then  $m^+ + n^+ = n^+ + m^+$

$\langle 3 \rangle 1.$  LET:  $n \in \mathbb{N}$

$\langle 3 \rangle 2.$  ASSUME:  $m^+ + n = n + m^+$

$\langle 3 \rangle 3.$   $m^+ + n^+ = n^+ + m^+$

PROOF:

$$\begin{aligned}
 m^+ + n^+ &= (m^+ + n)^+ \\
 &= (n + m^+)^+ && (\langle 3 \rangle 2) \\
 &= (n + m)^{++} \\
 &= (m + n)^{++} && (\langle 2 \rangle 2) \\
 &= (m + n^+)^+ \\
 &= (n^+ + m)^+ && (\langle 2 \rangle 2) \\
 &= n^+ + m^+
 \end{aligned}$$

□

**Definition 4.3.4** (Multiplication). *Multiplication*  $\cdot$  is the binary operation on  $\mathbb{N}$  defined recursively by:

$$\begin{aligned}
 m0 &= 0 \\
 mn^+ &= mn + m
 \end{aligned}$$

**Proposition 4.3.5.** *For any  $n \in \mathbb{N}$  we have  $n \cdot 1 = n$ .*

PROOF:

$$\begin{aligned}
 n \cdot 1 &= n0^+ \\
 &= n0 + n \\
 &= 0 + n \\
 &= n + 0 && (\text{Theorem 4.3.3}) \\
 &= n
 \end{aligned}$$

**Theorem 4.3.6** (Distributive Law). *For all  $m, n, p \in \mathbb{N}$ ,*

$$m(n + p) = mn + mp .$$

PROOF:

$\langle 1 \rangle 1.$   $\forall m, n \in \mathbb{N}. m(n + 0) = mn + m0$

PROOF:

$$\begin{aligned}
 m(n + 0) &= mn \\
 &= mn + 0 \\
 &= mn + m0
 \end{aligned}$$

$\langle 1 \rangle 2.$  For any  $p \in \mathbb{N}$ , if  $\forall m, n \in \mathbb{N}. m(n + p) = mn + mp$ , then  $\forall m, n \in \mathbb{N}. m(n + p^+) = mn + mp^+$

PROOF:

$$\begin{aligned}
 m(n + p^+) &= m(n + p)^+ \\
 &= m(n + p) + m \\
 &= (mn + mp) + m && (\text{induction hypothesis}) \\
 &= mn + (mp + m) && (\text{Theorem 4.3.2}) \\
 &= mn + mp^+
 \end{aligned}$$



□

**Theorem 4.3.7** (Associative Law for Multiplication). *For all  $m, n, p \in \mathbb{N}$ ,*

$$m(np) = (mn)p .$$

PROOF:

⟨1⟩1.  $\forall m, n \in \mathbb{N}. m(n0) = (mn)0$

PROOF:

$$\begin{aligned} m(n0) &= m0 \\ &= 0 \\ &= (mn)0 \end{aligned}$$

⟨1⟩2. For any  $p \in \mathbb{N}$ , if  $\forall m, n. m(np) = (mn)p$ , then  $\forall m, n. m(np^+) = (mn)p^+$

PROOF:

$$\begin{aligned} m(np^+) &= m(np + n) \\ &= m(np) + mn \\ &= (mn)p + mn && \text{(induction hypothesis)} \\ &= (mn)p^+ \end{aligned}$$

□

**Theorem 4.3.8** (Commutative Law for Multiplication). *For all  $m, n \in \mathbb{N}$ ,*

$$mn = nm .$$

PROOF:

⟨1⟩1.  $\forall m \in \mathbb{N}. m0 = 0m$

PROOF:

⟨2⟩1.  $0 \cdot 0 = 0 \cdot 0$

⟨2⟩2. For all  $m$ , if  $m0 = 0m$  then  $m^+0 = 0m^+$

PROOF:

$$\begin{aligned} 0m^+ &= 0m + 0 \\ &= 0m \\ &= m0 && \text{(induction hypothesis)} \\ &= 0 \\ &= m^+0 \end{aligned}$$

⟨1⟩2. For any  $n \in \mathbb{N}$ , if  $\forall m. mn = nm$  then  $\forall m. mn^+ = n^+m$

⟨2⟩1. LET:  $n \in \mathbb{N}$

⟨2⟩2. ASSUME:  $\forall m. mn = nm$

⟨2⟩3.  $0n^+ = n^+0$

PROOF: ⟨1⟩1

⟨2⟩4. For all  $m$ , if  $mn^+ = n^+m$  then  $m^+n^+ = n^+m^+$

PROOF:

⟨3⟩1. LET:  $m \in \mathbb{N}$

⟨3⟩2. ASSUME:  $mn^+ = n^+m$

⟨3⟩3.  $m^+n^+ = n^+m^+$

PROOF:

$$\begin{aligned}
m^+n^+ &= m^+n + m^+ \\
&= (m^+n + m)^+ \\
&= (nm^+ + m)^+ && (\langle 2 \rangle 2) \\
&= (nm + n + m)^+ \\
&= (mn + n + m)^+ && (\langle 2 \rangle 2) \\
&= (mn + m + n)^+ && (\text{Theorems 4.3.2, 4.3.3}) \\
&= (mn^+ + n)^+ \\
&= mn^+ + n^+ \\
&= n^+m + n^+ && (\langle 3 \rangle 2) \\
&= n^+m^+
\end{aligned}$$

□

**Proposition 4.3.9.** *For natural numbers  $m$  and  $n$ , if  $mn = 0$  then  $m = 0$  or  $n = 0$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $m, n \in \mathbb{N}$

$\langle 1 \rangle 2$ . ASSUME:  $m \neq 0$  and  $n \neq 0$

$\langle 1 \rangle 3$ . PICK  $p, q \in \mathbb{N}$  such that  $m = p^+$  and  $n = q^+$

PROOF: Theorem 4.1.9.

$\langle 1 \rangle 4$ .  $mn = (p^+q + p)^+$

PROOF:

$$\begin{aligned}
mn &= p^+q^+ && (\langle 1 \rangle 3) \\
&= p^+q + p^+ \\
&= (p^+q + p)^+
\end{aligned}$$

$\langle 1 \rangle 5$ .  $mn \neq 0$

□

**Definition 4.3.10** (Even). A natural number  $n$  is *even* iff there exists  $m \in \mathbb{N}$  such that  $n = 2m$ .

**Definition 4.3.11** (Odd). A natural number  $n$  is *odd* iff there exists  $p \in \mathbb{N}$  such that  $n = 2p + 1$ .

**Proposition 4.3.12** (Division Algorithm). *Let  $m$  be a natural number and  $d$  a nonzero natural number. Then there exist natural numbers  $q$  and  $r$  such that  $m = dq + r$  and  $r < d$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $d$  be a nonzero natural number.

$\langle 1 \rangle 2$ .  $\exists q, r. 0 = dq + r \wedge r < d$

PROOF: Take  $q = r = 0$ .

$\langle 1 \rangle 3$ . For any natural number  $m$ , if  $\exists q, r. m = dq + r \wedge r < d$  then  $\exists q, r. m^+ = dq + r \wedge r < d$

- ⟨2⟩1. LET:  $m$  be a natural number.
- ⟨2⟩2. ASSUME:  $m = dq + r$  and  $r < d$
- ⟨2⟩3.  $r^+ \leq d$
- ⟨2⟩4. CASE:  $r^+ < d$   
 PROOF: In this case we have  $m^+ = dq + r^+$ .
- ⟨2⟩5. CASE:  $r^+ = d$   
 PROOF: In this case we have  $m^+ = dq^+ + 0$ .

□

**Proposition 4.3.13.** *Every natural number is either even or odd.*

PROOF:

- ⟨1⟩1. 0 is even.  
 PROOF:  $0 = 2 \times 0$ .
- ⟨1⟩2. For any natural number  $n$ , if  $n$  is either even or odd then  $n^+$  is either even or odd.  
 PROOF:  
 ⟨2⟩1. LET:  $n \in \mathbb{N}$   
 ⟨2⟩2. If  $n$  is even then  $n^+$  is odd.  
 PROOF: If  $n = 2p$  then  $n^+ = 2p + 1$ .  
 ⟨2⟩3. If  $n$  is odd then  $n^+$  is even.  
 PROOF: If  $n = 2p + 1$  then  $n^+ = 2(p + 1)$ .

□

**Proposition 4.3.14.** *No natural number is both even and odd.*

PROOF:

- ⟨1⟩1. 0 is not odd.  
 PROOF: For any  $p$  we have  $2p + 1 = (2p)^+ \neq 0$ .
- ⟨1⟩2. For any natural number  $n$ , if  $n$  is not both even and odd, then  $n^+$  is not both even and odd.  
 ⟨2⟩1. LET:  $n$  be a natural number.  
 ⟨2⟩2. If  $n^+$  is even then  $n$  is odd.  
 ⟨3⟩1. ASSUME:  $n^+$  is even.  
 ⟨3⟩2. PICK  $p$  such that  $n^+ = 2p$   
 ⟨3⟩3.  $p \neq 0$   
 PROOF: Since  $n^+ \neq 0$ .  
 ⟨3⟩4. PICK  $q$  such that  $p = q^+$   
 PROOF: Theorem 4.1.9.  
 ⟨3⟩5.  $n^+ = 2q + 2$   
 PROOF: ⟨3⟩2, ⟨3⟩4.  
 ⟨3⟩6.  $n = 2q + 1$   
 PROOF: Proposition 4.1.11, ⟨3⟩5  
 ⟨3⟩7.  $n$  is odd.  
 ⟨2⟩3. If  $n^+$  is odd then  $n$  is even.  
 ⟨3⟩1. ASSUME:  $n^+$  is odd.  
 ⟨3⟩2. PICK  $p$  such that  $n^+ = 2p + 1$

⟨3⟩3.  $n = 2p$

PROOF: Proposition 4.1.11, ⟨3⟩2

⟨3⟩4.  $n$  is even.

□

**Definition 4.3.15** (Exponentiation). *Exponentiation* is the binary operation on  $\mathbb{N}$  defined recursively by:

$$\begin{aligned} m^0 &= 1 \\ m^{n^+} &= m^n m \end{aligned}$$

**Proposition 4.3.16.** For all  $m, n, p \in \mathbb{N}$ ,

$$m^{n+p} = m^n m^p$$

PROOF:

⟨1⟩1.  $\forall m, n. m^{n+0} = m^n m^0$

PROOF:

$$\begin{aligned} m^{n+0} &= m^n \\ &= m^n \cdot 1 && \text{(Proposition 4.3.5)} \\ &= m^n m^0 \end{aligned}$$

⟨1⟩2. For any  $p \in \mathbb{N}$ , if  $\forall m, n. m^{n+p} = m^n m^p$  then  $\forall m, n. m^{n+p^+} = m^n m^{p^+}$ .

PROOF:

$$\begin{aligned} m^{n+p^+} &= m^{(n+p)^+} \\ &= m^{n+p} m && \text{(induction hypothesis)} \\ &= (m^n m^p) m && \text{(Theorem 4.3.7)} \\ &= m^n (m^p m) \\ &= m^n m^{p^+} \end{aligned}$$

□

## 4.4 Ordering on $\mathbb{N}$

**Definition 4.4.1.** Given natural numbers  $m$  and  $n$ , we write  $m < n$  iff  $m \in n$ . We write  $m \leq n$  iff  $m < n$  or  $m = n$ .

**Proposition 4.4.2.** For any natural numbers  $m$  and  $n$ , we have  $m < n$  if and only if  $m^+ < n^+$ .

PROOF:

⟨1⟩1. For any natural numbers  $m$  and  $n$ , if  $m < n$  then  $m^+ < n^+$ .

⟨2⟩1. For any natural number  $m$ , if  $m < 0$  then  $m^+ < 0^+$

PROOF: Vacuous.

⟨2⟩2. For any natural number  $n$ , if  $\forall m < n. m^+ < n^+$  then  $\forall m < n^+. m^+ < n^{++}$

- (3)1. LET:  $m < n^+$
  - (3)2.  $m < n$  or  $m = n$
  - (3)3. CASE:  $m < n$ 
    - (4)1.  $m^+ < n^+$
  - PROOF: Induction hypothesis.
  - (4)2.  $m^+ < n^{++}$
  - (3)4. CASE:  $m = n$
  - PROOF:  $m^+ = n^+ < n^{++}$ .
- (1)2. For any natural numbers  $m$  and  $n$ , if  $m^+ < n^+$  then  $m < n$ .
  - (2)1. We never have  $m^+ < 0^+$ .
    - (3)1.  $m^+ \not< 0$
    - (3)2.  $m^+ \neq 0$
    - (3)3.  $m^+ \not< 0^+$
  - (2)2. For any natural number  $n$ , if  $\forall m.m^+ < n^+ \Rightarrow m < n$ , then  $\forall m.m^+ < n^{++} \Rightarrow m < n^+$ .
    - (3)1. LET:  $n$  be a natural number.
    - (3)2. ASSUME:  $\forall m.m^+ < n^+ \Rightarrow m < n$
    - (3)3. LET:  $m$  be a natural number.
    - (3)4. ASSUME:  $m^+ < n^{++}$
    - (3)5.  $m^+ < n^+$  or  $m^+ = n^+$
    - (3)6. CASE:  $m^+ < n^+$ 
      - (4)1.  $m < n$
    - PROOF: Induction hypothesis.
    - (4)2.  $m < n^+$
    - (3)7. CASE:  $m^+ = n^+$
    - PROOF:  $m = n < n^+$  by Proposition 4.1.11.

**Theorem 4.4.3** (Trichotomy Law for  $\mathbb{N}$ ). *For any natural numbers  $m$  and  $n$ , exactly one of  $m < n$ ,  $n < m$ ,  $m = n$  holds.*

PROOF:

- (1)1. For all  $m$  and  $n$ , at most one of  $m < n$ ,  $n < m$ ,  $m = n$  holds.
- (2)1. We do not have  $m < n$  and  $m = n$ .  
PROOF: This would imply  $n < n$  contradicting the Axiom of Regularity.
- (2)2. We do not have  $m < n$  and  $n < m$ .  
PROOF: This would imply  $n < n$  by Proposition 4.1.10, contradicting the Axiom of Regularity.
- (1)2. For all  $m$  and  $n$ , either  $m < n$  or  $n < m$  or  $m = n$ .
- (2)1. For all  $m$ , either  $m = 0$  or  $0 < m$ .
- (3)1.  $0 = 0$
- (3)2. For any natural number  $m$ , we have  $0 < m^+$ .
- (4)1.  $0 < 0^+$
- (4)2. For any natural number  $m$ , if  $0 < m^+$  then  $0 < m^{++}$ .
- (2)2. For any natural number  $n$ , if  $\forall m(m < n \vee n < m \vee m = n)$  then  $\forall m(m < n^+ \vee n^+ < m \vee m = n^+)$ .
- (3)1. LET:  $n$  be a natural number.

- ⟨3⟩2. ASSUME:  $\forall m(m < n \vee n < m \vee m = n)$
- ⟨3⟩3. LET:  $m$  be a natural number.
- ⟨3⟩4. CASE:  $m < n$   
PROOF: Then  $m < n^+$ .
- ⟨3⟩5. CASE:  $n < m$ 
  - ⟨4⟩1.  $m \neq 0$
  - ⟨4⟩2. PICK  $p$  such that  $m = p^+$
  - ⟨4⟩3.  $n < p$  or  $n = p$
  - ⟨4⟩4. CASE:  $n < p$   
PROOF: Then  $n^+ < p^+ = m$  by Proposition 4.4.2.
  - ⟨4⟩5. CASE:  $n = p$   
PROOF: Then  $n^+ = p^+ = m$ .
- ⟨3⟩6. CASE:  $m = n$   
PROOF: Then  $m < n^+$ .

□

**Corollary 4.4.3.1.** *For natural numbers  $m$  and  $n$ , we have  $m \leq n$  if and only if  $m \subseteq n$ .*

PROOF:

- ⟨1⟩1. If  $m \leq n$  then  $m \subseteq n$ 
  - ⟨2⟩1. ASSUME:  $m \leq n$
  - ⟨2⟩2. LET:  $p \in m$
  - ⟨2⟩3. CASE:  $m < n$   
PROOF: Then  $p \in n$  by Proposition 4.1.10.
  - ⟨2⟩4. CASE:  $m = n$   
PROOF: Then  $p \in n$  immediately.
- ⟨1⟩2. If  $m \subseteq n$  then  $m \leq n$ 
  - ⟨2⟩1. ASSUME:  $m \subseteq n$
  - ⟨2⟩2.  $n \not\subset m$   
PROOF: If  $n < m$  then  $n \in n$  contradicting the Axiom of Regularity.
  - ⟨2⟩3.  $m \leq n$   
PROOF: By trichotomy.

□

**Theorem 4.4.4** (Well-Ordering of  $\mathbb{N}$ ). *Every nonempty subset of  $\mathbb{N}$  has a least element.*

PROOF:

- ⟨1⟩1. LET:  $A \subseteq \mathbb{N}$
- ⟨1⟩2. ASSUME:  $A$  has no least element.  
PROVE:  $A = \emptyset$
- ⟨1⟩3.  $\forall n. \forall m < n. m \notin A$ 
  - ⟨2⟩1.  $\forall m < 0. m \notin A$   
PROOF: Vacuous.
  - ⟨2⟩2. For any natural number  $n$ , if  $\forall m < n. m \notin A$ , then  $\forall m < n^+. m \notin A$ .
    - ⟨3⟩1. LET:  $n$  be a natural number.

$\langle 3 \rangle 2$ . ASSUME:  $\forall m < n. m \notin A$

$\langle 3 \rangle 3$ .  $n \notin A$

PROOF: If  $n \in A$  then  $n$  is the least element in  $A$ .

$\langle 3 \rangle 4$ .  $\forall m < n^+. m \notin A$

$\langle 1 \rangle 4$ .  $A = \emptyset$

□

**Corollary 4.4.4.1.** *There is no function  $f : \mathbb{N} \rightarrow \mathbb{N}$  such that  $\forall n \in \mathbb{N}. f(n+1) < f(n)$ .*

**Theorem 4.4.5** (Strong Induction Principle for  $\mathbb{N}$ ). *Let  $A \subseteq \mathbb{N}$ . Assume that, for every  $n \in \mathbb{N}$ , if  $\forall m < n. m \in A$  then  $n \in A$ . Then  $A = \mathbb{N}$ .*

PROOF:

$\langle 1 \rangle 1$ . ASSUME: for a contradiction  $A \neq \mathbb{N}$

$\langle 1 \rangle 2$ . LET:  $n$  be the least element of  $\mathbb{N} - A$

PROOF: Since  $\mathbb{N}$  is well ordered.

$\langle 1 \rangle 3$ .  $\forall m < n. m \in A$

$\langle 1 \rangle 4$ .  $n \notin A$

$\langle 1 \rangle 5$ . Q.E.D.

PROOF: This contradicts the hypothesis of the theorem.

□

**Proposition 4.4.6.** *For any natural numbers  $m$  and  $n$ , we have  $m < n$  if and only if there exists  $p \in \mathbb{N}$  such that  $n = m + p^+$ .*

PROOF:

$\langle 1 \rangle 1$ . For any natural numbers  $m$  and  $p$  we have  $m < m + p^+$ .

$\langle 2 \rangle 1$ .  $\forall m. m < m + 0^+$

PROOF: Since  $m \in m^+ = m + 0^+$ .

$\langle 2 \rangle 2$ . For any natural number  $p$ , if  $\forall m. m < m + p^+$  then  $\forall m. m < m + p^{++}$

PROOF: If  $m \in m + p^+$  then  $m \in (m + p^+)^+ = m + p^{++}$ .

$\langle 1 \rangle 2$ . For any natural numbers  $m$  and  $n$ , if  $m < n$  then there exists  $p$  such that  $n = m + p^+$ .

$\langle 2 \rangle 1$ .  $\forall m < 0. \exists p. 0 = m + p^+$

PROOF: Vacuous.

$\langle 2 \rangle 2$ . For any natural number  $n$ , if  $\forall m < n. \exists p. n = m + p^+$ , then  $\forall m < n^+. \exists p. n^+ = m + p^+$ .

$\langle 3 \rangle 1$ . LET:  $n$  be a natural number.

$\langle 3 \rangle 2$ . ASSUME:  $\forall m < n. \exists p. n = m + p^+$

$\langle 3 \rangle 3$ . LET:  $m < n^+$

$\langle 3 \rangle 4$ .  $m < n$  or  $m = n$

$\langle 3 \rangle 5$ . CASE:  $m < n$

$\langle 4 \rangle 1$ . PICK  $p$  such that  $n = m + p^+$

$\langle 4 \rangle 2$ .  $n^+ = m + p^{++}$

$\langle 3 \rangle 6$ . CASE:  $m = n$

PROOF: Then  $n^+ = m + 0^+$ .

□

**Theorem 4.4.7.** *For natural numbers  $m$ ,  $n$  and  $p$ , we have  $m < n$  iff  $m + p < n + p$ .*

PROOF:

$\langle 1 \rangle 1.$   $\forall m, n. m < n \Leftrightarrow p + 0 < n + 0$

$\langle 1 \rangle 2.$  For any natural number  $p$ , if  $\forall m, n. m < n \Leftrightarrow m + p < n + p$  then  $\forall m, n. m < n \Leftrightarrow m + p^+ < n + p^+$

PROOF: Proposition 4.4.2.

□

**Corollary 4.4.7.1.** *For natural numbers  $m$ ,  $n$  and  $p$ , if  $m + p = n + p$  then  $m = n$ .*

PROOF: By trichotomy. □

**Theorem 4.4.8.** *For natural numbers  $m$ ,  $n$  and  $p$ , if  $m < n$  and  $p \neq 0$  then  $mp < np$ .*

PROOF:

$\langle 1 \rangle 1.$  LET:  $m$  and  $n$  be natural numbers.

$\langle 1 \rangle 2.$  ASSUME:  $m < n$

PROVE:  $\forall p. mp^+ < np^+$

$\langle 1 \rangle 3.$   $m0^+ < n0^+$

PROOF: Proposition 4.3.5.

$\langle 1 \rangle 4.$  For any natural number  $p$ , if  $mp < np$  then  $mp^+ < np^+$

PROOF:

$$mp^+ = mp + m$$

$$< np + m$$

(induction hypothesis. Theorem 4.4.7)

$$< np + n$$

( $\langle 1 \rangle 2$ , Theorem 4.4.7)

$$= np^+$$

□

**Corollary 4.4.8.1.** *For natural numbers  $m$ ,  $n$  and  $p$ , if  $p \neq 0$  then  $m < n$  if and only if  $mp < np$ .*

PROOF: Proposition 3.1.23. □

**Corollary 4.4.8.2.** *For natural numbers  $m$ ,  $n$  and  $p$ , if  $mp = np$  and  $p \neq 0$  then  $m = n$ .*

PROOF: By trichotomy. □

**Proposition 4.4.9.** *Let  $m$ ,  $n$ ,  $p$ ,  $q$  be natural numbers. Assume  $m + n = p + q$ . Then  $m < p$  if and only if  $q < n$ .*

PROOF:

$\langle 1 \rangle 1.$  If  $m < p$  then  $q < n$ .

PROOF: If  $m < p$  and  $n \leq q$  then  $m + n < p + q$ .

$\langle 1 \rangle 2.$  If  $q < n$  then  $m < p$ .



PROOF: Similar.

□

**Proposition 4.4.10.** *Let  $m, n, p$  and  $q$  be natural numbers. Assume  $n < m$  and  $q < p$ . Then*

$$mq + np < mp + nq .$$

PROOF:

⟨1⟩1. PICK positive natural numbers  $a$  and  $b$  such that  $m = n + a$  and  $p = q + b$ .

⟨1⟩2.  $mp + nq > mq + np$

PROOF:

$$\begin{aligned} mp + nq &= (n + a)(q + b) + nq \\ &= 2nq + nb + aq + ab \\ mq + np &= (n + a)q + n(q + b) \\ &= 2nq + aq + nb \\ \therefore mp + nq &= mq + np + ab \\ &> mq + np \end{aligned}$$

□

## 4.5 Cardinality

**Definition 4.5.1.** Let  $A$  be a set and  $n \in \mathbb{N}$ . We say that  $A$  has  $n$  elements iff there exists a bijection between  $A$  and  $n$ .

**Proposition 4.5.2.** *If  $A$  has  $m$  elements,  $B$  has  $n$  elements, and  $A \cap B = \emptyset$ , then  $A \cup B$  has  $m + n$  elements.*

PROOF:

⟨1⟩1. LET:  $P(n)$  be the property: For any natural number  $m$  and sets  $A$  and  $B$ , if  $A$  has  $m$  elements,  $B$  has  $n$  elements, and  $A \cap B = \emptyset$ , then  $A \cup B$  has  $m + n$  elements.

⟨1⟩2.  $P(0)$

⟨2⟩1. LET:  $A$  have  $m$  elements,  $B$  have 0 elements, and  $A \cap B = \emptyset$

⟨2⟩2.  $B = \emptyset$

⟨2⟩3.  $A \cup B = A$

⟨2⟩4.  $A \cup B$  has  $m$  elements.

⟨1⟩3.  $\forall n. P(n) \rightarrow P(n + 1)$

⟨2⟩1. ASSUME:  $P(n)$

⟨2⟩2. LET:  $A$  have  $m$  elements,  $B$  have  $n + 1$  elements, and  $A \cap B = \emptyset$

⟨2⟩3. PICK  $b \in B$

⟨2⟩4.  $B - \{b\}$  has  $n$  elements.

⟨2⟩5.  $A \cup B - \{b\}$  has  $m + n$  elements.

⟨2⟩6.  $A \cup B$  has  $m + n + 1$  elements.

⟨1⟩4.  $\forall n P(n)$

□

**Proposition 4.5.3.** *If  $A$  has  $m$  elements and  $B$  has  $n$  elements then  $A \times B$  has  $mn$  elements.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $P(n)$  be the property: for any natural number  $m$  and sets  $A$  and  $B$ , if  $A$  has  $m$  elements and  $B$  has  $n$  elements then  $A \times B$  has  $mn$  elements.

$\langle 1 \rangle 2$ .  $P(0)$

$\langle 2 \rangle 1$ . LET:  $A$  have  $m$  elements and  $B$  have 0 elements.

$\langle 2 \rangle 2$ .  $B = \emptyset$

$\langle 2 \rangle 3$ .  $A \times B = \emptyset$

$\langle 2 \rangle 4$ .  $A \times B$  has 0 elements.

$\langle 1 \rangle 3$ .  $\forall n. P(n) \rightarrow P(n+1)$

$\langle 2 \rangle 1$ . ASSUME:  $P(n)$

$\langle 2 \rangle 2$ . LET:  $A$  have  $m$  elements and  $B$  have  $n+1$  elements.

$\langle 2 \rangle 3$ . PICK  $b \in B$

$\langle 2 \rangle 4$ .  $B - \{b\}$  has  $n$  elements.

$\langle 2 \rangle 5$ .  $A \times (B - \{b\})$  has  $mn$  elements.

$\langle 2 \rangle 6$ .  $A \times B = (A \times (B - \{b\})) \cup (A \times \{b\})$

$\langle 2 \rangle 7$ .  $A \times \{b\}$  has  $m$  elements.

PROOF: It is bijective with  $A$ .

$\langle 2 \rangle 8$ .  $A \times B$  has  $mn + m$  elements.

PROOF: Proposition 4.5.2.

$\langle 1 \rangle 4$ .  $\forall n P(n)$

□

## Chapter 5

# Number Systems

### 5.1 The Integers

**Definition 5.1.1.** The set of *integers*  $\mathbb{Z}$  is the quotient set  $\mathbb{N}^2 / \sim$ , where  $(m, n) \sim (p, q)$  iff  $m + q = n + p$ .

We prove  $\sim$  is an equivalence relation on  $\mathbb{N}^2$ .

PROOF:

$\langle 1 \rangle 1.$   $\sim$  is reflexive.

PROOF: For all  $m, n \in \mathbb{N}$  we have  $m + n = n + m$ .

$\langle 1 \rangle 2.$   $\sim$  is symmetric.

PROOF: If  $m + q = n + p$  then  $p + n = q + m$ .

$\langle 1 \rangle 3.$   $\sim$  is transitive.

$\langle 2 \rangle 1.$  ASSUME:  $(m, n) \sim (p, q) \sim (r, s)$

$\langle 2 \rangle 2.$   $m + q = n + p$  and  $p + s = q + r$

$\langle 2 \rangle 3.$   $m + q + s = n + q + r$

$\langle 2 \rangle 4.$   $m + s = n + r$

PROOF: Corollary 4.4.7.1.

□

**Definition 5.1.2** (Addition). Define *addition*  $+$  on  $\mathbb{Z}$  by  $[(m, n)] + [(p, q)] = [(m + p, n + q)]$ .

We prove this is well-defined.

PROOF: If  $m + n' = n + m'$  and  $p + q' = q + p'$  then  $m + p + n' + q' = n + q + m' + p'$ .

□

**Proposition 5.1.3.** *Addition on  $\mathbb{Z}$  is commutative.*

PROOF:  $[(m, n)] + [(p, q)] = [(m + p, n + q)] = [(p + m, q + n)] = [(p, q)] + [(m, n)]$ .

□

**Proposition 5.1.4.** *Addition on  $\mathbb{Z}$  is associative.*

PROOF:  $[(m, n)] + [(p, q)] + [(r, s)] = [(m + p + r, n + q + s)] = [(m, n)] + [(p, q)] + [(r, s)]$ .  $\square$

**Proposition 5.1.5.** *Given natural numbers  $m$  and  $n$ , we have  $[(m, 0)] = [(n, 0)]$  iff  $m = n$ .*

PROOF: Immediate from definitions.  $\square$

**Definition 5.1.6.** We identify any natural number  $n$  with the integer  $[(n, 0)]$ .

**Proposition 5.1.7.** *Addition on integers agrees with addition on natural numbers.*

PROOF: Since  $[(m, 0)] + [(n, 0)] = [(m + n, 0)]$ .  $\square$

**Proposition 5.1.8.** *For all  $a \in \mathbb{Z}$  we have  $a + 0 = a$ .*

PROOF:  $[(m, n)] + [(0, 0)] = [(m + 0, n + 0)] = [(m, n)]$ .  $\square$

**Proposition 5.1.9.** *For all  $a \in \mathbb{Z}$ , there exists  $b \in \mathbb{Z}$  such that  $a + b = 0$ .*

PROOF:  $[(m, n)] + [(n, m)] = [(m + n, m + n)] = [(0, 0)]$   $\square$

**Definition 5.1.10.** Define multiplication  $\cdot$  on  $\mathbb{Z}$  by:  $[(m, n)][(p, q)] = [(mp + nq, mq + np)]$ .

We prove this is well defined.

PROOF:

$\langle 1 \rangle 1$ . ASSUME:  $m + n' = n + m'$  and  $p + q' = q + p'$

PROVE:  $mp + nq + m'q' + n'p' = mq + np + m'p' + n'q'$

$\langle 1 \rangle 2$ .  $mp + n'p = np + m'p$

$\langle 1 \rangle 3$ .  $nq + m'q = mq + n'q$

$\langle 1 \rangle 4$ .  $m'p + m'q' = m'q + m'p'$

$\langle 1 \rangle 5$ .  $n'q + n'p' = n'p + n'q'$

$\langle 1 \rangle 6$ .  $mp + n'p + nq + m'q + m'p + m'q' + n'q + n'p' = np + m'p + mq + n'q + m'q + m'p' + n'p + n'q'$

$\langle 1 \rangle 7$ .  $mp + nq + m'q' + n'p' = mq + np + m'p' + n'q'$

PROOF: Corollary 4.4.7.1.

$\square$

**Proposition 5.1.11.** *Multiplication on integers agrees with multiplication on natural numbers.*

PROOF: Since  $[(m, 0)][(n, 0)] = [(mn + 0, m0 + n0)] = [(mn, 0)]$ .  $\square$

**Proposition 5.1.12.** *Multiplication on  $\mathbb{Z}$  is commutative.*

PROOF:  $[(m, n)][(p, q)] = [(mp + nq, mq + np)] = [(pm + qn, pn + qm)] = [(p, q)][(m, n)]$ .  $\square$

**Proposition 5.1.13.** *Multiplication on  $\mathbb{Z}$  is associative.*

PROOF:

$$\begin{aligned}
 [(m, n)][(p, q)][(r, s)] &= [(m, n)][(pr + qs, ps + qr)] \\
 &= [(mpr + mqs + nps + nqr, mps + mqr + npr + nqs)] \\
 &= [(mp + nq, mq + np)][(r, s)] \\
 &= ([ (m, n) ] [ (p, q) ] ) [ (r, s) ] \quad \square
 \end{aligned}$$

**Proposition 5.1.14.** *Multiplication distributes over addition.*

PROOF:

$$\begin{aligned}
 [(m, n)]([(p, q)] + [(r, s)]) &= [(m, n)][(p + r, q + s)] \\
 &= [(mp + mr + nq + ns, np + nr + mq + ms)] \\
 [(m, n)][(p, q)] + [(m, n)][(r, s)] &= [(mp + nq, mq + np)] + [(mr + ns, ms + nr)] \\
 &= [(mp + nq + mr + ns, mq + np + ms + nr)] \quad \square
 \end{aligned}$$

**Proposition 5.1.15.** *For any integer  $a$  we have  $a1 = a$ .*

PROOF: Since  $[(m, n)][(1, 0)] = [(m1 + n0, m0 + n1)] = [(m, n)]$ .  $\square$



## Chapter 6

# Group Theory

### 6.1 Abelian Groups

**Definition 6.1.1** (Abelian group). An *Abelian group*  $G$  consists of a set  $G$  and a function  $\cdot : G^2 \rightarrow G$  such that:

1.  $\cdot$  is associative
2.  $\cdot$  is commutative
3. There exists  $e \in G$  such that  $\forall x \in G. xe = x$  and  $\forall x \in G. \exists y \in G. xy = e$ .

**Proposition 6.1.2.** *The integers form an Abelian group under addition.*

PROOF: Proposition 5.1.3, 5.1.4, 5.1.7, 5.1.8.  $\square$

**Proposition 6.1.3.** *The inverse of an element in an Abelian group is unique.*

PROOF:

$\langle 1 \rangle$ 1. ASSUME:  $b$  and  $b'$  are inverses of  $a$ .

$\langle 1 \rangle$ 2.  $b = b'$

PROOF:

$$\begin{aligned} b &= be \\ &= bab' \\ &= eb' \\ &= b' \end{aligned}$$

$\square$

**Definition 6.1.4.** Given an integer  $a$ , we write  $-a$  for the inverse of  $a$  under addition. We write  $b - a$  for  $b + (-a)$ .





## Chapter 7

# Complex Analysis

**Definition 7.0.1.** For  $p \geq 1$ , let  $l^p$  be the set of all sequences of complex numbers  $(x_n)$  such that  $\sum_{n=1}^{\infty} |x_n|^p < \infty$ .

**Proposition 7.0.2.** If  $(x_n), (y_n) \in l^p$  then  $(x_n + y_n) \in l^p$ .

PROOF:

$\langle 1 \rangle 1$ . LET:  $(x_n), (y_n) \in l^p$

$\langle 1 \rangle 2$ .  $\sum_{n=1}^{\infty} |x_n + y_n|^p \leq 2^p (\sum_{n=1}^{\infty} |x_n|^p + \sum_{n=1}^{\infty} |y_n|^p)$

PROOF:

$\langle 2 \rangle 1$ . For all  $n \in \mathbb{N}$  we have  $|x_n + y_n|^p \leq 2^p (|x_n|^p + |y_n|^p)$ .

PROOF:

$$\begin{aligned} |x_n + y_n|^p &\leq (|x_n| + |y_n|)^p && \text{(Triangle Inequality)} \\ &\leq (2 \max(|x_n|, |y_n|))^p \\ &\leq 2^p (|x_n|^p + |y_n|^p) \end{aligned}$$

□

**Theorem 7.0.3** (Hölder's Inequality). Let  $p$  and  $q$  be reals such that  $p > 1$ ,  $q > 1$  and  $1/p + 1/q = 1$ . Let  $(x_n) \in l^p$  and  $(y_n) \in l^q$ . Then

$$\sum_n |x_n y_n| \leq \left( \sum_n |x_n|^p \right)^{1/p} \left( \sum_n |y_n|^q \right)^{1/q}$$

PROOF:

$\langle 1 \rangle 1$ . ASSUME: w.l.o.g. neither  $(x_n)$  nor  $(y_n)$  are all zero.

$\langle 1 \rangle 2$ . For  $0 \leq x \leq 1$  we have

$$x^{1/p} \leq \frac{1}{p}x + \frac{1}{q}.$$

$\langle 2 \rangle 1$ . LET:  $f(x) = x/p + 1/q - x^{1/p}$

$\langle 2 \rangle 2$ .  $f'(x) = 1/p(1 - x^{(1-p)/p})$

$\langle 2 \rangle 3$ .  $f'(x) \geq 0$  for all  $x \in [0, 1]$

$\langle 2 \rangle 4$ .  $f$  is a monotonically decreasing function on  $[0, 1]$

- ⟨2⟩5.  $f(0) = 1/q$   
 ⟨2⟩6.  $f(1) = 0$   
 ⟨2⟩7.  $f(x) \geq 0$  for all  $x \in [0, 1]$   
 ⟨1⟩3. For any  $a, b \geq 0$  we have

$$ab \leq \frac{a^p}{p} + \frac{b^q}{q}.$$

- ⟨2⟩1. CASE:  $a^p \leq b^q$   
 ⟨3⟩1.  $ab^{-q/p} \leq \frac{1}{p} \frac{a^p}{b^q} + \frac{1}{q}$   
 PROOF: Substituting  $x = a^p/b^q$  in ⟨1⟩2.  
 ⟨3⟩2.  $ab^{1-q} \leq \frac{1}{p} \frac{a^p}{b^q} + \frac{1}{q}$   
 PROOF: From ⟨3⟩1 since  $1 - q = -q/p$ .  
 ⟨3⟩3.  $ab \leq \frac{a^p}{p} + \frac{b^q}{q}$   
 PROOF: Multiplying ⟨3⟩2 by  $b^q$ .  
 ⟨2⟩2. CASE:  $b^q \leq a^p$   
 PROOF: Similar.

- ⟨1⟩4. For any integers  $1 \leq j \leq n$ , we have

$$\frac{|x_j|}{(\sum_{k=1}^n |x_k|^p)^{1/p}} \frac{|y_j|}{(\sum_{k=1}^n |y_k|^q)^{1/q}} \leq \frac{1}{p} \frac{|x_j|^p}{\sum_{k=1}^n |x_k|^p} + \frac{1}{q} \frac{|y_j|^q}{\sum_{k=1}^n |y_k|^q}$$

PROOF: From ⟨1⟩3 substituting

$$a = \frac{|x_j|}{(\sum_{k=1}^n |x_k|^p)^{1/p}} \text{ and } b = \frac{|y_j|}{(\sum_{k=1}^n |y_k|^q)^{1/q}}$$

- ⟨1⟩5. For any positive integer  $n$  we have

$$\frac{\sum_{k=1}^n |x_k| |y_k|}{(\sum_{k=1}^n |x_k|^p)^{1/p} (\sum_{k=1}^n |y_k|^q)^{1/q}} \leq 1$$

PROOF:

$$\frac{\sum_{j=1}^n |x_j| |y_j|}{(\sum_{k=1}^n |x_k|^p)^{1/p} (\sum_{k=1}^n |y_k|^q)^{1/q}} \leq \frac{1}{p} + \frac{1}{q} \quad (\text{Summing } \langle 1 \rangle 4 \text{ from } j = 1 \text{ to } n)$$

$$= 1$$

- ⟨1⟩6.

$$\sum_n |x_n y_n| \leq \left( \sum_n |x_n|^p \right)^{1/p} \left( \sum_n |y_n|^q \right)^{1/q}$$

PROOF: Taking the limit  $n \rightarrow \infty$  in ⟨1⟩5.

□

**Theorem 7.0.4** (Minkowski's Inequality). *Let  $p \geq 1$ . Let  $(x_n), (y_n) \in l^p$ . Then*

$$\left( \sum_{n=1}^{\infty} |x_n + y_n|^p \right)^{1/p} \leq \left( \sum_{n=1}^{\infty} |x_n|^p \right)^{1/p} + \left( \sum_{n=1}^{\infty} |y_n|^p \right)^{1/p}$$

PROOF:

- ⟨1⟩1. CASE:  $p = 1$

PROOF: This is just the Triangle Inequality.

- ⟨1⟩2. CASE:  $p > 1$

- ⟨2⟩1. LET:  $q = p/(p-1)$

⟨2⟩2.

$$\begin{aligned} \sum_{n=1}^{\infty} |x_n + y_n|^p &\leq \left( \sum_{n=1}^{\infty} |x_n|^p \right)^{1/p} \left( \sum_{n=1}^{\infty} |x_n + y_n|^{q(p-1)} \right)^{1/q} \\ &\quad + \left( \sum_{n=1}^{\infty} |y_n|^p \right)^{1/p} \left( \sum_{n=1}^{\infty} |x_n + y_n|^{q(p-1)} \right)^{1/q} \end{aligned}$$

PROOF:

⟨3⟩1.  $(|x_n + y_n|^{p-1}) \in l^q$

PROOF:

$$\sum_{n=1}^{\infty} |x_n + y_n|^{(p-1)q} = \sum_{n=1}^{\infty} |x_n + y_n|^p \quad (\langle 2 \rangle 2)$$

$$< \infty$$

(Proposition 7.0.2)

⟨3⟩2. Q.E.D.

PROOF:

$$\begin{aligned} \sum_{n=1}^{\infty} |x_n + y_n|^p &= \sum_{n=1}^{\infty} |x_n + y_n| |x_n + y_n|^{p-1} \\ &\leq \sum_{n=1}^{\infty} |x_n| |x_n + y_n|^{p-1} + \sum_{n=1}^{\infty} |y_n| |x_n + y_n|^{p-1} \\ &\leq \left( \sum_{n=1}^{\infty} |x_n|^p \right)^{1/p} \left( \sum_{n=1}^{\infty} |x_n + y_n|^{q(p-1)} \right)^{1/q} \\ &\quad + \left( \sum_{n=1}^{\infty} |y_n|^p \right)^{1/p} \left( \sum_{n=1}^{\infty} |x_n + y_n|^{q(p-1)} \right)^{1/q} \quad (\text{Hölder's Inequality, } \langle 2 \rangle 2) \end{aligned}$$

⟨2⟩3.

$$\sum_{n=1}^{\infty} |x_n + y_n|^p \leq \left\{ \left( \sum_{n=1}^{\infty} |x_n|^p \right)^{1/p} + \left( \sum_{n=1}^{\infty} |y_n|^p \right)^{1/p} \right\} \left( \sum_{n=1}^{\infty} |x_n + y_n|^p \right)^{1/q}$$

⟨3⟩1.  $q(p-1) = p$

PROOF: ⟨2⟩2

⟨3⟩2. Q.E.D.

PROOF: From ⟨2⟩2, ⟨3⟩1.

□



**Part I**

**Linear Algebra**



# Chapter 8

## Vector Spaces

### 8.1 Vector Spaces

**Definition 8.1.1** (Vector Space). Let  $K$  be either  $\mathbb{R}$  or  $\mathbb{C}$ . A *vector space* over  $K$  is a triple  $(V, +, \cdot)$  such that:

- $V$  is a nonempty set, whose elements are called *vectors*;
- $+: V^2 \rightarrow V$
- $\cdot: K \times V \rightarrow V$

such that the following hold for all  $u, v, w \in V$  and  $\alpha, \beta \in K$ :

1.  $u + v = v + u$
2.  $u + (v + w) = (u + v) + w$
3. For every  $u, v \in V$  there exists  $w \in V$  such that  $u + w = v$
4.  $\alpha(\beta v) = (\alpha\beta)v$
5.  $(\alpha + \beta)v = \alpha v + \beta v$
6.  $\alpha(u + v) = \alpha u + \alpha v$
7.  $1v = v$

Elements of  $K$  are called *scalars*.

We write *real vector space* for 'vector space over  $\mathbb{R}$ ', and *complex vector space* for 'vector space over  $\mathbb{C}$ '.

**Proposition 8.1.2.** *Let  $K$  be either  $\mathbb{R}$  and  $\mathbb{C}$ . The set  $\{0\}$  is a vector space over  $K$  under the unique functions  $+: \{0\}^2 \rightarrow \{0\}$ ,  $\cdot: K \times \{0\} \rightarrow \{0\}$ .*

PROOF: Each axiom holds trivially because  $x = y$  holds for all  $x, y \in \{0\}$ .  $\square$

**Proposition 8.1.3.** *The set  $\mathbb{R}$  is a real vector space under real addition and real multiplication.*

PROOF: TODO — after we have proved these facts about  $\mathbb{R}$ .  $\square$

**Proposition 8.1.4.** *The set  $\mathbb{C}$  is a real vector space under complex addition and complex multiplication.*

PROOF: TODO

**Proposition 8.1.5.** *The set  $\mathbb{C}$  is a complex vector space under complex addition and complex multiplication.*

PROOF: TODO

**Proposition 8.1.6.** *Let  $K$  be either  $\mathbb{R}$  or  $\mathbb{C}$ . Let  $\{V_i\}_{i \in I}$  be a family of vector spaces over  $K$ . Then  $\prod_{i \in I} V_i$  is a vector space over  $K$  under the operations given by*

$$\begin{aligned}\{x_i\}_{i \in I} + \{y_i\}_{i \in I} &= \{x_i + y_i\}_{i \in I} \\ \alpha \{x_i\}_{i \in I} &= \{\alpha x_i\}_{i \in I}\end{aligned}$$

PROOF: Each axiom follows from the corresponding axiom in  $V_i$ .  $\square$

**Corollary 8.1.6.1.** *Let  $V$  be a vector space over  $K$ . For any set  $I$ , we have  $V^I$  is a vector space over  $K$ .*

**Corollary 8.1.6.2.** *Let  $n \in \mathbb{Z}_+$ . Then  $\mathbb{R}^n$  is a real vector space, and  $\mathbb{C}^n$  is both a real and a complex vector space, under*

$$\begin{aligned}(x_1, \dots, x_n) + (y_1, \dots, y_n) &= (x_1 + y_1, \dots, x_n + y_n) \\ \lambda(x_1, \dots, x_n) &= (\lambda x_1, \dots, \lambda x_n)\end{aligned}$$

**Proposition 8.1.7.** *Let  $V$  be a vector space over  $K$ . Then there exists a unique  $0 \in V$  such that, for all  $v \in V$ , we have  $v + 0 = v$ .*

PROOF:

$\langle 1 \rangle 1$ . There exists  $0 \in V$  such that  $\forall v \in V. v + 0 = v$

$\langle 2 \rangle 1$ . Pick  $v \in V$

$\langle 2 \rangle 2$ . Pick  $0 \in V$  such that  $v + 0 = v$

PROOF: Axiom 3.

$\langle 2 \rangle 3$ . For all  $u \in V$ , we have  $u + 0 = u$

$\langle 3 \rangle 1$ . LET:  $u \in V$

$\langle 3 \rangle 2$ . PICK  $u' \in V$  such that  $v + u' = u$

PROOF: Axiom 3.

$\langle 3 \rangle 3$ .  $u + 0 = u$

$$\begin{aligned}u + 0 &= v + u' + 0 && (\langle 3 \rangle 2) \\ &= v + u' && (\langle 2 \rangle 2) \\ &= u && (\langle 3 \rangle 2)\end{aligned}$$



$\langle 1 \rangle 2$ . If  $0, 0' \in V$  are such that  $\forall v \in V. v + 0 = v$  and  $\forall v \in V. v + 0' = v$ , then  $0 = 0'$ .

$\langle 2 \rangle 1$ . LET:  $0, 0' \in V$

$\langle 2 \rangle 2$ . ASSUME:  $\forall v \in V. v + 0 = v$

$\langle 2 \rangle 3$ . ASSUME:  $\forall v \in V. v + 0' = v$

$\langle 2 \rangle 4$ .  $0 = 0'$

$$0 = 0 + 0' \quad (\langle 2 \rangle 2)$$

$$= 0' \quad (\langle 2 \rangle 3)$$

□

**Proposition 8.1.8.** *Let  $V$  be a vector space. For any  $v \in V$ , there exists a unique  $-v \in V$  such that  $v + (-v) = 0$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $v \in V$

$\langle 1 \rangle 2$ . There exists  $-v \in V$  such that  $v + (-v) = 0$

PROOF: Axiom 3.

$\langle 1 \rangle 3$ . If  $v + x = 0$  and  $v + y = 0$  then  $x = y$

$\langle 2 \rangle 1$ . ASSUME:  $v + x = 0$

$\langle 2 \rangle 2$ . ASSUME:  $v + y = 0$

$\langle 2 \rangle 3$ .  $x = y$

PROOF:

$$x = x + 0 \quad (\text{Proposition 8.1.7})$$

$$= x + v + y \quad (\langle 2 \rangle 2)$$

$$= 0 + y \quad (\langle 2 \rangle 1)$$

$$= y \quad (\text{Proposition 8.1.7})$$

□

**Proposition 8.1.9.** *Let  $V$  be a vector space. For any  $u, v \in V$ , there exists a unique  $u - v \in V$  such that  $v + (u - v) = u$ , namely  $u - v = u + (-v)$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $u, v \in V$

$\langle 1 \rangle 2$ .  $v + (u + (-v)) = u$

PROOF:

$$v + u + (-v) = u + 0 \quad (\text{Proposition 8.1.8})$$

$$= u \quad (\text{Proposition 8.1.7})$$

$\langle 1 \rangle 3$ . For all  $x \in V$ , if  $v + x = u$  then  $x = u + (-v)$ .

$\langle 2 \rangle 1$ . LET:  $x \in V$

$\langle 2 \rangle 2$ . ASSUME:  $v + x = u$

$\langle 2 \rangle 3$ .  $x = u + (-v)$

PROOF:

$$u + (-v) = v + x + (-v) \quad (\langle 2 \rangle 2)$$

$$= x + 0 \quad (\text{Proposition 8.1.8})$$

$$= x \quad (\text{Proposition 8.1.7})$$

□

**Proposition 8.1.10.** *Let  $V$  be a vector space over  $K$ . Let  $u, v, w \in V$ . If  $u + v = u + w$  then  $v = w$ .*

PROOF:

$\langle 1 \rangle 1$ . ASSUME:  $u + v = u + w$

$\langle 1 \rangle 2$ .  $v = w$

PROOF:

$$v = v + 0 \quad (\text{Proposition 8.1.7})$$

$$= v + u + (-u) \quad (\text{Proposition 8.1.8})$$

$$= w + u + (-u) \quad (\langle 1 \rangle 1)$$

$$= w + 0 \quad (\text{Proposition 8.1.8})$$

$$= w \quad (\text{Proposition 8.1.7})$$

**Proposition 8.1.11.** *Let  $V$  be a vector space over  $K$ . Let  $\lambda \in K$ . Then  $\lambda 0 = 0$ .*

PROOF:

$\langle 1 \rangle 1$ .  $\lambda 0 + \lambda 0 = \lambda 0 + 0$

PROOF:

$$\lambda 0 + \lambda 0 = \lambda(0 + 0) \quad (\text{Axiom 6})$$

$$= \lambda 0 \quad (\text{Proposition 8.1.7})$$

$\langle 1 \rangle 2$ .  $\lambda 0 = 0$

PROOF: Proposition 8.1.10.

□

**Proposition 8.1.12.** *Let  $V$  be a vector space over  $K$ . Let  $\lambda \in K$  and  $v \in V$ . If  $\lambda v = 0$  then  $\lambda = 0$  or  $v = 0$ .*

PROOF:

$\langle 1 \rangle 1$ . ASSUME:  $\lambda \neq 0$

$\langle 1 \rangle 2$ . ASSUME:  $\lambda v = 0$

$\langle 1 \rangle 3$ .  $v = 0$

PROOF:

$$v = 1v \quad (\text{Axiom 7})$$

$$= \lambda^{-1} \lambda v$$

$$= \lambda^{-1} 0 \quad (\langle 1 \rangle 2)$$

$$= 0$$

□

**Proposition 8.1.13.** *Let  $V$  be a vector space over  $K$ . For all  $v \in V$  we have  $0v = 0$ .*

PROOF:

$\langle 1 \rangle 1$ .  $0v + 0 = 0v + 0v$

$$\begin{aligned}
0v + 0 &= 0v && \text{(Proposition 8.1.7)} \\
&= (0 + 0)v \\
&= 0v + 0v && \text{(Axiom 5)}
\end{aligned}$$

$\langle 1 \rangle 2.$   $0v = 0$

PROOF: Proposition 8.1.10,  $\langle 1 \rangle 1.$

□

**Proposition 8.1.14.** *Let  $V$  be a vector space over  $K$ . Let  $v \in V$ . Then  $(-1)v = -v$ .*

PROOF:

$\langle 1 \rangle 1.$   $v + (-1)v = 0$

PROOF:

$$\begin{aligned}
v + (-1)v &= 1v + (-1)v && \text{(Axiom 7)} \\
&= (1 + (-1))v && \text{(Axiom 5)} \\
&= 0v \\
&= 0 && \text{(Proposition 8.1.13)}
\end{aligned}$$

$\langle 1 \rangle 2.$  Q.E.D.

PROOF: Proposition 8.1.8.

□

## 8.2 Subspaces

**Definition 8.2.1** (Subspace). Let  $V$  be a vector space over  $K$  and  $U \subseteq V$ . Then  $U$  is a *subspace* of  $V$  iff  $\forall \alpha, \beta \in K. \forall u, v \in U. \alpha u + \beta v \in U$ . It is a *proper* subspace iff in addition  $U \neq V$ .

**Proposition 8.2.2.** *Let  $V$  be a vector space over  $K$  and  $U$  a subspace of  $V$ . Then  $U$  is a vector space over  $K$  under the restrictions of the operations of  $V$ .*

PROOF: Each of the axioms follows from the corresponding axiom in  $V$ . For axiom 3, we have if  $u, v \in U$  then  $v - u = 1v + (-1)u \in U$ . □

**Proposition 8.2.3.** *Every vector space is a subspace of itself.*

PROOF: Trivial. □

**Proposition 8.2.4.** *Let  $\Omega$  be a subset of  $\mathbb{R}^N$ . Let  $\mathcal{C}(\Omega)$  be the set of all continuous functions  $\Omega \rightarrow \mathbb{C}$ . Then  $\mathcal{C}(\Omega)$  is a subspace of  $\mathbb{C}^\Omega$ .*

PROOF: If  $f, g : \Omega \rightarrow \mathbb{C}$  are continuous then so is  $\alpha f + \beta g$ . □

**Proposition 8.2.5.** *Let  $\Omega$  be an open set in  $\mathbb{R}^N$ . Let  $\mathcal{C}^k(\Omega)$  be the set of all continuous functions  $\Omega \rightarrow \mathbb{C}$  with continuous partial derivatives of order  $k$ . Then  $\mathcal{C}^k(\Omega)$  is a subspace of  $\mathbb{C}^\Omega$ .*

PROOF: If  $f, g : \Omega \rightarrow \mathbb{C}$  have continuous partial derivatives of order  $k$  then so does  $\alpha f + \beta g$ .  $\square$

**Proposition 8.2.6.** *Let  $\Omega$  be an open set in  $\mathbb{R}^N$ . Let  $\mathcal{C}^\infty(\Omega)$  be the set of all infinitely differentiable functions  $\Omega \rightarrow \mathbb{C}$ . Then  $\mathcal{C}^\infty(\Omega)$  is a subspace of  $\mathbb{C}^\Omega$ .*

PROOF: If  $f, g : \Omega \rightarrow \mathbb{C}$  are infinitely differentiable then so is  $\alpha f + \beta g$ .  $\square$

**Proposition 8.2.7.** *Let  $\Omega$  be an open set in  $\mathbb{R}^N$ . Let  $\mathcal{P}(\Omega)$  be the set of all polynomials in  $N$  variables considered as functions  $\Omega \rightarrow \mathbb{C}$ . Then  $\mathcal{P}(\Omega)$  is a subspace of  $\mathbb{C}^\Omega$ .*

PROOF: If  $f, g : \Omega \rightarrow \mathbb{C}$  are polynomials in  $N$  variables then so is  $\alpha f + \beta g$ .  $\square$

**Proposition 8.2.8.** *Let  $V$  be a vector space and  $U_1, U_2$  subspaces of  $V$ . If  $U_1 \subseteq U_2$  then  $U_1$  is a subspace of  $U_2$ .*

PROOF: Trivial.  $\square$

**Proposition 8.2.9.** *Let  $V$  be a vector space over  $K$ . The intersection of a set of subspaces of  $V$  is a subspace of  $V$ .*

PROOF:

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

$\langle 1 \rangle 2$ . LET:  $u, v \in \bigcap \mathcal{U}$  and  $\lambda, \mu \in K$

$\langle 1 \rangle 3$ .  $\lambda u + \mu v \in \bigcap \mathcal{U}$

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

$\langle 2 \rangle 2$ .  $u, v \in U$

PROOF:  $\langle 1 \rangle 2, \langle 2 \rangle 1$ .

$\langle 2 \rangle 3$ .  $\lambda u + \beta v \in U$

PROOF:  $\langle 1 \rangle 1, \langle 1 \rangle 2, \langle 2 \rangle 1, \langle 2 \rangle 2$ .

$\square$

**Proposition 8.2.10.** *The set of all bounded complex sequences is a proper subspace of  $\mathbb{C}^\mathbb{N}$ .*

PROOF: If  $(x_n)$  and  $(y_n)$  are bounded then so is  $(\lambda x_n + \mu y_n)$ .  $\square$

**Proposition 8.2.11.** *The set of all convergent complex sequences is a proper subspace of the space of all bounded complex sequences.*

PROOF: If  $(x_n)$  and  $(y_n)$  converge then so does  $(\lambda x_n + \mu y_n)$ .  $\square$

**Proposition 8.2.12.** *The set  $l^p$  of all sequences  $(x_n)$  in  $\mathbb{C}$  such that  $\sum_n |x_n|^p < \infty$  is a subspace of  $\mathbb{C}^\mathbb{N}$ .*

PROOF: It is closed under addition by Proposition 7.0.2, and it is easy to see that it is closed under scalar multiplication.  $\square$

### 8.3 Linear Independence and Bases

**Definition 8.3.1** (Linear Combination). Let  $V$  be a vector space over  $K$ . Let  $v, v_1, \dots, v_n \in V$ . Then  $v$  is a *linear combination* of  $v_1, \dots, v_n$  iff there exist scalars  $\lambda_1, \dots, \lambda_n \in K$  such that

$$v = \lambda_1 v_1 + \dots + \lambda_n v_n .$$

**Definition 8.3.2** (Linearly Independent). Let  $V$  be a vector space over  $K$ . Let  $A \subseteq V$ . Then  $A$  is *linearly independent* iff, for all  $\lambda_1, \dots, \lambda_n \in K$  and  $v_1, \dots, v_n \in A$ , if  $\lambda_1 v_1 + \dots + \lambda_n v_n = 0$  then  $\lambda_1 = \dots = \lambda_n = 0$ .

**Definition 8.3.3** (Span). Let  $V$  be a vector space over  $K$  and  $A \subseteq V$ . The *span* of  $A$ , or the subspace of  $V$  *spanned* by  $A$ , is the set of all linear combinations of vectors in  $A$ .

**Proposition 8.3.4.** Let  $V$  be a vector space over  $K$  and  $A \subseteq V$ . Then  $\text{span } A$  is a subspace of  $V$ .

PROOF: Given  $\alpha, \beta \in K$  and  $\lambda_1 u_1 + \dots + \lambda_m u_m, \mu_1 v_1 + \dots + \mu_n v_n \in \text{span } A$ , we have

$$\begin{aligned} & \alpha(\lambda_1 u_1 + \dots + \lambda_m u_m) + \beta(\mu_1 v_1 + \dots + \mu_n v_n) \\ &= \alpha\lambda_1 u_1 + \dots + \alpha\lambda_m u_m + \beta\mu_1 v_1 + \dots + \beta\mu_n v_n \\ &\in \text{span } A \end{aligned} \quad \square$$

**Definition 8.3.5** (Basis). Let  $V$  be a vector space over  $K$  and  $B \subseteq V$ . Then  $B$  is a *basis* for  $V$  iff  $B$  is linearly independent and  $\text{span } B = V$ .

**Definition 8.3.6** (Finite Dimensional). A vector space is *finite dimensional* iff there exists a finite basis; otherwise it is *infinite dimensional*.

**Proposition 8.3.7.** In a finite dimensional space, any two bases have the same size.

TODO

**Definition 8.3.8** (Dimension). The *dimension* of a finite dimensional vector space  $V$ ,  $\dim V$ , is the number of vectors in any basis.

**Proposition 8.3.9.** Let  $K$  be either  $\mathbb{R}$  or  $\mathbb{C}$ . Then  $K^n$  as a vector space over  $K$  has dimension  $n$ .

PROOF: The vectors with one component 1 and all other components 0 form a basis.  $\square$

**Proposition 8.3.10.** As a real vector space,  $\mathbb{C}^n$  has dimension  $2n$ .

PROOF: The vectors with one component either 1 or  $i$  and all other components 0 form a basis.  $\square$

**Proposition 8.3.11.** *Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . The space  $\mathcal{C}(\Omega)$  is infinite dimensional.*

PROOF: Let  $\pi_1 : \mathbb{R}^n \rightarrow \mathbb{R}$  be the first projection. The functions  $1, \pi_1(x), \pi_1(x)^2, \pi_1(x)^3, \dots$  form an infinite linearly independent set in  $\mathcal{C}(\Omega)$ .  $\square$

**Proposition 8.3.12.** *The spaces  $\mathcal{C}^k(\mathbb{R}^n)$  and  $\mathcal{C}^\infty(\mathbb{R}^n)$  are infinite dimensional.*

PROOF: The monomials  $1, x, x^2, \dots$  form an infinite linearly independent set.  $\square$

## 8.4 Linear Mappings

**Definition 8.4.1** (Kernel). Let  $U$  and  $V$  be vector spaces and  $T : U \rightarrow V$ . The *kernel* of  $T$  is

$$\ker T := \{u \in U \mid T(u) = 0\} .$$

**Definition 8.4.2** (Linear Mapping). Let  $U$  and  $V$  be vector spaces over  $K$ . A function  $L : U \rightarrow V$  is a *linear mapping* iff  $\forall x, y \in U, \forall \alpha, \beta \in K. L(\alpha x + \beta y) = \alpha L(x) + \beta L(y)$ .

**Proposition 8.4.3.** *Let  $U$  and  $V$  be vector spaces over  $K$ . The set of linear mappings from  $U$  to  $V$  is a subspace of  $V^U$ .*

## 8.5 Eigenvalues and Eigenvectors

**Definition 8.5.1** (Eigenvalue and Eigenvector). Let  $V$  be a vector space over  $K$ . Let  $A : V \rightarrow V$  be a linear transformation. Let  $v \in V$  and  $\lambda \in K$ . Then  $v$  is an *eigenvector* of  $A$  with *eigenvalue*  $\lambda$  iff  $A(v) = \lambda v$ .

## Chapter 9

# Normed Spaces

**Definition 9.0.1** (Norm). Let  $K$  be either  $\mathbb{R}$  or  $\mathbb{C}$ . Let  $V$  be a vector space over  $K$ . A *norm* on  $V$  is a function  $\| \cdot \| : V \rightarrow \mathbb{R}$  such that, for all  $u, v \in V$  and  $\lambda \in K$ :

1. If  $\|v\| = 0$  then  $v = 0$ .
2.  $\|\lambda v\| = |\lambda| \|v\|$
3. (*Triangle Inequality*)  $\|u + v\| \leq \|u\| + \|v\|$

A *normed space* over  $K$  is a pair  $(V, \| \cdot \|)$  where  $V$  is a vector space over  $K$  and  $\| \cdot \|$  is a norm on  $V$ .

**Proposition 9.0.2.** *In a normed space,  $\|0\| = 0$ .*

PROOF:  $\|0\| = |0| \|0\| = 0$  by Axiom 2.  $\square$

**Proposition 9.0.3.** *Let  $V$  be a normed vector space over  $K$ . For all  $v \in V$  we have  $\|v\| \geq 0$ .*

PROOF:

$$\begin{aligned} 0 &= \|0\| && \text{(Proposition 9.0.2)} \\ &= \|v - v\| \\ &\leq \|v\| + \|-v\| && \text{(Triangle Inequality)} \\ &= 2\|v\| && \text{(Axiom 2)} \end{aligned}$$

**Proposition 9.0.4.** *Let  $V$  be a normed space. Let  $u, v \in V$ . Then*

$$|\|u\| - \|v\|| \leq \|u - v\| .$$

PROOF:

$$\begin{aligned}
 \|u\| &\leq \|u - v\| + \|v\| && \text{(Triangle Inequality)} \\
 \therefore \|u\| - \|v\| &\leq \|u - v\| \\
 \|v\| &\leq \|v - u\| + \|u\| && \text{(Triangle Inequality)} \\
 &= \|u - v\| + \|u\| && \text{(Axiom 2)} \\
 \therefore \|v\| - \|u\| &\leq \|u - v\|
 \end{aligned}$$

**Definition 9.0.5** (Euclidean Norm). The *Euclidean norm* on  $K^n$  is defined by

$$\|(x_1, \dots, x_n)\| = \sqrt{|x_1|^2 + \dots + |x_n|^2}.$$

**Proposition 9.0.6.** The *Euclidean norm* on  $K^n$  is a norm.

PROOF:

$\langle 1 \rangle 1$ . If  $\|\vec{x}\| = 0$  then  $\vec{x} = \vec{0}$

PROOF: If  $\sqrt{|x_1|^2 + \dots + |x_n|^2} = 0$  then  $x_1 = \dots = x_n = 0$ .

$\langle 1 \rangle 2$ .  $\|\lambda \vec{x}\| = |\lambda| \|\vec{x}\|$

PROOF:

$$\begin{aligned}
 \|\lambda \vec{x}\| &= \sqrt{|\lambda x_1|^2 + \dots + |\lambda x_n|^2} \\
 &= \sqrt{|\lambda|^2 |x_1|^2 + \dots + |\lambda|^2 |x_n|^2} \\
 &= |\lambda| \sqrt{|x_1|^2 + \dots + |x_n|^2} \\
 &= |\lambda| \|\vec{x}\|
 \end{aligned}$$

$\langle 1 \rangle 3$ .  $\|\vec{u} + \vec{v}\| \leq \|\vec{u}\| + \|\vec{v}\|$

PROOF:

$$\begin{aligned}
 \|\vec{u} + \vec{v}\|^2 &= |u_1 + v_1|^2 + \dots + |u_n + v_n|^2 \\
 &= |u_1|^2 + \dots + |u_n|^2 + |v_1|^2 + \dots + |v_n|^2 \\
 &\quad + 2|u_1||v_1| + \dots + 2|u_n||v_n| \\
 &\leq \|\vec{u}\|^2 + \|\vec{v}\|^2 + 2|u_1 v_1| + \dots + 2|u_n v_n| \\
 &\leq \|\vec{u}\|^2 + \|\vec{v}\|^2 + 2\|\vec{u}\|\|\vec{v}\| && \text{(Cauchy-Schwarz)} \\
 &= (\|\vec{u}\| + \|\vec{v}\|)^2
 \end{aligned}$$

□

**Corollary 9.0.6.1.** The absolute value function  $|\cdot|$  is a norm on  $K$ .

**Proposition 9.0.7.** The function  $\|\vec{x}\| = |x_1| + \dots + |x_n|$  is a norm on  $\mathbb{C}^n$ .

PROOF:

$\langle 1 \rangle 1$ . If  $\|\vec{x}\| = 0$  then  $\vec{x} = \vec{0}$

PROOF: If  $|x_1| + \dots + |x_n| = 0$  then  $x_1 = \dots = x_n = 0$ .

$\langle 1 \rangle 2$ .  $\|\lambda \vec{x}\| = |\lambda| \|\vec{x}\|$

PROOF:

$$\begin{aligned}
 \|\lambda \vec{x}\| &= |\lambda x_1| + \dots + |\lambda x_n| \\
 &= |\lambda|(|x_1| + \dots + |x_n|) \\
 &= |\lambda| \|\vec{x}\|
 \end{aligned}$$



$$\langle 1 \rangle 3. \|\vec{u} + \vec{v}\| \leq \|\vec{u}\| + \|\vec{v}\|$$

PROOF:

$$\begin{aligned} \|\vec{u} + \vec{v}\|^2 &= |u_1 + v_1| + \cdots + |u_n + v_n| \\ &\leq |u_1| + |v_1| + \cdots + |u_n| + |v_n| \\ &= \|\vec{u}\| + \|\vec{v}\| \end{aligned}$$

□

**Proposition 9.0.8.** *The function  $\|\vec{x}\| = \max(|x_1|, \dots, |x_n|)$  is a norm on  $\mathbb{C}^n$ .*

PROOF:

$$\langle 1 \rangle 1. \text{ If } \|\vec{x}\| = 0 \text{ then } \vec{x} = \vec{0}$$

PROOF: If  $\max(|x_1|, \dots, |x_n|) = 0$  then  $x_1 = \cdots = x_n = 0$ .

$$\langle 1 \rangle 2. \|\lambda \vec{x}\| = |\lambda| \|\vec{x}\|$$

PROOF:

$$\begin{aligned} \|\lambda \vec{x}\| &= \max(|\lambda x_1|, \dots, |\lambda x_n|) \\ &= |\lambda| \max(|x_1|, \dots, |x_n|) \\ &= |\lambda| \|\vec{x}\| \end{aligned}$$

$$\langle 1 \rangle 3. \|\vec{u} + \vec{v}\| \leq \|\vec{u}\| + \|\vec{v}\|$$

PROOF:

$$\begin{aligned} \|\vec{u} + \vec{v}\| &= \max(|u_1 + v_1|, \dots, |u_n + v_n|) \\ &\leq \max(|u_1| + |v_1|, \dots, |u_n| + |v_n|) \\ &\leq \max(|u_1|, \dots, |u_n|) + \max(|v_1|, \dots, |v_n|) \end{aligned}$$

□

**Definition 9.0.9** (Uniform Convergence Norm). Let  $\Omega$  be a closed bounded subset of  $\mathbb{R}^n$ . The *uniform convergence norm* on  $\mathcal{C}(\Omega)$  is the function defined by  $\|f\| = \max_{x \in \Omega} |f(x)|$ .

**Proposition 9.0.10.** *Let  $\Omega$  be a closed bounded subset of  $\mathbb{R}^n$ . The uniform convergence norm is a norm on  $\mathcal{C}(\Omega)$ .*

PROOF:

$$\langle 1 \rangle 1. \text{ If } \|f\| = 0 \text{ then } f = 0$$

PROOF: If  $\max_x |f(x)| = 0$  then  $f(x) = 0$  for all  $x$ .

$$\langle 1 \rangle 2. \|\lambda f\| = |\lambda| \|f\|$$

PROOF:

$$\begin{aligned} \|\lambda f\| &= \max_x |\lambda f(x)| \\ &= |\lambda| \max_x |f(x)| \\ &= |\lambda| \|f\| \end{aligned}$$

$$\langle 1 \rangle 3. \|f + g\| \leq \|f\| + \|g\|$$

PROOF:

$$\begin{aligned}
 \|f + g\| &= \max_x |f(x) + g(x)| \\
 &\leq \max_x (|f(x)| + |g(x)|) \\
 &\leq \max_x |f(x)| + \max_x |g(x)| \\
 &= \|f\| + \|g\|
 \end{aligned}$$

□

**Proposition 9.0.11.** *Let  $p \geq 1$ . The function  $\|(z_n)\| = (\sum_{n=1}^{\infty} |z_n|^p)^{1/p}$  is a norm on  $l^p$ .*

PROOF:

⟨1⟩1. If  $\|(z_n)\| = 0$  then  $(z_n) = (0)$

PROOF: If  $(\sum_n |z_n|^p)^{1/p} = 0$  then  $\sum_n |z_n|^p = 0$  so  $|z_n|^p = 0$  for all  $n$ , and so  $z_n = 0$  for all  $n$ .

⟨1⟩2.  $\|(\lambda z_n)\| = |\lambda| \|(z_n)\|$

PROOF:

$$\begin{aligned}
 \|(\lambda z_n)\| &= \left( \sum_n |\lambda z_n|^p \right)^{1/p} \\
 &= |\lambda| \left( \sum_n |z_n|^p \right)^{1/p} \\
 &= |\lambda| \|(z_n)\|
 \end{aligned}$$

⟨1⟩3. The triangle inequality holds.

PROOF: This is Minkowski's Inequality. □

**Proposition 9.0.12.** *Let  $V$  be a normed space and  $U$  a vector subspace of  $V$ . Then  $U$  is a normed space under the restriction of the norm to  $U$ .*

PROOF: Each axiom follows from the fact it holds in  $V$ . □

**Proposition 9.0.13.** *Let  $V$  be a normed space over  $K$ . Let  $x_1, \dots, x_n$  be linearly independent elements of  $V$ . Then there exists a real number  $c > 0$  such that, for all  $\alpha_1, \dots, \alpha_n \in K$ , we have*

$$\|\alpha_1 x_1 + \dots + \alpha_n x_n\| \geq c(|\alpha_1| + \dots + |\alpha_n|) .$$

PROOF:

⟨1⟩1. Define  $f : K^n \rightarrow \mathbb{R}$  by

$$f(\alpha_1, \dots, \alpha_n) = \|\alpha_1 x_1 + \dots + \alpha_n x_n\|$$

⟨1⟩2.  $f$  is continuous.

⟨2⟩1. LET:  $(\alpha_1, \dots, \alpha_n) \in K^n$  and  $\epsilon > 0$

⟨2⟩2. LET:  $\delta = \epsilon / (\|x_1\| + \dots + \|x_n\|)$

PROOF:  $x_1, \dots, x_n$  are not all zero because they are linearly independent.

⟨2⟩3. LET:  $(\beta_1, \dots, \beta_n)$  with  $|\alpha_i - \beta_i| < \delta$  for all  $i$

⟨2⟩4.  $\|(\alpha_1 x_1 + \dots + \alpha_n x_n) - (\beta_1 x_1 + \dots + \beta_n x_n)\| < \epsilon$

PROOF:

$$\begin{aligned}
 & \|(\alpha_1 x_1 + \cdots + \alpha_n x_n) - (\beta_1 x_1 + \beta_n x_n)\| \\
 & \leq |\alpha_1 - \beta_1| \|x_1\| + \cdots + |\alpha_n - \beta_n| \|x_n\| \quad (\text{Axioms 2 and 3}) \\
 & < \delta (\|x_1\| + \cdots + \|x_n\|) \quad (\langle 2 \rangle 3) \\
 & = \epsilon \quad (\langle 2 \rangle 2)
 \end{aligned}$$

$\langle 1 \rangle 3$ . PICK  $(\beta_1, \dots, \beta_n) \in \{(\beta_1, \dots, \beta_n) \in K^n \mid |\beta_1| + \cdots + |\beta_n| = 1\}$  at which  $f$  attains its minimum.

PROOF: Extreme Value Theorem.

$\langle 1 \rangle 4$ . Let  $c = f(\beta_1, \dots, \beta_n)$

$\langle 1 \rangle 5$ .  $c > 0$

PROOF: Linear independence.

$\langle 1 \rangle 6$ . LET:  $\alpha_1, \dots, \alpha_n \in K$

$\langle 1 \rangle 7$ .  $\|\alpha_1 x_1 + \cdots + \alpha_n x_n\| \geq c(|\alpha_1| + \cdots + |\alpha_n|)$

$\langle 2 \rangle 1$ . ASSUME: w.l.o.g.  $\alpha_1, \dots, \alpha_n$  are not all zero.

$\langle 2 \rangle 2$ . LET:  $\beta_i = \alpha_i / (|\alpha_1| + \cdots + |\alpha_n|)$  for  $i = 1, \dots, n$

$\langle 2 \rangle 3$ .  $|\beta_1| + \cdots + |\beta_n| = 1$

$\langle 2 \rangle 4$ .  $f(\beta_1, \dots, \beta_n) \geq c$

$\langle 2 \rangle 5$ . Q.E.D.

PROOF: Multiply both sides by  $|\alpha_1| + \cdots + |\alpha_n|$ .

□

**Proposition 9.0.14.** *Let  $V$  be a normed space over  $K$ . Define  $d : V^2 \rightarrow \mathbb{R}$  by  $d(x, y) = \|x - y\|$ . Then  $d$  is a metric on  $V$ .*

PROOF:

$\langle 1 \rangle 1$ . For all  $x, y \in V$  we have  $d(x, y) \geq 0$

PROOF: Proposition 9.0.3.

$\langle 1 \rangle 2$ . For all  $x, y \in V$  we have  $d(x, y) = 0$  iff  $x = y$

$\langle 2 \rangle 1$ . If  $d(x, y) = 0$  then  $x = y$

PROOF: Axiom 1.

$\langle 2 \rangle 2$ . If  $x = y$  then  $d(x, y) = 0$

PROOF: Proposition 9.0.2.

$\langle 1 \rangle 3$ .  $\forall x, y \in V. d(x, y) = d(y, x)$

PROOF: By Axiom 2.

$\langle 1 \rangle 4$ .  $\forall x, y, z \in V. d(x, z) \leq d(x, y) + d(y, z)$

PROOF: By Axiom 3.

□

Henceforth we identify any normed space with this metric space.

## 9.1 Convergence

**Proposition 9.1.1.** *Let  $V$  be a normed space over  $K$ . Let  $(x_n)$  be a sequence in  $V$  and  $l \in V$ . Then  $x_n \rightarrow l$  as  $n \rightarrow \infty$  in  $V$  if and only if  $\|x_n - l\| \rightarrow 0$  as  $n \rightarrow \infty$  in  $\mathbb{R}$ .*

PROOF: Immediate from definitions. □

**Proposition 9.1.2.** *In a normed space, a sequence has at most one limit.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $V$  be a vector space over  $K$ .

$\langle 1 \rangle 2$ . ASSUME:  $x_n \rightarrow l$  and  $x_n \rightarrow m$  as  $n \rightarrow \infty$ .

$\langle 1 \rangle 3$ . ASSUME: for a contradiction  $l \neq m$

$\langle 1 \rangle 4$ . LET:  $\epsilon = \|l - m\|/2$

$\langle 1 \rangle 5$ . PICK  $N$  such that  $\forall n \geq N, \|x_n - l\| < \epsilon$  and  $\forall n \geq N, \|x_n - m\| < \epsilon$

PROOF:  $\langle 1 \rangle 2, \langle 1 \rangle 4$

$\langle 1 \rangle 6$ .  $\|l - m\| < \|l - m\|$

PROOF:

$$\|l - m\| \leq \|x_N - l\| + \|x_N - m\| \quad (\text{Triangle Inequality})$$

$$< 2\epsilon \quad (\langle 1 \rangle 5)$$

$$= \|l - m\| \quad (\langle 1 \rangle 4)$$

$\langle 1 \rangle 7$ . Q.E.D.

PROOF: This is a contradiction.

□

**Definition 9.1.3** (Bounded). Let  $V$  be a normed space over  $K$ . A sequence  $(x_n)$  in  $V$  is *bounded* iff there exists  $B$  such that  $\forall n \leq N, \|x_n\| < B$ .

**Proposition 9.1.4.** *Every convergent sequence is bounded.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $x_n \rightarrow l$  as  $n \rightarrow \infty$

$\langle 1 \rangle 2$ . PICK  $N$  such that  $\forall n \geq N, \|x_n - l\| < 1$

$\langle 1 \rangle 3$ . LET:  $B = \max(\|x_1\|, \|x_2\|, \dots, \|x_{N-1}\|, \|l\| + 1)$

$\langle 1 \rangle 4$ . LET:  $n \in \mathbb{N}$

$\langle 1 \rangle 5$ .  $\|x_n\| \leq B$

$\langle 2 \rangle 1$ . CASE:  $n < N$

PROOF:  $\|x_n\| \leq B$  from  $\langle 1 \rangle 3$ .

$\langle 2 \rangle 2$ . CASE:  $n \geq N$

PROOF:

$$\|x_n\| \leq \|l\| + \|x_n - l\| \quad (\text{Triangle Inequality})$$

$$< \|l\| + 1 \quad (\langle 1 \rangle 2)$$

$$\leq B \quad (\langle 1 \rangle 3)$$

□

**Proposition 9.1.5.** *Let  $V$  be a normed space over  $K$ . If  $x_n \rightarrow l$  as  $n \rightarrow \infty$  in  $V$ , and  $\lambda_n \rightarrow \lambda$  as  $n \rightarrow \infty$  in  $K$ , then  $\lambda_n x_n \rightarrow \lambda l$  as  $n \rightarrow \infty$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $V$  be a normed space over  $K$ .

$\langle 1 \rangle 2$ . LET:  $x_n \rightarrow l$  as  $n \rightarrow \infty$

$\langle 1 \rangle 3$ . LET:  $\lambda_n \rightarrow \lambda$  as  $n \rightarrow \infty$

$\langle 1 \rangle 4$ . LET:  $\epsilon > 0$

- (1)5. PICK  $N$  such that, for all  $n \geq N$ , we have  $\|x_n - l\| < \epsilon/2|\lambda|$  and  $|\lambda_n - \lambda| < \sqrt{\epsilon/2}$  and  $\|x_n\| < \sqrt{\epsilon/2}$   
 (1)6. LET:  $n \geq N$   
 (1)7.  $\|\lambda_n x_n - \lambda l\| < \epsilon$

PROOF:

$$\begin{aligned}
 \|\lambda_n x_n - \lambda l\| &\leq \|\lambda_n x_n - \lambda x_n\| + \|\lambda x_n - \lambda l\| && \text{(Triangle Inequality)} \\
 &= |\lambda_n - \lambda| \|x_n\| + |\lambda| \|x_n - l\| && \text{(Axiom 2)} \\
 &< \sqrt{\epsilon/2} \sqrt{\epsilon/2} + |\lambda| \epsilon/2|\lambda| && \text{((1)5)} \\
 &= \epsilon
 \end{aligned}$$

□

**Proposition 9.1.6.** *Let  $V$  be a normed space over  $K$ . If  $x_n \rightarrow l$  and  $y_n \rightarrow m$  as  $n \rightarrow \infty$ , then  $x_n + y_n \rightarrow l + m$  as  $n \rightarrow \infty$ .*

PROOF:

- (1)1. LET:  $\epsilon > 0$   
 (1)2. PICK  $N$  such that, for all  $n \geq N$ , we have  $\|x_n - l\| < \epsilon/2$  and  $\|y_n - m\| < \epsilon/2$   
 (1)3. LET:  $n \geq N$   
 (1)4.  $\|(x_n + y_n) - (l + m)\| < \epsilon$

PROOF:

$$\begin{aligned}
 \|(x_n + y_n) - (l + m)\| &\leq \|x_n - l\| + \|y_n - m\| && \text{(Triangle Inequality)} \\
 &< \epsilon/2 + \epsilon/2 && \text{((1)2)} \\
 &= \epsilon
 \end{aligned}$$

□

**Definition 9.1.7** (Uniform Convergence). Let  $\Omega$  be a closed bounded subset of  $\mathbb{R}^n$ . Let  $(f_n)$  be a sequence in  $\mathcal{C}(\Omega)$  and  $f \in \mathcal{C}(\Omega)$ . Then  $(f_n)$  converges uniformly to  $f$  iff, for every  $\epsilon > 0$ , there exists  $N$  such that  $\forall x \in \Omega, \forall n \geq N, |f_n(x) - f(x)| < \epsilon$ .

**Proposition 9.1.8.** *Let  $\Omega$  be a closed bounded subset of  $\mathbb{R}^n$ . Let  $(f_n)$  be a sequence in  $\mathcal{C}(\Omega)$  and  $f \in \mathcal{C}(\Omega)$ . Then  $(f_n)$  converges uniformly to  $f$  iff  $f_n$  converges to  $f$  under the uniform convergence norm.*

PROOF:

$$\begin{aligned}
 &(f_n) \text{ converges to } f \text{ under the uniform convergence norm} \\
 &\Leftrightarrow \forall \epsilon > 0. \exists N. \forall n \geq N. \|f_n - f\| < \epsilon \\
 &\Leftrightarrow \forall \epsilon > 0. \exists N. \forall n \geq N. \forall x \in X. |f_n(x) - f(x)| < \epsilon
 \end{aligned}$$

□

**Definition 9.1.9** (Pointwise Convergence). Let  $(f_n)$  be a sequence in  $\mathcal{C}([0, 1])$  and  $f \in \mathcal{C}([0, 1])$ . Then  $(f_n)$  converges pointwise to  $f$  iff, for all  $t \in [0, 1]$ , we have  $|f_n(t) - f(t)| \rightarrow 0$  as  $n \rightarrow \infty$ .

**Proposition 9.1.10.** *There is no norm  $n$  on  $\mathcal{C}([0, 1])$  such that, for every sequence  $(f_n)$  and function  $f$  in  $\mathcal{C}([0, 1])$ , we have  $(f_n)$  converges pointwise to  $f$  if and only if  $(f_n)$  converges to  $f$  under  $n$ .*

PROOF:

(1)1. ASSUME: for a contradiction  $\| \cdot \|$  is a norm on  $\mathcal{C}([0, 1])$  such that, for every sequence  $(f_n)$  and function  $f$  in  $\mathcal{C}([0, 1])$ , we have  $(f_n)$  converges pointwise to  $f$  if and only if  $(f_n)$  converges to  $f$  under  $\| \cdot \|$ .

(1)2. For  $n \in \mathbb{Z}_+$ , define  $g_n \in \mathcal{C}([0, 1])$  by

$$g_n(t) = \begin{cases} 2^n t & \text{if } 0 \leq t \leq 2^{-n} \\ 2 - 2^n t & \text{if } 2^{-n} \leq t \leq 2^{1-n} \\ 0 & \text{if } 2^{1-n} \leq t \leq 1 \end{cases}$$

(1)3. For all  $n$ ,  $\|g_n\| \neq 0$

PROOF: Axiom 1.

(1)4. For  $n \in \mathbb{Z}_+$ , define  $f_n \in \mathcal{C}([0, 1])$  by  $f_n = g_n / \|g_n\|$

(1)5. For all  $n$ ,  $\|f_n\| = 1$

PROOF: Axiom 2.

(1)6.  $(f_n)$  does not converge under  $\| \cdot \|$

(1)7.  $(f_n)$  converges pointwise to 0.

(1)8. This is a contradiction.

□

**Definition 9.1.11** (Equivalence of Norms). Let  $\| \cdot \|_1$  and  $\| \cdot \|_2$  be two norms on the same vector space  $V$ . Then the norms are *equivalent* if and only if, for any sequence  $(x_n)$  in  $V$  and  $l \in V$ , we have that  $(x_n)$  converges to  $l$  under  $\| \cdot \|_1$  if and only if  $(x_n)$  converges to  $l$  under  $\| \cdot \|_2$ .

**Theorem 9.1.12.** Let  $\| \cdot \|_1$  and  $\| \cdot \|_2$  be two norms on the same vector space  $E$  over  $K$ . Then  $\| \cdot \|_1$  and  $\| \cdot \|_2$  are equivalent if and only if there exist positive real numbers  $\alpha$  and  $\beta$  such that, for all  $x \in E$ ,

$$\alpha \|x\|_1 \leq \|x\|_2 \leq \beta \|x\|_1 .$$

PROOF:

(1)1. If  $\| \cdot \|_1$  and  $\| \cdot \|_2$  are equivalent then there exist positive real numbers  $\alpha$  and  $\beta$  such that, for all  $x \in E$ ,  $\alpha \|x\|_1 \leq \|x\|_2 \leq \beta \|x\|_1$ .

(2)1. ASSUME:  $\| \cdot \|_1$  and  $\| \cdot \|_2$  are equivalent.

(2)2. There exists  $\alpha > 0$  such that, for all  $x \in E$ , we have  $\alpha \|x\|_1 \leq \|x\|_2$

(3)1. ASSUME: for a contradiction there is no  $\alpha > 0$  such that, for all  $x \in E$ , we have  $\alpha \|x\|_1 \leq \|x\|_2$ .

(3)2. For all  $n \in \mathbb{Z}_+$ , PICK  $x_n \in E$  such that  $1/n \|x_n\|_1 > \|x_n\|_2$

(3)3. For all  $n \in \mathbb{Z}_+$ ,

LET:

$$y_n = \frac{1}{\sqrt{n}} \frac{x_n}{\|x_n\|_2}$$

(3)4.  $(y_n)$  converges to 0 under  $\| \cdot \|_2$

(3)5.  $(y_n)$  converges to 0 under  $\| \cdot \|_1$

(3)6. For all  $n \in \mathbb{Z}_+$ , we have  $\|y_n\| > \sqrt{n}$

(3)7. This is a contradiction.

(2)3. There exists  $\beta > 0$  such that, for all  $x \in E$ , we have  $\|x\|_2 \leq \beta \|x\|_1$

PROOF: Similar.

- (1)2. If there exist positive real numbers  $\alpha$  and  $\beta$  such that, for all  $x \in E$ ,  
 $\alpha\|x\|_1 \leq \|x\|_2 \leq \beta\|x\|_1$ , then  $\|\cdot\|_1$  and  $\|\cdot\|_2$  are equivalent.  
 (2)1. ASSUME:  $\alpha$  and  $\beta$  are positive reals with  $\forall x \in E. \alpha\|x\|_1 \leq \|x\|_2 \leq \beta\|x\|_1$ .  
 (2)2. Let  $(x_n)$  be a sequence in  $E$  and  $l \in E$   
 (2)3. If  $(x_n)$  converges to  $l$  under  $\|\cdot\|_1$  then  $(x_n)$  converges to  $l$  under  $\|\cdot\|_2$ .  
 (3)1. ASSUME:  $(x_n)$  converges to  $l$  under  $\|\cdot\|_1$   
 (3)2. LET:  $\epsilon > 0$   
 (3)3. PICK  $N$  such that  $\forall n \geq N. \|x_n - l\|_1 < \epsilon/\beta$   
 (3)4.  $\forall n \geq N. \|x_n - l\|_2 < \epsilon$   
 (2)4. If  $(x_n)$  converges to  $l$  under  $\|\cdot\|_2$  then  $(x_n)$  converges to  $l$  under  $\|\cdot\|_1$ .  
 PROOF: Similar.

□

**Theorem 9.1.13.** *Any two norms on a finite dimensional vector space are equivalent.*

PROOF:

- (1)1. LET:  $V$  be a finite dimensional vector space over  $K$ .  
 (1)2. ASSUME: w.l.o.g.  $\dim V > 0$   
 (1)3. PICK a basis  $\{e_1, \dots, e_n\}$  for  $V$ .  
 (1)4. LET:  $\|\cdot\|_0 : V \rightarrow \mathbb{R}$  be the function:  $\|\alpha_1 e_1 + \dots + \alpha_n e_n\|_0 = |\alpha_1| + \dots + |\alpha_n|$ .  
 (1)5.  $\|\cdot\|_0$  is a norm.  
 (2)1. If  $\|v\|_0 = 0$  then  $v = 0$   
 PROOF: If  $|\alpha_1| + \dots + |\alpha_n| = 0$  then  $\alpha_1 = \dots = \alpha_n = 0$  so  $\alpha_1 e_1 + \dots + \alpha_n e_n = 0$ .  
 (2)2.  $\|\lambda v\|_0 = |\lambda| \|v\|_0$   
 PROOF:  

$$\begin{aligned} \|\lambda(\alpha_1 e_1 + \dots + \alpha_n e_n)\|_0 &= \|\lambda \alpha_1 e_1 + \dots + \lambda \alpha_n e_n\|_0 \\ &= |\lambda \alpha_1| + \dots + |\lambda \alpha_n| & (\langle 1 \rangle 4) \\ &= |\lambda|(|\alpha_1| + \dots + |\alpha_n|) \\ &= |\lambda| \|\alpha_1 e_1 + \dots + \alpha_n e_n\|_0 & (\langle 1 \rangle 4) \end{aligned}$$
  
 (2)3.  $\|u + v\|_0 \leq \|u\|_0 + \|v\|_0$   
 PROOF:  

$$\begin{aligned} \|(\alpha_1 e_1 + \dots + \alpha_n e_n) + (\beta_1 e_1 + \dots + \beta_n e_n)\| &= |\alpha_1 + \beta_1| + \dots + |\alpha_n + \beta_n| \\ &\leq |\alpha_1| + \dots + |\alpha_n| + |\beta_1| + \dots + |\beta_n| \\ &= \|\alpha_1 e_1 + \dots + \alpha_n e_n\|_0 + \|\beta_1 e_1 + \dots + \beta_n e_n\|_0 \end{aligned}$$
  
 (1)6. Any norm on  $V$  is equivalent to  $\|\cdot\|_0$ .  
 (2)1. LET:  $\|\cdot\|$  be any norm on  $V$ .  
 (2)2. PICK  $\alpha > 0$  such that, for all  $\alpha_1, \dots, \alpha_n \in K$ , we have  $\|\alpha_1 e_1 + \dots + \alpha_n e_n\| \geq \alpha(|\alpha_1| + \dots + |\alpha_n|)$   
 PROOF: Proposition 9.0.13, (2)1, (1)3.  
 (2)3. LET:  $\beta = \max(\|e_1\|, \dots, \|e_n\|)$   
 (2)4.  $\beta > 0$   
 PROOF:  $e_1, \dots, e_n$  cannot all be zero by (1)3.

$\langle 2 \rangle 5$ . For all  $x \in V$  we have  $\alpha \|x\|_0 \leq \|x\| \leq \beta \|x\|_0$

$\langle 3 \rangle 1$ . LET:  $x \in V$

$\langle 3 \rangle 2$ .  $\alpha \|x\|_0 \leq \|x\|$

PROOF:  $\langle 1 \rangle 3$ ,  $\langle 1 \rangle 4$ ,  $\langle 2 \rangle 2$ .

$\langle 3 \rangle 3$ .  $\|x\| \leq \beta \|x\|_0$

$\langle 4 \rangle 1$ . LET:  $x = \alpha_1 e_1 + \cdots + \alpha_n e_n$

$\langle 4 \rangle 2$ . Q.E.D.

PROOF:

$$\|x\| = \|\alpha_1 e_1 + \cdots + \alpha_n e_n\| \quad (\langle 4 \rangle 1)$$

$$\leq |\alpha_1| \|e_1\| + \cdots + |\alpha_n| \|e_n\| \quad (\langle 2 \rangle 1)$$

$$\leq \beta(|\alpha_1| + \cdots + |\alpha_n|) \quad (\langle 2 \rangle 3)$$

$$= \beta \|x\|_0 \quad (\langle 1 \rangle 4)$$

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

PROOF: Theorem 9.1.12,  $\langle 1 \rangle 5$ ,  $\langle 2 \rangle 1$ ,  $\langle 2 \rangle 2$ ,  $\langle 2 \rangle 4$ ,  $\langle 2 \rangle 5$ .

□

**Definition 9.1.14** (Open Ball). Let  $V$  be a normed space over  $K$ . Let  $x \in V$ . Let  $r > 0$ . The *open ball* with *centre*  $x$  and *radius*  $r$  is

$$B(x, r) := \{y \in V \mid \|y - x\| < r\} .$$

**Definition 9.1.15** (Closed Ball). Let  $V$  be a normed space over  $K$ . Let  $x \in V$ . Let  $r > 0$ . The *closed ball* with *centre*  $x$  and *radius*  $r$  is

$$\overline{B}(x, r) := \{y \in V \mid \|y - x\| \leq r\} .$$

**Definition 9.1.16** (Sphere). Let  $V$  be a normed space over  $K$ . Let  $x \in V$ . Let  $r > 0$ . The *sphere* with *centre*  $x$  and *radius*  $r$  is

$$S(x, r) := \{y \in V \mid \|y - x\| = r\} .$$

**Definition 9.1.17** (Open Set). Let  $V$  be a normed space over  $K$ . A set  $S \subseteq V$  is *open* iff, for all  $x \in S$ , there exists  $\epsilon > 0$  such that  $B(x, \epsilon) \subseteq S$ .

**Proposition 9.1.18**. *Equivalent norms define the same set of open sets.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $V$  be a normed space over  $K$ .

$\langle 1 \rangle 2$ . LET:  $\|\cdot\|_1$  and  $\|\cdot\|_2$  be equivalent norms on  $V$ .

$\langle 1 \rangle 3$ . PICK reals  $\alpha, \beta > 0$  such that, for all  $x \in V$ , we have  $\alpha \|x\|_1 \leq \|x\|_2 \leq \beta \|x\|_1$

$\langle 1 \rangle 4$ . LET:  $S \subseteq V$

$\langle 1 \rangle 5$ . If  $S$  is open under  $\|\cdot\|_1$  then  $S$  is open under  $\|\cdot\|_2$ .

$\langle 2 \rangle 1$ . ASSUME:  $S$  is open under  $\|\cdot\|_1$ .

$\langle 2 \rangle 2$ . LET:  $x \in S$

$\langle 2 \rangle 3$ . PICK  $\epsilon > 0$  such that  $\{y \in V \mid \|x - y\|_1 < \epsilon\} \subseteq S$ .

$\langle 2 \rangle 4$ . LET:  $\delta = \alpha \epsilon$



- $\langle 2 \rangle 5. \{y \in V \mid \|x - y\|_2 < \delta\} \subseteq S$   
 $\langle 1 \rangle 6. \text{ If } S \text{ is open under } \|\cdot\|_2 \text{ then } S \text{ is open under } \|\cdot\|_1.$

PROOF: Similar.

□

**Proposition 9.1.19.** *Every open ball is open.*

PROOF:

$\langle 1 \rangle 1. \text{ LET: } V \text{ be a normed space over } K.$

$\langle 1 \rangle 2. \text{ LET: } c \in V \text{ and } r > 0$

PROVE:  $B(c, r)$  is open.

$\langle 1 \rangle 3. \text{ LET: } x \in B(c, r)$

$\langle 1 \rangle 4. \text{ LET: } \epsilon = r - \|x - c\|$

PROVE:  $B(x, \epsilon) \subseteq B(c, r)$

$\langle 1 \rangle 5. \text{ LET: } y \in B(x, \epsilon)$

PROVE:  $y \in B(c, r)$

$\langle 1 \rangle 6. \|y - c\| < r$

PROOF:

$$\begin{aligned} \|y - c\| &\leq \|y - x\| + \|x - c\| && \text{(Triangle Inequality)} \\ &< \epsilon + \|x - c\| && (\langle 1 \rangle 5) \\ &= r && (\langle 1 \rangle 4) \end{aligned}$$

□

**Proposition 9.1.20.** *Let  $\Omega$  be a closed bounded set in  $\mathbb{R}^n$ . Let  $f \in \mathcal{C}(\Omega)$ . Then  $U = \{g \in \mathcal{C}(\Omega) \mid \forall x \in \Omega, g(x) < f(x)\}$  is open.*

PROOF:

$\langle 1 \rangle 1. \text{ LET: } g \in U$

$\langle 1 \rangle 2. \text{ LET: } \epsilon = \max_{x \in \Omega} (f(x) - g(x))$

PROVE:  $B(g, \epsilon) \subseteq U$

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

$\langle 1 \rangle 4. \text{ LET: } h \in B(g, \epsilon/2)$

PROVE:  $h \in U$

$\langle 1 \rangle 5. \text{ LET: } x \in \Omega$

$\langle 1 \rangle 6. h(x) < f(x)$

PROOF:

$$\begin{aligned} h(x) &\leq g(x) + \epsilon/2 && (\langle 1 \rangle 4) \\ &< g(x) + \epsilon && (\langle 1 \rangle 3) \\ &\leq f(x) && (\langle 1 \rangle 2) \end{aligned}$$

□

**Proposition 9.1.21.** *Let  $\Omega$  be a closed bounded set in  $\mathbb{R}^n$ . Let  $f \in \mathcal{C}(\Omega)$ . Then  $U = \{g \in \mathcal{C}(\Omega) \mid \forall x \in \Omega, g(x) > f(x)\}$  is open.*

PROOF: Given  $g \in U$ , let  $\epsilon = \max_x (g(x) - f(x))/2$ . Then  $B(g, \epsilon) \subseteq U$ . □

**Proposition 9.1.22.** *Let  $\Omega$  be a closed bounded set in  $\mathbb{R}^n$ . Let  $f \in \mathcal{C}(\Omega)$  be such that  $f(x) > 0$  for all  $x \in \Omega$ . Then  $U = \{g \in \mathcal{C}(\Omega) \mid \forall x \in \Omega, |g(x)| < f(x)\}$  is open.*

PROOF: Given  $g \in U$ , let  $\epsilon = \max_x (f(x) - |g(x)|)/2$ . Then  $B(g, \epsilon) \subseteq U$ .  $\square$

**Proposition 9.1.23.** *Let  $\Omega$  be a closed bounded set in  $\mathbb{R}^n$ . Let  $f \in \mathcal{C}(\Omega)$  be such that  $f(x) > 0$  for all  $x \in \Omega$ . Then  $U = \{g \in \mathcal{C}(\Omega) \mid \forall x \in \Omega, |g(x)| > f(x)\}$  is open.*

PROOF: Given  $g \in U$ , let  $\epsilon = \max_x (|g(x)| - f(x))/2$ . Then  $B(g, \epsilon) \subseteq U$ .  $\square$

**Proposition 9.1.24.** *The union of a set of open sets is open.*

PROOF:

- $\langle 1 \rangle 1$ . LET:  $V$  be a normed space over  $K$ .
- $\langle 1 \rangle 2$ . LET:  $\mathcal{U}$  be a set of open sets in  $V$ .
- $\langle 1 \rangle 3$ . LET:  $x \in \bigcup \mathcal{U}$
- $\langle 1 \rangle 4$ . PICK  $U \in \mathcal{U}$  such that  $x \in U$ .
- $\langle 1 \rangle 5$ . PICK  $\epsilon > 0$  such that  $B(x, \epsilon) \subseteq U$
- $\langle 1 \rangle 6$ .  $B(x, \epsilon) \subseteq \bigcup \mathcal{U}$

$\square$

**Proposition 9.1.25.** *The intersection of two open sets is open.*

PROOF:

- $\langle 1 \rangle 1$ . LET:  $V$  be a normed space over  $K$ .
- $\langle 1 \rangle 2$ . LET:  $U_1$  and  $U_2$  be open sets in  $V$ .
- $\langle 1 \rangle 3$ . LET:  $x \in U_1 \cap U_2$
- $\langle 1 \rangle 4$ . PICK  $\epsilon_1 > 0$  such that  $B(x, \epsilon_1) \subseteq U_1$
- $\langle 1 \rangle 5$ . PICK  $\epsilon_2 > 0$  such that  $B(x, \epsilon_2) \subseteq U_2$
- $\langle 1 \rangle 6$ . LET:  $\epsilon = \min(\epsilon_1, \epsilon_2)$
- $\langle 1 \rangle 7$ .  $B(x, \epsilon) \subseteq U_1 \cap U_2$

$\square$

**Proposition 9.1.26.** *In any normed space,  $\emptyset$  is open.*

PROOF: Vacuous.  $\square$

**Proposition 9.1.27.** *In any normed space  $V$ , the whole space  $V$  is open.*

PROOF: For any  $x \in V$  we have  $B(x, 1) \subseteq V$ .  $\square$

**Definition 9.1.28** (Closed Set). Let  $V$  be a normed space over  $K$ . A set  $S \subseteq V$  is *closed* iff  $V - S$  is open.

**Proposition 9.1.29.** *Every closed ball is closed.*

PROOF:

- $\langle 1 \rangle 1$ . LET:  $V$  be a normed space over  $K$ .
- $\langle 1 \rangle 2$ . LET:  $c \in V$  and  $r > 0$   
           PROVE:  $\overline{B}(c, r)$  is closed.
- $\langle 1 \rangle 3$ . LET:  $x \in V - \overline{B}(c, r)$
- $\langle 1 \rangle 4$ . LET:  $\epsilon = \|x - c\| - r$   
           PROVE:  $B(x, \epsilon) \subseteq V - \overline{B}(c, r)$

(1)5.  $\epsilon > 0$

PROOF: Since  $\|x - c\| > r$  by (1)3.

(1)6. LET:  $y \in B(x, \epsilon)$

(1)7.  $\|y - c\| > r$

PROOF:

$$\begin{aligned} \|y - c\| &\geq \|x - c\| - \|x - y\| && \text{(Triangle Inequality)} \\ &> \|x - c\| - \epsilon && ((1)6) \\ &= r && ((1)4) \end{aligned}$$

□

**Proposition 9.1.30.** *The intersection of a set of closed sets is closed.*

PROOF: From Proposition 9.1.24. □

**Proposition 9.1.31.** *The union of two closed sets is closed.*

PROOF: From Proposition 9.1.25. □

**Proposition 9.1.32.** *Every sphere is closed.*

PROOF:  $S(c, r) = \overline{B}(c, r) - B(c, r)$ . □

**Proposition 9.1.33.** *Let  $\Omega$  be a closed bounded set in  $\mathbb{R}^n$ . Let  $f \in \mathcal{C}(\Omega)$ . Then  $\{g \in \mathcal{C}(\Omega) \mid \forall x \in \Omega. g(x) \leq f(x)\}$  is closed.*

PROOF: It is  $\mathcal{C}(\Omega) - \{g \mid \forall x \in \Omega. g(x) > f(x)\}$ . □

**Proposition 9.1.34.** *Let  $\Omega$  be a closed bounded set in  $\mathbb{R}^n$ . Let  $f \in \mathcal{C}(\Omega)$ . Then  $\{g \in \mathcal{C}(\Omega) \mid \forall x \in \Omega. g(x) \geq f(x)\}$  is closed.*

PROOF: It is  $\mathcal{C}(\Omega) - \{g \mid \forall x \in \Omega. g(x) < f(x)\}$ . □

**Proposition 9.1.35.** *Let  $\Omega$  be a closed bounded set in  $\mathbb{R}^n$ . Let  $f \in \mathcal{C}(\Omega)$ . Then  $\{g \in \mathcal{C}(\Omega) \mid \forall x \in \Omega. |g(x)| \leq f(x)\}$  is closed.*

PROOF: It is  $\mathcal{C}(\Omega) - \{g \mid \forall x \in \Omega. |g(x)| > f(x)\}$ . □

**Proposition 9.1.36.** *Let  $\Omega$  be a closed bounded set in  $\mathbb{R}^n$ . Let  $f \in \mathcal{C}(\Omega)$ . Then  $\{g \in \mathcal{C}(\Omega) \mid \forall x \in \Omega. |g(x)| \geq f(x)\}$  is closed.*

PROOF: It is  $\mathcal{C}(\Omega) - \{g \mid \forall x \in \Omega. |g(x)| < f(x)\}$ . □

**Proposition 9.1.37.** *Let  $\Omega$  be a closed bounded set in  $\mathbb{R}^n$ . Let  $x_0 \in \Omega$  and  $\lambda \in \mathbb{C}$ . Then  $C = \{g \in \mathcal{C}(\Omega) \mid g(x_0) = \lambda\}$  is closed.*

PROOF: Given  $g \in \mathcal{C}(\Omega) - C$ , let  $\epsilon = |g(x_0) - \lambda|/2$ . Then  $B(g, \epsilon) \subseteq \mathcal{C}(\Omega) - C$ . □

**Proposition 9.1.38.** *In any normed space  $V$ , we have  $\emptyset$  is closed.*

PROOF: Since  $V - \emptyset = V$  is open. □

**Proposition 9.1.39.** *In any normed space  $V$ , the whole space  $V$  is closed.*

PROOF: Since  $V - V = \emptyset$  is open.  $\square$

**Theorem 9.1.40.** *Let  $V$  be a normed space over  $K$ . Let  $S$  be a subset of  $V$ . Then  $S$  is closed if and only if, for any sequence  $(x_n)$  in  $S$ , if  $x_n \rightarrow l$  as  $n \rightarrow \infty$  then  $l \in S$ .*

PROOF:

- (1)1. If  $S$  is closed then, for any sequence  $(x_n)$  in  $S$ , if  $x_n \rightarrow l$  as  $n \rightarrow \infty$  then  $l \in S$ .
  - (2)1. ASSUME:  $S$  is closed.
  - (2)2. LET:  $(x_n)$  be a sequence in  $S$ .
  - (2)3. ASSUME:  $x_n \rightarrow l$  as  $n \rightarrow \infty$ .
  - (2)4. ASSUME: for a contradiction  $l \notin S$ .
  - (2)5. PICK  $\epsilon > 0$  such that  $B(l, \epsilon) \subseteq V - S$
  - (2)6. PICK  $N$  such that  $\forall n \geq N. x_n \in B(l, \epsilon)$
  - (2)7.  $x_N \in V - S$
  - (2)8. This contradicts (2)2.
- (1)2. If, for any sequence  $(x_n)$  in  $S$ , if  $x_n \rightarrow l$  as  $n \rightarrow \infty$  then  $l \in S$ , then  $S$  is closed.
  - (2)1. ASSUME: for any sequence  $(x_n)$  in  $S$ , if  $x_n \rightarrow l$  as  $n \rightarrow \infty$  then  $l \in S$ .
  - (2)2. LET:  $x \in V - S$
  - (2)3. ASSUME: for a contradiction there is no  $\epsilon > 0$  such that  $B(x, \epsilon) \subseteq V - S$ .
  - (2)4. For  $n \in \mathbb{Z}_+$ , PICK  $x_n \in B(x, 1/n) \cap S$
  - (2)5.  $x_n \rightarrow x$  as  $n \rightarrow \infty$
  - (2)6.  $x \in S$
  - (2)7. This contradicts (2)2.

$\square$

**Definition 9.1.41** (Closure). Let  $V$  be a normed space over  $K$ . Let  $S$  be a subset of  $V$ . The *closure* of  $S$ ,  $\text{cl } S$ , is the intersection of the set of closed sets that include  $S$ .

**Proposition 9.1.42.** *Let  $V$  be a normed space over  $K$ . Let  $S$  be a subset of  $V$ . Then the closure of  $S$  is the smallest closed set that includes  $S$ .*

PROOF: Proposition 9.1.30.  $\square$

**Theorem 9.1.43.** *Let  $V$  be a normed space over  $K$ . Let  $S$  be a subset of  $V$ . Then*

$$\text{cl } S = \{l \in V \mid \exists \text{ a sequence } (x_n) \text{ in } S. x_n \rightarrow l \text{ as } n \rightarrow \infty\} .$$

PROOF:

- (1)1. For all  $l \in \text{cl } S$ , there exists a sequence  $(x_n)$  in  $S$  such that  $x_n \rightarrow l$  as  $n \rightarrow \infty$ .
    - (2)1. LET:  $l \in \text{cl } S$
    - (2)2. For  $n \in \mathbb{Z}_+$ , pick  $x_n \in B(l, 1/n) \cap S$
- PROOF: There must be such an  $x_n$  otherwise  $S - B(l, 1/n)$  would be a smaller closed set that includes  $S$ .

- ⟨2⟩3.  $x_n \rightarrow l$  as  $n \rightarrow \infty$   
 ⟨1⟩2. For any sequence  $(x_n)$  in  $S$ , if  $x_n \rightarrow l$  as  $n \rightarrow \infty$  then  $l \in \text{cl } S$ .  
 PROOF: Theorem 9.1.40.

□

**Definition 9.1.44** (Dense). Let  $V$  be a normed space over  $K$ . Let  $S \subseteq V$ . Then  $S$  is *dense* if and only if  $\text{cl } S = V$ .

**Theorem 9.1.45** (Weierstrass Approximation Theorem). Let  $a$  and  $b$  be real numbers with  $a < b$ . In  $\mathcal{C}([a, b])$ , the set of polynomials is dense.

PROOF: TODO

**Proposition 9.1.46.** Let  $p \geq 1$ . The set of all sequences that have only finitely many non-zero terms is dense in  $l^p$ .

PROOF:

- ⟨1⟩1. LET:  $(z_n) \in l^p$   
 ⟨1⟩2. LET:  $\epsilon > 0$   
 PROVE: There exists a sequence  $(x_n)$  with only finitely many non-zero terms such that  $(\sum_{n=1}^{\infty} |z_n - x_n|^p)^{1/p} < \epsilon$   
 ⟨1⟩3. PICK  $N$  such that  $|\sum_{n=1}^{\infty} |z_n|^p - \sum_{n=1}^N |z_n|^p| < \epsilon^p$   
 ⟨1⟩4. LET:  $(x_n)$  be the sequence that agrees with  $(z_n)$  up to term  $N$ , and then zeros after that.  
 ⟨1⟩5.  $(\sum_{n=1}^{\infty} |z_n - x_n|^p)^{1/p} < \epsilon$

PROOF:

$$\left( \sum_{n=1}^{\infty} |z_n - x_n|^p \right)^{1/p} = \left( \sum_{n=N+1}^{\infty} |z_n|^p \right)^{1/p} < \epsilon \quad (\langle 1 \rangle 4)$$

$$< \epsilon \quad (\langle 1 \rangle 2)$$

□

**Theorem 9.1.47.** Let  $V$  be a normed space over  $K$ . Let  $S \subseteq V$ . Then the following are equivalent.

1.  $S$  is dense.
2. For all  $l \in V$ , there exists a sequence  $(x_n)$  in  $S$  such that  $x_n \rightarrow l$  as  $n \rightarrow \infty$ .
3. Every nonempty open subset of  $V$  intersects  $S$ .

PROOF:

- ⟨1⟩1.  $1 \Leftrightarrow 2$   
 PROOF: Theorem 9.1.43.  
 ⟨1⟩2.  $1 \Rightarrow 3$   
 ⟨2⟩1. ASSUME:  $S$  is dense.  
 ⟨2⟩2. LET:  $U$  be a nonempty open subset of  $V$ .  
 ⟨2⟩3.  $X - U$  does not include  $S$ .

PROOF: Lest we have  $\text{cl } S \subseteq X - U$ .

$\langle 2 \rangle 4$ .  $U$  intersects  $S$ .

$\langle 1 \rangle 3$ .  $3 \Rightarrow 1$

$\langle 2 \rangle 1$ . ASSUME: Every nonempty subset of  $V$  intersects  $S$ .

$\langle 2 \rangle 2$ . Every closed proper subset of  $V$  does not include  $S$ .

$\langle 2 \rangle 3$ .  $\text{cl } S = V$

□

**Definition 9.1.48** (Compact). Let  $V$  be a normed space over  $K$  and  $S \subseteq V$ . Then  $S$  is *compact* if and only if every sequence in  $S$  has a convergent subsequence whose limit is in  $S$ .

**Proposition 9.1.49.** *In  $K^n$ , a set is compact if and only if it is bounded and closed.*

PROOF: TODO

**Definition 9.1.50** (Bounded). Let  $V$  be a normed space over  $K$  and  $S \subseteq V$ . Then  $S$  is *bounded* iff there exists  $r > 0$  such that  $S \subseteq B(0, r)$ .

**Theorem 9.1.51.** *Every compact set is closed and bounded.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $V$  be a normed space over  $K$ .

$\langle 1 \rangle 2$ . LET:  $S \subseteq V$  be compact.

$\langle 1 \rangle 3$ .  $S$  is closed.

$\langle 2 \rangle 1$ . LET:  $(x_n)$  be a sequence in  $S$  that converges to  $l$

$\langle 2 \rangle 2$ . PICK a sequence  $(x_{n_r})$  that converges to  $x \in S$

PROOF:  $\langle 1 \rangle 2$ ,  $\langle 2 \rangle 1$

$\langle 2 \rangle 3$ .  $x_{n_r} \rightarrow l$  as  $n \rightarrow \infty$

PROOF:  $\langle 2 \rangle 1$ ,  $\langle 2 \rangle 2$

$\langle 2 \rangle 4$ .  $l = x$

PROOF: Proposition 9.1.2.

$\langle 2 \rangle 5$ .  $l \in S$

PROOF:  $\langle 2 \rangle 2$ ,  $\langle 2 \rangle 4$

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

PROOF: Theorem 9.1.40.

$\langle 1 \rangle 4$ .  $S$  is bounded.

$\langle 2 \rangle 1$ . ASSUME: for a contradiction  $S$  is unbounded.

$\langle 2 \rangle 2$ . For  $n \in \mathbb{Z}_+$ , PICK  $x_n \in S - B(0, n)$

$\langle 2 \rangle 3$ . PICK a convergent subsequence  $(x_{n_r})$  that converges to  $l$ , say.

$\langle 2 \rangle 4$ . PICK  $N \in \mathbb{Z}_+$  such that  $\|l\| < N$

$\langle 2 \rangle 5$ . PICK  $r$  such that  $n_r > N$  and  $\|x_{n_r} - l\| < N - \|l\|$

$\langle 2 \rangle 6$ .  $\|x_{n_r}\| < N < n_r$

$\langle 2 \rangle 7$ . This contradicts  $\langle 2 \rangle 2$ .

□

**Proposition 9.1.52.** *In  $\mathcal{C}([0, 1])$ , the closed ball  $\overline{B}(0, 1)$  is closed and bounded but not compact.*

PROOF: The sequence of functions  $(x^n)$  is in  $\overline{B}(0, 1)$  but has no convergent subsequence.  $\square$

**Theorem 9.1.53** (Riesz's Lemma). *Let  $V$  be a normed vector space over  $K$ . Let  $X$  be a closed proper subspace of  $V$ . Let  $0 < \epsilon < 1$ . Then there exists  $x \in V$  such that  $\|x\| = 1$  and  $\forall y \in X, \|x - y\| \geq \epsilon$ .*

PROOF:

$\langle 1 \rangle 1$ . PICK  $z \in V - X$

$\langle 1 \rangle 2$ . LET:  $d = \inf_{x \in X} \|z - x\|$

$\langle 1 \rangle 3$ .  $d > 0$

PROOF: Since  $X$  is closed, there exists  $e > 0$  such that  $B(z, d) \subseteq V - X$  and hence  $\|z - x\| \geq d$  for all  $x \in X$ .

$\langle 1 \rangle 4$ . PICK  $x_0 \in X$  such that  $d \leq \|z - x_0\| \leq d/\epsilon$

PROOF: One exists since  $d/\epsilon$  is not a lower bound for  $\{\|z - x\| \mid x \in X\}$ .

$\langle 1 \rangle 5$ . LET:  $x = (z - x_0)/\|z - x_0\|$

$\langle 1 \rangle 6$ . LET:  $y \in X$

$\langle 1 \rangle 7$ .  $\|x - y\| \geq \epsilon$

PROOF:

$$\|x - y\| = \left\| \frac{z - x_0}{\|z - x_0\|} - y \right\| \quad (\langle 1 \rangle 5)$$

$$= \frac{1}{\|z - x_0\|} \|z - (x_0 + \|z - x_0\|y)\|$$

$$\geq \frac{1}{\|z - x_0\|} d \quad (\langle 1 \rangle 2)$$

$$\geq \epsilon \quad (\langle 1 \rangle 4)$$

$\square$

**Theorem 9.1.54.** *Let  $V$  be a normed space over  $K$ . Then  $V$  is finite dimensional if and only if  $\overline{B}(0, 1)$  is compact.*

PROOF:

$\langle 1 \rangle 1$ . If  $V$  is finite dimensional then  $\overline{B}(0, 1)$  is compact.

$\langle 2 \rangle 1$ . ASSUME:  $V$  is finite dimensional.

$\langle 2 \rangle 2$ . PICK a basis  $\{e_1, \dots, e_n\}$

$\langle 2 \rangle 3$ . ASSUME: w.l.o.g.  $\|\alpha_1 e_1 + \dots + \alpha_n e_n\| = |\alpha_1| + \dots + |\alpha_n|$

$\langle 2 \rangle 4$ . LET:  $(\alpha_{k1} e_1 + \dots + \alpha_{kn} e_n)$  be a sequence in  $\overline{B}(0, 1)$

$\langle 2 \rangle 5$ . PICK a convergent subsequence  $(\alpha_{k_r, 1})$  of  $(\alpha_{k1})$ , a convergent subsequence  $(\alpha_{k_r', 2})$  of  $(\alpha_{k_r, 2})$ ,  $\dots$ , a convergent subsequence  $(\alpha_{k_r'', n})$ .

$\langle 2 \rangle 6$ .  $(\alpha_{k_r'', 1} e_1 + \dots + \alpha_{k_r'', n} e_n)$  converges.

$\langle 1 \rangle 2$ . If  $V$  is infinite dimensional then  $\overline{B}(0, 1)$  is not compact.

$\langle 2 \rangle 1$ . ASSUME:  $V$  is infinite dimensional.

$\langle 2 \rangle 2$ . Choose a sequence  $(x_n)$  with  $\|x_n\| = 1$  and  $\|x_m - x_n\| \geq 1/2$  for  $m \neq n$

$\langle 3 \rangle 1$ . ASSUME:  $x_1, \dots, x_n$  satisfy  $\|x_i\| = 1$  and  $\|x_i - x_j\| \geq 1/2$  for  $i \neq j$

$\langle 3 \rangle 2$ . PICK  $x_{n+1} \in V$  such that  $\|x_{n+1}\| = 1$  and for all  $y \in \text{span}\{x_1, \dots, x_n\}$  we have  $\|x_{n+1} - y\| \geq 1/2$

- ⟨4⟩1.  $\text{span}\{x_1, \dots, x_n\}$  is closed.
- ⟨5⟩1. LET:  $S = \text{span}\{x_1, \dots, x_n\}$
- ⟨5⟩2. LET:  $(a_n)$  be a sequence in  $S$  that converges to  $a \in V$   
PROVE:  $a \in S$
- ⟨5⟩3.  $(a_n)$  is a Cauchy sequence in  $V$ .
- ⟨5⟩4.  $(a_n)$  is a Cauchy sequence in  $S$ .
- ⟨5⟩5. A finite dimensional normed space is a Banach space.
- ⟨5⟩6.  $S$  is complete.
- ⟨5⟩7.  $a \in S$
- ⟨4⟩2.  $\text{span}\{x_1, \dots, x_n\}$  is a proper subspace of  $V$ .  
PROOF: ⟨2⟩1
- ⟨4⟩3. Q.E.D.  
PROOF: Riesz's Lemma.
- ⟨2⟩3. ASSUME: for a contradiction  $(x_{n_r})$  is a subsequence that converges to  $l$
- ⟨2⟩4. For all  $r \in \mathbb{N}$ , we have  $\|x_{n_r} - l\| + \|x_{n_{r+1}} - l\| \geq 1/2$
- ⟨2⟩5. This is a contradiction.

□

**Proposition 9.1.55.** *Let  $V$  be a normed space. The closure of a subspace of  $V$  is a subspace.*

PROOF:

- ⟨1⟩1. LET:  $U$  be a subspace of  $V$
- ⟨1⟩2. LET:  $x, y \in \text{cl}U$  and  $\alpha, \beta \in K$
- ⟨1⟩3. PICK sequences  $(x_n), (y_n)$  in  $U$  that converge to  $x$  and  $y$  respectively.
- ⟨1⟩4.  $\alpha x_n + \beta y_n \rightarrow \alpha x + \beta y$  as  $n \rightarrow \infty$
- ⟨1⟩5.  $\alpha x + \beta y \in \text{cl}U$

□

## 9.2 Continuous Linear Mappings

**Definition 9.2.1** (Continuous). Let  $U$  and  $V$  be normed spaces. Let  $f : U \rightarrow V$  and  $x \in U$ . Then  $f$  is *continuous at  $x$*  iff, for any sequence  $(x_n)$  in  $U$ , if  $x_n \rightarrow x$  as  $n \rightarrow \infty$  then  $f(x_n) \rightarrow f(x)$  as  $n \rightarrow \infty$ . The function  $f$  is *continuous* iff  $f$  is continuous at every point.

**Proposition 9.2.2.** *Let  $V$  be a normed space. Then the norm is a continuous function  $V \rightarrow \mathbb{R}$ .*

PROOF: From Proposition 9.0.4. □

**Proposition 9.2.3.** *Let  $U$  and  $V$  be normed space. Let  $f : U \rightarrow V$ . Then the following are equivalent.*

1.  $f$  is continuous.
2. For any open set  $S$  in  $V$ , we have  $f^{-1}(S)$  is open in  $U$ .



3. For any closed set  $C$  in  $V$ , we have  $f^{-1}(C)$  is closed in  $U$ .

**Proposition 9.2.4.** *Let  $U$  and  $V$  be normed spaces over  $K$ . Let  $T : U \rightarrow V$  be a linear transformation. If  $T$  is continuous at some point, then it is continuous.*

PROOF:

- $\langle 1 \rangle 1$ . ASSUME:  $T$  is continuous at  $u_0$
- $\langle 1 \rangle 2$ . LET:  $x_n \rightarrow l$  as  $n \rightarrow \infty$  in  $U$
- $\langle 1 \rangle 3$ .  $x_n - l + u_0 \rightarrow u_0$  as  $n \rightarrow \infty$ .
- $\langle 1 \rangle 4$ .  $T(x_n - l + u_0) \rightarrow T(u_0)$  as  $n \rightarrow \infty$ .
- $\langle 1 \rangle 5$ .  $T(x_n) - T(l) + T(u_0) \rightarrow T(u_0)$  as  $n \rightarrow \infty$ .
- $\langle 1 \rangle 6$ .  $T(x_n) \rightarrow T(l)$  as  $n \rightarrow \infty$ .

□

**Definition 9.2.5** (Bounded). Let  $U$  and  $V$  be normed spaces over  $K$ . Let  $T : U \rightarrow V$  be a linear transformation. Then  $T$  is *bounded* iff there exists  $\alpha > 0$  such that, for all  $x \in U$ , we have  $\|T(x)\| \leq \alpha\|x\|$ .

**Theorem 9.2.6.** *Let  $U$  and  $V$  be normed spaces over  $K$ . Let  $T : U \rightarrow V$  be a linear transformation. Then  $T$  is continuous if and only if it is bounded.*

PROOF:

- $\langle 1 \rangle 1$ . If  $T$  is continuous then  $T$  is bounded.
- $\langle 2 \rangle 1$ . ASSUME:  $T$  is not bounded.
- $\langle 2 \rangle 2$ . For  $n \in \mathbb{Z}_+$ , PICK  $x_n \in U$  such that  $\|T(x_n)\| > n\|x_n\|$ .
- $\langle 2 \rangle 3$ . For  $n \in \mathbb{Z}_+$ ,  
LET:

$$y_n = \frac{x_n}{n\|x_n\|}$$

- $\langle 2 \rangle 4$ .  $y_n \rightarrow 0$  as  $n \rightarrow \infty$
- $\langle 2 \rangle 5$ .  $T(y_n) \not\rightarrow 0$  as  $n \rightarrow \infty$
- $\langle 2 \rangle 6$ .  $T$  is not continuous.
- $\langle 1 \rangle 2$ . If  $T$  is bounded then  $T$  is continuous.
- $\langle 2 \rangle 1$ . ASSUME:  $T$  is bounded.
- $\langle 2 \rangle 2$ . PICK  $\alpha > 0$  such that  $\forall x \in U, \|T(x)\| \leq \alpha\|x\|$ .
- $\langle 2 \rangle 3$ .  $T$  is continuous at 0.
- $\langle 3 \rangle 1$ . LET:  $(x_n)$  be a sequence that converges to 0 in  $U$
- $\langle 3 \rangle 2$ .  $T(x_n) \rightarrow 0$  as  $n \rightarrow \infty$

PROOF:

$$\begin{aligned} \|T(x_n)\| &\leq \alpha\|x_n\| && (\langle 2 \rangle 2) \\ &\rightarrow 0 && \text{as } n \rightarrow \infty \end{aligned}$$

- $\langle 2 \rangle 4$ .  $T$  is continuous.

PROOF: Proposition 9.2.4.

□

**Proposition 9.2.7.** *Let  $U$  and  $V$  be normed spaces over  $K$  where  $U$  is finite dimensional. Let  $T : U \rightarrow V$  be a linear transformation. Then  $T$  is bounded.*

PROOF:

- (1)1. PICK a basis  $\{e_1, \dots, e_n\}$  of unit vectors for  $U$ .  
 (1)2. LET:  $M = \max(\|T(e_1)\|, \dots, \|T(e_n)\|)$   
 (1)3. PICK  $C > 0$  such that, for all  $\alpha_1, \dots, \alpha_n \in K$ , we have  $|\alpha_1| + \dots + |\alpha_n| \leq C\|\alpha_1 e_1 + \dots + \alpha_n e_n\|$

PROOF: Theorem 9.1.13.

- (1)4. LET:  $x \in U$   
 PROVE:  $\|T(x)\| \leq CM\|x\|$   
 (1)5. LET:  $x = \alpha_1 e_1 + \dots + \alpha_n e_n$   
 (1)6.  $\|T(x)\| \leq CM\|x\|$

PROOF:

$$\begin{aligned}
 \|T(x)\| &= \|\alpha_1 T(e_1) + \dots + \alpha_n T(e_n)\| && (T \text{ linear}) \\
 &\leq |\alpha_1| \|T(e_1)\| + \dots + |\alpha_n| \|T(e_n)\| && (\text{Triangle inequality}) \\
 &\leq M(|\alpha_1| + \dots + |\alpha_n|) && ((1)2) \\
 &\leq CM\|x\| && ((1)3)
 \end{aligned}$$

□

**Corollary 9.2.7.1.** *Let  $U$  and  $V$  be normed spaces over  $K$  where  $U$  is finite dimensional. Let  $T : U \rightarrow V$  be a linear transformation. Then  $T$  is continuous.*

**Proposition 9.2.8.** *Let  $U$  and  $V$  be normed spaces over  $K$ . Let  $T : U \rightarrow V$  be a linear transformation. If  $T$  is continuous, then  $T$  is uniformly continuous.*

PROOF:

- (1)1. ASSUME:  $T$  is continuous  
 (1)2. PICK  $B > 0$  such that  $\forall x \in U. \|T(x)\| \leq B\|x\|$   
 (1)3. LET:  $\epsilon > 0$   
 (1)4. LET:  $\delta = \epsilon/B$   
 (1)5. LET:  $x, y \in U$   
 (1)6. ASSUME:  $\|x - y\| < \delta$   
 (1)7.  $\|T(x) - T(y)\| < \epsilon$

PROOF:

$$\begin{aligned}
 \|T(x) - T(y)\| &= \|T(x - y)\| && (T \text{ linear}) \\
 &\leq B\|x - y\| && ((1)2) \\
 &< B\delta && ((1)6) \\
 &= \epsilon && ((1)4)
 \end{aligned}$$

□

**Proposition 9.2.9.** *Let  $U$  and  $V$  be normed spaces over  $K$ . The set  $\mathcal{B}(U, V)$  of all bounded linear maps from  $U$  to  $V$  forms a subspace of the space of all linear maps from  $U$  to  $V$ .*

PROOF:

- (1)1. LET:  $S, T : U \rightarrow V$  be bounded linear maps and  $\alpha, \beta \in K$ .  
 PROVE:  $\alpha S + \beta T$  is bounded.  
 (1)2. PICK  $B, C > 0$  such that  $\forall x \in U. \|S(x)\| \leq B\|x\|$  and  $\|T(x)\| \leq C\|x\|$   
 (1)3.  $\forall x \in U. \|(\alpha S + \beta T)(x)\| \leq (|\alpha|B + |\beta|C)\|x\|$

□

**Proposition 9.2.10.** *Let  $U$  and  $V$  be normed spaces over  $K$ . Define the operator norm  $\| \cdot \|$  on  $\mathcal{B}(U, V)$  by  $\|T\| := \sup\{\|T(x)\| \mid x \in U, \|x\| = 1\}$ . Then  $\| \cdot \|$  is a norm on  $\mathcal{B}(U, V)$ .*

PROOF:

$\langle 1 \rangle 1$ . For all  $T \in \mathcal{B}(U, V)$ , the set  $\{\|T(x)\| \mid x \in U, \|x\| = 1\}$  is bounded above.

$\langle 2 \rangle 1$ . LET:  $T \in \mathcal{B}(U, V)$

$\langle 2 \rangle 2$ . PICK  $B$  such that  $\forall x \in U, \|T(x)\| \leq B\|x\|$ .

$\langle 2 \rangle 3$ .  $B$  is an upper bound for  $\{\|T(x)\| \mid x \in U, \|x\| = 1\}$ .

$\langle 1 \rangle 2$ . If  $\|T\| = 0$  then  $T = 0$ .

$\langle 2 \rangle 1$ . ASSUME:  $\|T\| = 0$

$\langle 2 \rangle 2$ . LET:  $x \in U$

PROVE:  $T(x) = 0$

$\langle 2 \rangle 3$ . ASSUME: w.l.o.g.  $\|x\| \neq 0$

$\langle 2 \rangle 4$ . LET:  $y = x/\|x\|$

$\langle 2 \rangle 5$ .  $\|y\| = 1$

$\langle 2 \rangle 6$ .  $\|T(y)\| = 0$

$\langle 2 \rangle 7$ .  $T(y) = 0$

$\langle 2 \rangle 8$ .  $T(x) = 0$

$\langle 1 \rangle 3$ . For all  $\lambda \in K$  and  $T \in \mathcal{B}(U, V)$ , we have  $\|\lambda T\| = |\lambda|\|T\|$

$\langle 2 \rangle 1$ . LET:  $\lambda \in K$  and  $T \in \mathcal{B}(U, V)$

$\langle 2 \rangle 2$ .  $\|\lambda T\| = |\lambda|\|T\|$

PROOF:

$$\begin{aligned} \|\lambda T\| &= \sup\{\|\lambda T(x)\| \mid x \in U, \|x\| = 1\} \\ &= \sup\{|\lambda|\|T(x)\| \mid x \in U, \|x\| = 1\} \\ &= |\lambda| \sup\{\|T(x)\| \mid x \in U, \|x\| = 1\} \\ &= |\lambda|\|T\| \end{aligned}$$

$\langle 1 \rangle 4$ . For all  $S, T \in \mathcal{B}(U, V)$ , we have  $\|S + T\| \leq \|S\| + \|T\|$ .

$\langle 2 \rangle 1$ . LET:  $S, T \in \mathcal{B}(U, V)$

$\langle 2 \rangle 2$ .  $\|S + T\| \leq \|S\| + \|T\|$

PROOF:

$$\begin{aligned} \|S + T\| &= \sup\{\|S(x) + T(x)\| \mid x \in U, \|x\| = 1\} \\ &\leq \sup\{\|S(x)\| + \|T(x)\| \mid x \in U, \|x\| = 1\} \\ &\leq \sup\{\|S(x)\| \mid x \in U, \|x\| = 1\} + \sup\{\|T(x)\| \mid x \in U, \|x\| = 1\} \\ &= \|S\| + \|T\| \end{aligned}$$

□

**Proposition 9.2.11.** *Let  $U$  and  $V$  be normed spaces. Let  $T \in \mathcal{B}(U, V)$ . Then  $\|T\|$  is the least number such that  $\forall u \in U, \|T(u)\| \leq \|T\|\|u\|$ .*

PROOF:

$\langle 1 \rangle 1$ .  $\forall u \in U, \|T(u)\| \leq \|T\|\|u\|$

$\langle 2 \rangle 1$ . LET:  $u \in U$

$\langle 2 \rangle 2$ . LET:  $v = u/\|u\|$

- ⟨2⟩3.  $\|T(v)\| \leq \|T\|$
- ⟨2⟩4.  $\|T(u)\| \leq \|T\|\|u\|$
- ⟨1⟩2. If  $\alpha$  satisfies  $\forall u \in U. \|T(u)\| \leq \alpha\|u\|$ , then  $\|T\| \leq \alpha$
- ⟨2⟩1. ASSUME:  $\forall u \in U. \|T(u)\| \leq \alpha\|u\|$
- ⟨2⟩2. For all  $x \in U$ , if  $\|x\| = 1$  then  $\|T(x)\| \leq \alpha$
- ⟨2⟩3.  $\|T\| \leq \alpha$

□

**Proposition 9.2.12.** *Let  $V$  be a normed space. Then  $\text{id}_V$  is a bounded linear function  $V \rightarrow V$ , and  $\|\text{id}_V\| = 1$ .*

**Proposition 9.2.13.** *Let  $U$  and  $V$  be normed spaces. The constant zero function  $U \rightarrow V$  is a bounded linear transformation with norm 0.*

**Proposition 9.2.14.** *Let  $N \in \mathbb{N}$ . Let  $T : \mathbb{C}^N \rightarrow \mathbb{C}^N$  be a linear transformation with matrix  $A = (a_{ij})$ . Then  $T$  is bounded and*

$$\|T\| \leq \sqrt{\sum_{i=1}^N \sum_{j=1}^N |a_{ij}|^2}.$$

**Definition 9.2.15** (Uniform Convergence). Let  $U$  and  $V$  be normed spaces. Let  $(T_n)$  be a sequence in  $\mathcal{B}(U, V)$  and  $T \in \mathcal{B}(U, V)$ . Then  $(T_n)$  converges uniformly to  $T$  iff  $(T_n)$  converges to  $T$  under the standard norm defined above.

**Theorem 9.2.16.** *Let  $U$  and  $V$  be normed spaces. Let  $T : U \rightarrow V$  be a continuous linear function. Then  $\ker T$  is a closed subspace of  $U$ .*

PROOF:

⟨1⟩1.  $\ker T$  is a subspace of  $U$

PROOF: If  $x, y \in \ker T$  and  $\alpha, \beta \in K$  then  $T(\alpha x + \beta y) = \alpha T(x) + \beta T(y) = 0$ .

⟨1⟩2.  $\ker T$  is closed.

PROOF: Let  $(x_n)$  be a sequence in  $\ker T$  and  $x_n \rightarrow l$ . Then  $T(l) = \lim_{n \rightarrow \infty} T(x_n) = 0$ .

□

**Theorem 9.2.17.** *Let  $U$  and  $V$  be normed spaces. Let  $W$  be a closed subspace of  $U$  and  $T : W \rightarrow V$  be a continuous linear mapping. Then the graph  $G = \{(x, T(x)) \mid x \in W\}$  is closed in  $U \times V$ .*

PROOF:

⟨1⟩1. ASSUME: w.l.o.g.  $T \neq 0$

⟨1⟩2. LET:  $(x, y) \in (U \times V) - G$ , i.e.  $y \neq T(x)$

⟨1⟩3. LET:  $\epsilon = \|y - T(x)\| > 0$

⟨1⟩4. LET:  $x' \in W$  with  $\|x - x'\| < \epsilon/3\|T\|$

⟨1⟩5. LET:  $y' \in V$  with  $\|y - y'\| < \epsilon/3$

⟨1⟩6.  $y' \neq T(x')$

PROOF:

$$\begin{aligned}\|y' - T(x')\| &\geq \|y - T(x)\| - \|y - y'\| - \|T(x) - T(x')\| \\ &> \epsilon/3 \\ &> 0\end{aligned}$$

□

**Theorem 9.2.18** (Diagonal Theorem). *Let  $E$  be a normed space over  $K$ . Let  $(x_{ij})$  be an infinite matrix of elements of  $V$ . If:*

1. *For all  $j \in \mathbb{Z}_+$ , we have  $x_{ij} \rightarrow 0$  as  $i \rightarrow \infty$ ;*
2. *Every increasing sequence of positive integers  $(p_j)$  has a subsequence  $(p_{j_r})$  such that*

$$\sum_{s=1}^{\infty} x_{p_{j_r} p_{j_s}} \rightarrow 0 \text{ as } r \rightarrow \infty$$

*then  $x_{ii} \rightarrow 0$  as  $i \rightarrow \infty$ .*

PROOF:

- (1)1. ASSUME: for a contradiction  $x_{ii} \not\rightarrow 0$  as  $i \rightarrow \infty$
- (1)2. PICK  $\epsilon > 0$  such that, for all  $N$ , there exists  $n \geq N$  such that  $\|x_{nn}\| \geq \epsilon$
- (1)3. PICK an increasing sequence of integers  $(p_j)$  such that  $\|x_{p_j p_j}\| \geq \epsilon$  for all  $j$ .
- (1)4. PICK a subsequence  $(q_i)$  such that  $\sum_{j=1}^{\infty} x_{q_i q_j} \rightarrow 0$  as  $i \rightarrow \infty$
- (1)5. For all  $i$ , we have  $x_{q_i q_j} \rightarrow 0$  as  $j \rightarrow \infty$
- (1)6. For all  $j$ , we have  $x_{q_i q_j} \rightarrow 0$  as  $i \rightarrow \infty$
- (1)7. Define a subsequence  $(r_n)$  of  $(q_i)$  by  $r_1 = q_1$  and, for all  $n$ ,  $r_{n+1}$  is the first entry such that  $r_{n+1} > r_n$ ,  $\|x_{q_i r_n}\| < \epsilon/2^{n+1}$  for all  $q_i \geq r_{n+1}$ , and  $\|x_{r_j r_{n+1}}\| < \epsilon/2^{n+2}$  for  $j = 1, \dots, n$ .
- (1)8.  $\|x_{r_i r_j}\| < \epsilon/2^{j+1}$  for all  $i, j$  such that  $i \neq j$
- (1)9. PICK a subsequence  $(s_j)$  of  $(r_j)$  such that  $\sum_{j=1}^{\infty} x_{s_i s_j} \rightarrow 0$  as  $i \rightarrow \infty$
- (1)10. For all  $i$  we have  $\|\sum_{j=1}^{\infty} x_{s_i s_j}\| \geq \epsilon/2$

PROOF:

$$\begin{aligned}\left\| \sum_{j=1}^{\infty} x_{s_i s_j} \right\| &= \left\| x_{s_i s_i} + \sum_{i \neq j} x_{s_i s_j} \right\| \\ &\geq \left| \|x_{s_i s_i}\| - \left\| \sum_{i \neq j} x_{s_i s_j} \right\| \right| && \text{(Proposition 9.0.4)} \\ &\geq \left| \|x_{s_i s_i}\| - \sum_{i \neq j} \|x_{s_i s_j}\| \right| \\ &\geq \epsilon/2 && ((1)2, (1)8)\end{aligned}$$

(1)11. Q.E.D.

PROOF: (1)9 and (1)10 form a contradiction.

□

### 9.3 Banach Spaces

**Definition 9.3.1** (Cauchy Sequence). Let  $V$  be a normed space over  $K$ . A *Cauchy sequence* is a sequence of points  $(x_n)$  such that, for every  $\epsilon > 0$ , there exists  $N$  such that  $\forall m, n \geq N, \|x_m - x_n\| < \epsilon$ .

**Theorem 9.3.2.** Let  $V$  be a normed space over  $K$ . Let  $(x_n)$  be a sequence in  $V$ . The following are equivalent.

1.  $(x_n)$  is Cauchy.
2. For every pair of increasing sequences of positive integers  $(p_n)$  and  $(q_n)$ , we have  $\|x_{p_n} - x_{q_n}\| \rightarrow 0$  as  $n \rightarrow \infty$ .
3. For every increasing sequence of positive integers  $(p_n)$ , we have  $\|x_{p_n} - x_n\| \rightarrow 0$  as  $n \rightarrow \infty$ .

PROOF:

$\langle 1 \rangle 1. 1 \Rightarrow 2$

- $\langle 2 \rangle 1$ . ASSUME:  $(x_n)$  is Cauchy.
- $\langle 2 \rangle 2$ . LET:  $(p_n)$  and  $(q_n)$  are increasing sequences of positive integers.
- $\langle 2 \rangle 3$ . LET:  $\epsilon > 0$
- $\langle 2 \rangle 4$ . PICK  $N$  such that  $\forall m, n \geq N, \|x_m - x_n\| < \epsilon$
- $\langle 2 \rangle 5$ .  $\forall n \geq N, \|x_{p_n} - x_{q_n}\| < \epsilon$

PROOF: Since  $p_n, q_n \geq n \geq N$ .

$\langle 1 \rangle 2. 2 \Rightarrow 3$

PROOF: Trivial.

$\langle 1 \rangle 3. 2 \Rightarrow 1$

- $\langle 2 \rangle 1$ . ASSUME:  $(x_n)$  is not Cauchy
- $\langle 2 \rangle 2$ . Pick  $\epsilon > 0$  such that, for every  $N \in \mathbb{Z}_+$ , there exist  $m_N, n_N \geq N$  such that  $\|x_{m_N} - x_{n_N}\| \geq \epsilon$
- $\langle 2 \rangle 3$ . ASSUME: w.l.o.g.  $(m_N)$  and  $(n_N)$  are increasing sequences.
- $\langle 2 \rangle 4$ .  $\|x_{m_N} - x_{n_N}\| \not\rightarrow 0$  as  $N \rightarrow \infty$ .

$\langle 1 \rangle 4. 3 \Rightarrow 2$

- $\langle 2 \rangle 1$ . ASSUME: 3
- $\langle 2 \rangle 2$ . LET:  $(p_n)$  and  $(q_n)$  be increasing sequences of positive integers.
- $\langle 2 \rangle 3$ . LET:  $\epsilon > 0$
- $\langle 2 \rangle 4$ . PICK  $N$  such that  $\forall n \geq N, \|x_{p_n} - x_n\| < \epsilon/2$  and  $\forall n \geq N, \|x_{q_n} - x_n\| < \epsilon/2$
- $\langle 2 \rangle 5$ .  $\forall n \geq N, \|x_{p_n} - x_{q_n}\| < \epsilon$

□

**Proposition 9.3.3.** Every convergent sequence is Cauchy.

PROOF:

- $\langle 1 \rangle 1$ . LET:  $x_n \rightarrow l$  as  $n \rightarrow \infty$ .
- $\langle 1 \rangle 2$ . LET:  $\epsilon > 0$
- $\langle 1 \rangle 3$ . PICK  $N$  such that  $\forall n \geq N, \|x_n - l\| < \epsilon/2$

⟨1⟩4. For all  $m, n \geq N$  we have  $\|x_m - x_n\| < \epsilon$ .

□

**Proposition 9.3.4.** *In  $\mathcal{P}([0, 1])$ , let*

$$P_n(x) = 1 + x + \frac{x^2}{2} + \cdots + \frac{x^n}{n!}.$$

*Then  $(P_n)$  is Cauchy but does not converge.*

PROOF: It converges to  $e^x$  in  $\mathcal{C}([0, 1])$ , therefore it is Cauchy in  $\mathcal{C}([0, 1])$ , hence Cauchy in  $\mathcal{P}([0, 1])$ . Since  $e^x \notin \mathcal{P}([0, 1])$ , it does not converge in that space. □

**Proposition 9.3.5.** *Let  $V$  be a normed space over  $K$ . Let  $(x_n)$  be a Cauchy sequence in  $V$ . Then  $(\|x_n\|)$  converges in  $\mathbb{R}$ .*

PROOF:

⟨1⟩1.  $(\|x_n\|)$  is Cauchy.

⟨2⟩1. LET:  $\epsilon > 0$

⟨2⟩2. PICK  $N$  such that  $\forall m, n \geq N, \|x_m - x_n\| < \epsilon$

⟨2⟩3.  $\forall m, n \geq N, \|\|x_m\| - \|x_n\|\| < \epsilon$

PROOF: Proposition 9.0.4.

⟨1⟩2. Q.E.D.

PROOF: Since every Cauchy sequence in  $\mathbb{R}$  converges.

□

**Proposition 9.3.6.** *Every Cauchy sequence is bounded.*

PROOF:

⟨1⟩1. LET:  $V$  be a normed space over  $K$ .

⟨1⟩2. LET:  $(x_n)$  be a Cauchy sequence in  $V$ .

⟨1⟩3. PICK  $N$  such that  $\forall m, n \geq N, \|x_m - x_n\| < 1$ .

⟨1⟩4. LET:  $B = \max(\|x_1\|, \dots, \|x_{N-1}\|, \|x_N\|) + 1$

⟨1⟩5.  $\forall n, \|x_n\| \leq B$

□

**Definition 9.3.7** (Banach Space). A normed space  $V$  over  $K$  is *complete* or a *Banach space* iff every Cauchy sequence converges.

**Proposition 9.3.8.**  *$l^2$  is complete.*

PROOF:

⟨1⟩1. LET:  $(a_n)$  be a Cauchy sequence in  $l^2$  where  $a_n = (\alpha_{n1}, \alpha_{n2}, \dots)$ .

⟨1⟩2. For all  $\epsilon > 0$ , there exists  $n_0 \in \mathbb{Z}_+$  such that  $\forall m, n \geq n_0, \sum_{k=1}^{\infty} |\alpha_{mk} - \alpha_{nk}|^2 < \epsilon^2$ .

⟨1⟩3. For every  $k \in \mathbb{Z}_+$  and  $\epsilon > 0$ , there exists  $n_0 \in \mathbb{Z}_+$  such that  $\forall m, n \geq n_0, |\alpha_{mk} - \alpha_{nk}| < \epsilon$ .

⟨1⟩4. For every  $k \in \mathbb{Z}_+$ ,  $(\alpha_{nk})$  is Cauchy in  $\mathbb{C}$ .

⟨1⟩5. For every  $k \in \mathbb{Z}_+$ ,  $(\alpha_{nk})$  converges in  $\mathbb{C}$ .

⟨1⟩6. For  $k \in \mathbb{Z}_+$ ,

- LET:  $\alpha_k = \lim_{n \rightarrow \infty} \alpha_{nk}$
- $\langle 1 \rangle 7$ . Let  $a$  be the sequence  $(\alpha_k)$
- $\langle 1 \rangle 8$ . For all  $\epsilon > 0$ , there exists  $n_0$  such that  $\forall n \geq n_0, \sum_{k=1}^{\infty} |\alpha_k - \alpha_{nk}|^2 \leq \epsilon^2$ .
- PROOF: Letting  $m \rightarrow \infty$  in  $\langle 1 \rangle 2$ .
- $\langle 1 \rangle 9$ .  $a \in l^2$
- $\langle 2 \rangle 1$ . PICK  $n_0$  such that  $\forall n \geq n_0, \sum_{k=1}^{\infty} |\alpha_k - \alpha_{nk}|^2 \leq 1$
- PROOF:  $\langle 1 \rangle 8$
- $\langle 2 \rangle 2$ .  $(\alpha_k - \alpha_{n_0 k}) \in l^2$
- $\langle 2 \rangle 3$ .  $(\alpha_{n_0 k}) \in l^2$
- PROOF: By  $\langle 1 \rangle 1$  since the sequence is  $a_{n_0}$ .
- $\langle 2 \rangle 4$ .  $(\alpha_k) \in l^2$
- PROOF: Proposition 7.0.2.
- $\langle 1 \rangle 10$ .  $a_n \rightarrow a$  as  $n \rightarrow \infty$
- PROOF: By  $\langle 1 \rangle 8$  since  $\|a - a_n\| = \sqrt{\sum_{k=1}^{\infty} |\alpha_k - \alpha_{nk}|^2}$ .
- 

**Proposition 9.3.9.** *Let  $a$  and  $b$  be real numbers with  $a < b$ . The space  $\mathcal{C}([a, b])$  is complete.*

PROOF:

- $\langle 1 \rangle 1$ . LET:  $X = [a, b]$
- $\langle 1 \rangle 2$ . LET:  $(f_n)$  be a Cauchy sequence in  $\mathcal{C}([a, b])$ .
- $\langle 1 \rangle 3$ . For all  $\epsilon > 0$ , there exists  $n_0$  such that  $\forall n, m \geq n_0, \|f_n - f_m\| < \epsilon$ .
- $\langle 1 \rangle 4$ . For all  $\epsilon > 0$ , there exists  $n_0$  such that  $\forall n, m \geq n_0, \forall x \in X, |f_n(x) - f_m(x)| < \epsilon$ .
- $\langle 1 \rangle 5$ . For all  $x \in [a, b]$ ,  $(f_n(x))$  is Cauchy.
- $\langle 1 \rangle 6$ . Define  $f : [a, b] \rightarrow \mathbb{C}$  by  $f(x) = \lim_{n \rightarrow \infty} f_n(x)$ .
- $\langle 1 \rangle 7$ . For all  $\epsilon > 0$ , there exists  $n_0$  such that  $\forall n \geq n_0, \forall x \in X, |f_n(x) - f(x)| < \epsilon$
- PROOF: Letting  $m \rightarrow \infty$  in  $\langle 1 \rangle 4$ .
- $\langle 1 \rangle 8$ .  $f$  is continuous
- $\langle 2 \rangle 1$ . LET:  $x_0 \in X$
- $\langle 2 \rangle 2$ . LET:  $\epsilon > 0$
- $\langle 2 \rangle 3$ . PICK  $n_0$  such that  $\forall n \geq n_0, \forall x \in X, |f_n(x) - f(x)| < \epsilon/3$
- PROOF: By  $\langle 1 \rangle 7$ .
- $\langle 2 \rangle 4$ . PICK  $\delta > 0$  such that  $\forall x \in X, |x - x_0| < \delta \Rightarrow |f_{n_0}(x) - f_{n_0}(x_0)| < \epsilon/3$
- PROOF: Since  $f_{n_0}$  is continuous.
- $\langle 2 \rangle 5$ . LET:  $x \in X$
- $\langle 2 \rangle 6$ . ASSUME:  $|x - x_0| < \delta$
- $\langle 2 \rangle 7$ .  $|f(x) - f(x_0)| < \epsilon$
- PROOF:
- $$|f(x) - f(x_0)| \leq |f(x) - f_{n_0}(x)| + |f_{n_0}(x) - f_{n_0}(x_0)| + |f_{n_0}(x_0) - f(x_0)| \quad (\text{Triangle Inequality})$$
- $$< \epsilon/3 + \epsilon/3 + \epsilon/3 \quad (\langle 2 \rangle 3, \langle 2 \rangle 4)$$
- $$= \epsilon$$
- $\langle 1 \rangle 9$ .  $(f_n)$  converges to  $f$  uniformly.
- PROOF: From  $\langle 1 \rangle 7$
-



**Definition 9.3.10** (Series). Let  $V$  be a normed space over  $K$ . A *convergent series* in  $V$  is a sequence  $(x_n)$  in  $V$  such that  $(x_1 + \cdots + x_n)$  is a convergent sequence, in which case we write  $\sum_{n=1}^{\infty} x_n$  for its limit.

**Definition 9.3.11** (Absolutely Convergent Series). Let  $V$  be a normed space over  $K$ . An *absolutely convergent series* in  $V$  is a sequence  $(x_n)$  such that  $\sum_{n=1}^{\infty} \|x_n\| < \infty$ .

**Proposition 9.3.12.** In  $\mathcal{P}([0, 1])$ , the series  $\sum_{n=0}^{\infty} x^n/n!$  is absolutely convergent but not convergent.

PROOF: Proposition 9.3.4.  $\square$

**Theorem 9.3.13.** A normed space is complete if and only if every absolutely convergent series is convergent.

PROOF:

$\langle 1 \rangle 1$ . LET:  $V$  be a normed space over  $K$ .

$\langle 1 \rangle 2$ . If  $V$  is complete then every absolutely convergent series is convergent.

$\langle 2 \rangle 1$ . ASSUME:  $V$  is complete.

$\langle 2 \rangle 2$ . LET:  $\sum_{n=1}^{\infty} a_n$  be absolutely convergent in  $V$ .

$\langle 2 \rangle 3$ . For  $n \in \mathbb{Z}_+$ ,  
LET:  $s_n = \sum_{k=1}^n a_k$

$\langle 2 \rangle 4$ .  $(s_n)$  is Cauchy.

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

$\langle 3 \rangle 2$ . PICK  $k$  such that  $\sum_{n=k+1}^{\infty} \|a_n\| < \epsilon$

$\langle 3 \rangle 3$ . LET:  $m > n > k$

$\langle 3 \rangle 4$ .  $\|s_m - s_n\| < \epsilon$

PROOF:

$$\begin{aligned} \|s_m - s_n\| &= \left\| \sum_{i=n+1}^m a_i \right\| && (\langle 2 \rangle 3, \langle 3 \rangle 3) \\ &\leq \sum_{i=n+1}^m \|a_i\| && (\text{Triangle inequality}) \\ &\leq \sum_{i=k+1}^{\infty} \|a_i\| \\ &< \epsilon && (\langle 3 \rangle 2, \langle 3 \rangle 3) \end{aligned}$$

$\langle 2 \rangle 5$ .  $(s_n)$  converges.

$\langle 1 \rangle 3$ . If every absolutely convergent series is convergent then  $V$  is complete.

$\langle 2 \rangle 1$ . ASSUME: Every absolutely convergent series in  $V$  is convergent.

$\langle 2 \rangle 2$ . LET:  $(a_n)$  be a Cauchy sequence in  $V$ .

$\langle 2 \rangle 3$ . PICK a strictly increasing sequence of positive integers  $(p_n)$  such that  
 $\forall k. \forall m, n \geq p_k. \|x_m - x_n\| < 2^{-k}$ .

$\langle 2 \rangle 4$ .  $\sum_{k=1}^{\infty} (x_{p_{k+1}} - x_{p_k})$  is absolutely convergent.

PROOF:

$$\sum_{k=1}^{\infty} \|x_{p_{k+1}} - x_{p_k}\| < \sum_{k=1}^{\infty} 2^{-k} < \infty \quad (\langle 2 \rangle 3)$$

$\langle 2 \rangle 5$ .  $\sum_{k=1}^{\infty} (x_{p_{k+1}} - x_{p_k})$  is convergent.

PROOF:  $\langle 2 \rangle 1$ ,  $\langle 2 \rangle 5$

$\langle 2 \rangle 6$ . LET:  $s = \sum_{k=1}^{\infty} (x_{p_{k+1}} - x_{p_k})$

$\langle 2 \rangle 7$ .  $x_{p_k} \rightarrow s + x_{p_1}$  as  $k \rightarrow \infty$ .

$\langle 3 \rangle 1$ .  $\sum_{i=1}^k (x_{p_{i+1}} - x_{p_i}) \rightarrow s$  as  $k \rightarrow \infty$

PROOF:  $\langle 2 \rangle 6$

$\langle 3 \rangle 2$ .  $x_{p_{k+1}} - x_{p_1} \rightarrow s$  as  $k \rightarrow \infty$

$\langle 2 \rangle 8$ .  $x_n \rightarrow s + x_{p_1}$  as  $k \rightarrow \infty$ .

PROOF:

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

$\langle 3 \rangle 2$ . PICK  $N$  such that  $\forall k \geq N, \|x_{p_k} - (s + x_{p_1})\| < \epsilon/2$  and  $\forall m, n \geq N, \|x_m - x_n\| < \epsilon/2$

PROOF:  $\langle 2 \rangle 2$ ,  $\langle 2 \rangle 7$

$\langle 3 \rangle 3$ .  $\forall n \geq N, \|x_n - (s + x_{p_1})\| < \epsilon$

□

**Theorem 9.3.14.** *A closed vector subspace of a Banach space is a Banach space.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $V$  be a Banach space over  $K$ .

$\langle 1 \rangle 2$ . LET:  $U$  be a closed vector subspace of  $V$ .

$\langle 1 \rangle 3$ . LET:  $(a_n)$  be a Cauchy sequence in  $U$ .

$\langle 1 \rangle 4$ .  $(a_n)$  is a Cauchy sequence in  $V$ .

$\langle 1 \rangle 5$ . LET:  $l = \lim_{n \rightarrow \infty} a_n$

$\langle 1 \rangle 6$ .  $l \in U$

PROOF: Theorem 9.1.40.

$\langle 1 \rangle 7$ .  $a_n \rightarrow l$  as  $n \rightarrow \infty$  in  $U$ .

□

**Definition 9.3.15** (Completion). Let  $V$  be a normed space over  $K$ . A *completion* of  $V$  consists of a normed space  $W$  over  $K$  and an injection  $\phi : V \rightarrow W$  such that:

1.  $\forall x, y \in V, \forall \alpha, \beta \in K, \phi(\alpha x + \beta y) = \alpha \phi(x) + \beta \phi(y)$
2.  $\forall x \in V, \|\phi(x)\| = \|x\|$
3.  $\phi(V)$  is dense in  $W$ .
4.  $W$  is complete.

**Proposition 9.3.16.** *Every normed space has a completion.*

PROOF:

- (1)1. LET:  $V$  be a normed space over  $K$ .  
 (1)2. Let us say two Cauchy sequences  $(x_n), (y_n)$  are *equivalent* iff  $x_n - y_n \rightarrow 0$  as  $n \rightarrow \infty$ .  
 (1)3. Equivalence is an equivalence relation on the set of Cauchy sequences.  
 (1)4. LET:  $W$  be the set of Cauchy sequences in  $V$  quotiented by equivalence.  
 (1)5. Define addition and multiplication on  $W$  by

$$\begin{aligned}
 [(x_n)] + [(y_n)] &= [(x_n + y_n)] \\
 \lambda[(x_n)] &= [(\lambda x_n)]
 \end{aligned}$$

- (1)6. Define a norm on  $W$  by  $\|[(x_n)]\| = \lim_{n \rightarrow \infty} \|x_n\|$   
 (1)7. Define  $\phi : V \rightarrow W$  by  $\phi(v) = [(v)]$ .  
 (1)8.  $\phi$  is injective.  
 (1)9.  $\forall x, y \in V. \forall \alpha, \beta \in K. \phi(\alpha x + \beta y) = \alpha \phi(x) + \beta \phi(y)$   
 (1)10.  $\forall x \in V. \|\phi(x)\| = \|x\|$   
 (1)11.  $\phi(V)$  is dense in  $W$ .

- (2)1. LET:  $[(a_n)] \in W$  and  $\epsilon > 0$ .

PROVE:  $B([(a_n)], \epsilon)$  intersects  $\phi(V)$ .

- (2)2. PICK  $N$  such that  $\forall m, n \geq N. \|a_m - a_n\| < \epsilon/2$

- (2)3.  $\phi(a_N) \in B([(a_n)], \epsilon)$

PROOF:

$$\begin{aligned}
 \|[(a_n)] - \phi(a_N)\| &= \lim_{n \rightarrow \infty} \|a_n - a_N\| \\
 &\leq \epsilon/2 & (\langle 2 \rangle 2) \\
 &< \epsilon
 \end{aligned}$$

- (1)12.  $W$  is complete.

- (2)1. LET:  $(X_n)$  be a Cauchy sequence in  $W$ .

- (2)2. For  $n \in \mathbb{Z}_+$ , PICK  $x_n \in V$  such that

$$\|\phi(x_n) - X_n\| < 1/n.$$

- (2)3.  $(x_n)$  is Cauchy in  $V$ .

- (3)1. LET:  $\epsilon > 0$

- (3)2. PICK  $N$  such that  $\forall m, n \geq N. \|X_n - X_m\| < \epsilon/3$  and  $1/N < \epsilon/3$

- (3)3. LET:  $m, n \geq N$

- (3)4.  $\|x_m - x_n\| < \epsilon$

PROOF:

$$\begin{aligned}
 \|x_m - x_n\| &= \|\phi(x_m) - \phi(x_n)\| \\
 &\leq \|\phi(x_m) - X_m\| + \|X_m - X_n\| + \|X_n - \phi(x_n)\| \\
 &< \|X_m - X_n\| + 1/m + 1/n \\
 &< \epsilon
 \end{aligned}$$

- (2)4. LET:  $X = [(x_n)]$

- (2)5.  $X_n \rightarrow X$  as  $n \rightarrow \infty$

PROOF:

$$\begin{aligned}
 \|X_n - X\| &\leq \|X_n - \phi(x_n)\| + \|\phi(x_n) - X\| \\
 &< \|\phi(x_n) - X\| + 1/n \\
 &\rightarrow 0
 \end{aligned}$$

as  $n \rightarrow \infty$

□

**Proposition 9.3.17.** *Let  $U$  be a normed space and  $V$  a Banach space. Then  $\mathcal{B}(U, V)$  is a Banach space.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $(T_n)$  be a Cauchy sequence in  $\mathcal{B}(U, V)$

$\langle 1 \rangle 2$ . For all  $u \in U$ ,  $(T_n(u))$  is a Cauchy sequence in  $V$ .

$\langle 2 \rangle 1$ . LET:  $u \in U$

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

PROVE:  $\exists N. \forall m, n \geq N. \|T_m(u) - T_n(u)\| < \epsilon$

$\langle 2 \rangle 3$ . ASSUME: w.l.o.g.  $u \neq 0$

$\langle 2 \rangle 4$ . PICK  $N$  such that  $\forall m, n \geq N. \|T_m - T_n\| < \epsilon/\|u\|$

$\langle 2 \rangle 5$ . LET:  $m, n \geq N$

$\langle 2 \rangle 6$ .  $\|T_m(u) - T_n(u)\| < \epsilon$

PROOF:

$$\|T_m(u) - T_n(u)\| \leq \|T_m - T_n\| \|u\| \quad (\text{Proposition 9.2.11})$$

$$< \epsilon$$

$\langle 1 \rangle 3$ . Define  $T : U \rightarrow V$  by  $T(u) = \lim_{n \rightarrow \infty} T_n(u)$

$\langle 1 \rangle 4$ .  $T \in \mathcal{B}(U, V)$

$\langle 2 \rangle 1$ . For all  $x, y \in U$  and  $\alpha, \beta \in K$  we have  $T(\alpha x + \beta y) = \alpha T(x) + \beta T(y)$

$\langle 3 \rangle 1$ . LET:  $x, y \in U$

$\langle 3 \rangle 2$ . LET:  $\alpha, \beta \in K$

$\langle 3 \rangle 3$ .  $T(\alpha x + \beta y) = \alpha T(x) + \beta T(y)$

PROOF:

$$\begin{aligned} T(\alpha x + \beta y) &= \lim_{n \rightarrow \infty} T_n(\alpha x + \beta y) \\ &= \lim_{n \rightarrow \infty} (\alpha T_n(x) + \beta T_n(y)) \\ &= \alpha T(x) + \beta T(y) \end{aligned}$$

$\langle 2 \rangle 2$ .  $T$  is bounded.

$\langle 3 \rangle 1$ . PICK  $N$  such that  $\forall n \geq N. \|T_n - T\| < 1$

$\langle 3 \rangle 2$ . PICK  $B > 0$  such that  $\forall x \in U. \|T_N(x)\| \leq B\|x\|$

$\langle 3 \rangle 3$ . LET:  $x \in U$

$\langle 3 \rangle 4$ .  $\|T(x)\| \leq (B + 1)\|x\|$

PROOF:

$$\begin{aligned} \|T(x)\| &\leq \|T_N(x) - T(x)\| + \|T_N(x)\| && (\text{Triangle inequality}) \\ &\leq \|T_N - T\| \|x\| + \|T_N\| \|x\| && (\text{Proposition 9.2.11}) \\ &< \|x\| + B\|x\| && (\langle 3 \rangle 1, \langle 3 \rangle 2) \\ &= (B + 1)\|x\| \end{aligned}$$

$\langle 1 \rangle 5$ .  $T_n \rightarrow T$  as  $n \rightarrow \infty$

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

$\langle 2 \rangle 2$ . PICK  $N$  such that  $\forall m, n \geq N. \|T_m - T_n\| < \epsilon/2$

$\langle 2 \rangle 3$ . LET:  $n \geq N$

PROVE:  $\|T_n - T\| < \epsilon$

$\langle 2 \rangle 4$ . LET:  $x \in U$  with  $\|x\| = 1$

$\langle 2 \rangle 5$ .  $\|T_n(x) - T(x)\| \leq \epsilon/2$

PROOF: Let  $n \rightarrow \infty$  in  $\langle 2 \rangle 2$ .

□

**Corollary 9.3.17.1.** *For any normed space  $V$  over  $K$ , the space  $\mathcal{B}(V, K)$  is a Banach space.*

**Theorem 9.3.18.** *Let  $U$  be a normed space and  $V$  a Banach space. Let  $W$  be a subspace of  $U$ . Let  $T : W \rightarrow V$  be a continuous linear transformation. Then  $T$  has a unique extension to a continuous linear transformation  $\text{cl } W \rightarrow V$ .*

PROOF:

- (1)1. Define  $S : \text{cl } W \rightarrow V$  by:  $S(x) = \lim_{n \rightarrow \infty} T(x_n)$ , where  $(x_n)$  is any sequence in  $W$  that converges to  $x$ .
- (2)1. For all  $x \in \text{cl } W$ , there exists a sequence  $(x_n)$  in  $W$  that converges to  $x$ .  
PROOF: Theorem 9.1.43.
- (2)2. If  $(x_n)$  is a Cauchy sequence in  $W$  then  $(T(x_n))$  is Cauchy in  $V$ .
  - (3)1. ASSUME: w.l.o.g.  $T \neq 0$
  - (3)2. LET:  $(x_n)$  be a Cauchy sequence in  $W$ .
  - (3)3. PICK  $B > 0$  such that  $\forall x \in W. \|T(x)\| \leq B\|x\|$
  - (3)4. LET:  $\epsilon > 0$
  - (3)5. PICK  $N$  such that  $\forall m, n \geq N. \|x_m - x_n\| < \epsilon/\|T\|$
  - (3)6. LET:  $m, n \geq N$
  - (3)7.  $\|T(x_m) - T(x_n)\| < \epsilon$
- (2)3. If  $(x_n)$  and  $(y_n)$  are sequences in  $W$  that converge to the same element in  $\text{cl } W$  then  $(T(x_n))$  and  $(T(y_n))$  have the same limit in  $V$ .
  - (3)1. ASSUME: w.l.o.g.  $T \neq 0$
  - (3)2. ASSUME:  $x_n \rightarrow l$  and  $y_n \rightarrow l$  as  $n \rightarrow \infty$
  - (3)3. LET:  $T(x_n) \rightarrow a$  and  $T(y_n) \rightarrow b$  as  $n \rightarrow \infty$
  - (3)4. ASSUME: for a contradiction  $a \neq b$
  - (3)5. LET:  $\epsilon = \|a - b\|$
  - (3)6. PICK  $N$  such that  $\forall n \geq N. \|x_n - l\| < \epsilon/3\|T\|$  and  $\forall n \geq N. \|y_n - l\| < \epsilon/3\|T\|$
  - (3)7.  $\forall n \geq N. \|T(x_n) - T(y_n)\| < 2\epsilon/3$
  - (3)8.  $\|a - b\| \leq 2\epsilon/3$
  - (3)9. This contradicts (3)5.
- (1)2.  $S$  extends  $T$ 
  - (2)1. LET:  $w \in W$
  - (2)2.  $w \rightarrow w$  as  $n \rightarrow \infty$
  - (2)3.  $T(w) \rightarrow T(w)$  as  $n \rightarrow \infty$
  - (2)4.  $S(w) = T(w)$
- (1)3.  $S$  is bounded.
  - (2)1. LET:  $x \in \text{cl } W$   
PROVE:  $\|S(x)\| \leq \|T\|\|x\|$
  - (2)2. PICK a sequence  $(x_n)$  in  $W$  that converges to  $x$ .
  - (2)3.  $\|T(x_n)\| \leq \|T\|\|x_n\|$  for all  $n$ .
  - (2)4.  $\|S(x)\| \leq \|T\|\|x\|$
  - PROOF: Taking the limit as  $n \rightarrow \infty$ .
- (1)4.  $S$  is linear.

- ⟨2⟩1. LET:  $x, y \in \text{cl } W$  and  $\alpha, \beta \in K$
- ⟨2⟩2. PICK sequences  $(x_n)$  and  $(y_n)$  in  $W$  that converge to  $x$  and  $y$ .
- ⟨2⟩3.  $T(\alpha x_n + \beta y_n) = \alpha T(x_n) + \beta T(y_n)$  for all  $n$ .
- ⟨2⟩4.  $S(\alpha x + \beta y) = \alpha S(x) + \beta S(y)$

PROOF: Taking the limit as  $n \rightarrow \infty$ .

- ⟨1⟩5.  $S$  is unique.
- ⟨2⟩1. LET:  $S'$  be a continuous linear extension of  $S$  defined on  $\text{cl } W$ .
- ⟨2⟩2. LET:  $x \in W$
- PROVE:  $S(x) = S'(x)$
- ⟨2⟩3. PICK a sequence  $(x_n)$  in  $W$  that converges to  $x$ .
- ⟨2⟩4.  $T(x_n) = S'(x_n) \rightarrow S'(x)$  as  $n \rightarrow \infty$
- ⟨2⟩5.  $S'(x) = S(x)$

□

**Corollary 9.3.18.1.** *Let  $U$  be a normed space and  $V$  a Banach space. Let  $W$  be a dense subspace of  $U$ . Let  $T : W \rightarrow V$  be a continuous linear transformation. Then  $T$  has a unique extension to a continuous linear transformation  $U \rightarrow V$ .*

**Definition 9.3.19** (Functional). Let  $V$  be a normed space over  $K$ . A *functional* on  $V$  is a bounded linear mapping  $V \rightarrow K$ . The *dual space* of  $V$  is the space  $\mathcal{B}(V, K)$  of all functionals.

**Theorem 9.3.20** (Banach-Steinhaus Theorem). *Let  $\mathcal{T}$  be a family of bounded linear mappings from a Banach space  $X$  into a normed space  $Y$ . If, for every  $x \in X$ , there exists a constant  $M_x$  such that  $\forall T \in \mathcal{T}. \|T(x)\| \leq M_x$ , then there exists a constant  $M > 0$  such that  $\forall T \in \mathcal{T}. \|T\| \leq M$ .*

PROOF:

- ⟨1⟩1. ASSUME: for a contradiction no such  $M$  exists.
- ⟨1⟩2. For  $n \in \mathbb{Z}_+$ , PICK  $T_n \in \mathcal{T}$  such that  $\|T_n\| > n2^n$ .
- ⟨1⟩3. For  $n \in \mathbb{Z}_+$ , PICK  $x_n \in X$  such that  $\|x_n\| = 1$  and  $\|T_n(x_n)\| > n2^n$ .
- ⟨1⟩4. For  $n \in \mathbb{Z}_+$ ,

$$\left\| \frac{1}{n} T_n \left( \frac{x_n}{2^n} \right) \right\| > 1 .$$

- ⟨1⟩5. For  $i, j \in \mathbb{Z}_+$ ,  
LET:  $y_{ij} = \frac{1}{i} T_i \left( \frac{x_j}{2^j} \right)$ .
  - ⟨1⟩6. For all  $j \in \mathbb{Z}_+$ ,  $y_{ij} \rightarrow 0$  as  $i \rightarrow \infty$ 
    - ⟨2⟩1. LET:  $j \in \mathbb{Z}_+$
    - ⟨2⟩2. PICK  $M$  such that  $\forall T \in \mathcal{T}. \|T(x_j/2^j)\| \leq M$
    - ⟨2⟩3. For all  $i$ ,  $\|y_{ij}\| \leq M/i$
  - ⟨1⟩7. For any increasing sequence of positive integers  $(p_i)$ , we have  $\sum_{j=1}^{\infty} y_{p_i p_j} \rightarrow 0$  as  $i \rightarrow \infty$ 
    - ⟨2⟩1. LET:  $(p_i)$  be an increasing sequence of positive integers.
    - ⟨2⟩2. LET:  $z = \sum_{j=1}^{\infty} x_{p_j} / 2^{p_j}$
- PROOF: This converges by Theorem 9.3.13.
- ⟨2⟩3. PICK  $C$  such that  $\forall T \in \mathcal{T}. \|T(z)\| \leq C$
  - ⟨2⟩4. For all  $i$ ,  $\|\sum_{j=1}^{\infty} y_{p_i p_j}\| \leq C/p_i$ .

PROOF:

$$\left\| \sum_{j=1}^{\infty} y_{p_i p_j} \right\| = \left\| \sum_{j=1}^{\infty} \frac{1}{p_i} T_{p_i} \left( \frac{x_{p_j}}{2^{p_j}} \right) \right\| \quad (\langle 1 \rangle 5)$$

$$= \frac{1}{p_i} \left\| T_{p_i} \left( \sum_{j=1}^{\infty} \frac{x_{p_j}}{2^{p_j}} \right) \right\| \quad (T_{p_i} \text{ continuous})$$

$$= \frac{1}{p_i} \|T_{p_i}(z)\| \quad (\langle 2 \rangle 2)$$

$$\leq \frac{C}{p_i} \quad (\langle 2 \rangle 3)$$

$$\langle 2 \rangle 5. \sum_{j=1}^{\infty} y_{p_i p_j} \rightarrow 0 \text{ as } i \rightarrow \infty$$

$$\langle 1 \rangle 8. y_{ii} \rightarrow 0 \text{ as } i \rightarrow \infty$$

PROOF: Diagonal Theorem,  $\langle 1 \rangle 6$ ,  $\langle 1 \rangle 7$ . $\langle 1 \rangle 9$ . Q.E.D.PROOF:  $\langle 1 \rangle 4$  and  $\langle 1 \rangle 8$  form a contradiction.

□

## 9.4 Contraction Mappings

**Definition 9.4.1** (Contraction Mapping). Let  $E$  be a normed space over  $K$ . Let  $A \subseteq E$ . A function  $f : A \rightarrow E$  is a *contraction (mapping)* iff there exists a real  $\alpha$  such that  $0 < \alpha < 1$  and

$$\forall x, y \in A. \|f(x) - f(y)\| \leq \alpha \|x - y\| .$$

**Proposition 9.4.2.** *Contraction mappings are uniformly continuous.*

PROOF:

 $\langle 1 \rangle 1$ . LET:  $E$  be a normed space over  $K$ . $\langle 1 \rangle 2$ . LET:  $A \subseteq E$  $\langle 1 \rangle 3$ . LET:  $f : A \rightarrow E$  be a contraction mapping. $\langle 1 \rangle 4$ . PICK  $\alpha$  such that  $0 < \alpha < 1$  and  $\forall x, y \in A. \|f(x) - f(y)\| \leq \alpha \|x - y\|$ . $\langle 1 \rangle 5$ . LET:  $\epsilon > 0$  $\langle 1 \rangle 6$ . LET:  $\delta = \epsilon/\alpha$  $\langle 1 \rangle 7$ . For all  $x, y \in A$ , if  $\|x - y\| < \delta$  then  $\|f(x) - f(y)\| < \epsilon$ .

□

**Theorem 9.4.3** (Banach Fixed Point Theorem). *Let  $E$  be a Banach space over  $K$ . Let  $F$  be a nonempty closed subset of  $E$ . Let  $f : F \rightarrow F$  be a contraction mapping. Then there exists a unique  $z \in F$  such that  $f(z) = z$ .*

PROOF:

 $\langle 1 \rangle 1$ . PICK  $\alpha$  such that  $0 < \alpha < 1$  and

$$\forall x, y \in F. \|f(x) - f(y)\| \leq \alpha \|x - y\| .$$

 $\langle 1 \rangle 2$ . PICK  $x_0 \in F$

⟨1⟩3. For  $n \in \mathbb{Z}_+$ ,

LET:  $x_n = f^n(x_0)$ .

⟨1⟩4.  $(x_n)$  is a Cauchy sequence.

⟨2⟩1. For all  $n \in \mathbb{Z}_+$  we have  $\|x_{n+1} - x_n\| \leq \alpha^n \|x_1 - x_0\|$ .

⟨2⟩2. For all  $m, n \in \mathbb{Z}_+$  with  $m < n$  we have  $\|x_n - x_m\| < \alpha^m \|x_1 - x_0\| / (1 - \alpha)$ .

PROOF:

$$\|x_n - x_m\| \leq \|x_n - x_{n-1}\| + \|x_{n-1} - x_{n-2}\| + \cdots + \|x_{m+1} - x_m\| \quad (\text{Triangle inequality})$$

$$\leq (\alpha^{n-1} + \alpha^{n-2} + \cdots + \alpha^m) \|x_1 - x_0\| \quad (\langle 2 \rangle 1)$$

$$< \frac{\|x_1 - x_0\|}{1 - \alpha} \alpha^m$$

⟨2⟩3. LET:  $\epsilon > 0$

⟨2⟩4. PICK  $N$  such that  $\alpha^N \|x_1 - x_0\| / (1 - \alpha) < \epsilon$

⟨2⟩5. For all  $m, n \geq N$ , we have  $\|x_n - x_m\| < \epsilon$

⟨1⟩5. LET:  $z = \lim_{n \rightarrow \infty} x_n$

⟨1⟩6.  $f(z) = z$

PROOF:

$$\begin{aligned} f(z) &= f\left(\lim_{n \rightarrow \infty} x_n\right) \\ &= \lim_{n \rightarrow \infty} f(x_n) && (\text{Proposition 9.4.2}) \\ &= \lim_{n \rightarrow \infty} x_{n+1} \\ &= z \end{aligned}$$

⟨1⟩7. For any  $w \in F$ , if  $f(w) = w$  then  $w = z$ .

⟨2⟩1. LET:  $w \in F$

⟨2⟩2. ASSUME:  $f(w) = w$

⟨2⟩3.  $\|z - w\| \leq \alpha \|z - w\|$

PROOF:  $\|z - w\| = \|f(z) - f(w)\| \leq \alpha \|z - w\|$

⟨2⟩4.  $\|z - w\| = 0$

⟨2⟩5.  $z = w$

□



## Chapter 10

# Inner Product Spaces

**Definition 10.0.1** (Inner Product Space). Let  $E$  be a complex vector space. An *inner product* on  $E$  is a function  $\langle \cdot, \cdot \rangle : E^2 \rightarrow \mathbb{C}$  such that, for all  $x, y, z \in E$  and  $\alpha, \beta \in \mathbb{C}$ , we have:

1.  $\langle x, y \rangle = \overline{\langle y, x \rangle}$
2.  $\langle \alpha x + \beta y, z \rangle = \alpha \langle x, z \rangle + \beta \langle y, z \rangle$
3.  $\langle x, x \rangle \geq 0$
4. 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  $V$ .

**Proposition 10.0.2.** Let  $E$  be an inner product space. For any  $x \in E$ , we have  $\langle x, x \rangle$  is real.

PROOF: Since  $\langle x, x \rangle = \overline{\langle x, x \rangle}$ .  $\square$

**Proposition 10.0.3.**

$$\langle x, \alpha y + \beta z \rangle = \overline{\alpha} \langle x, y \rangle + \overline{\beta} \langle x, z \rangle$$

**Proposition 10.0.4.**

$$\langle 0, y \rangle = \langle x, 0 \rangle = 0$$

**Proposition 10.0.5.** The function  $\langle \vec{x}, \vec{y} \rangle = \sum_{i=1}^n x_i \overline{y_i}$  is an inner product on  $\mathbb{C}^n$ .

**Proposition 10.0.6.** The function  $\langle (x_n), (y_n) \rangle = \sum_{i=1}^{\infty} x_i \overline{y_i}$  is an inner product on  $l^2$ .

**Proposition 10.0.7.** The function  $\langle f, g \rangle = \int_a^b f(x) \overline{g(x)} dx$  is an inner product on  $\mathcal{C}([a, b])$ .

**Proposition 10.0.8.** *Let  $p > 1$  and  $\Omega \subseteq \mathbb{R}^N$ . Let  $L^p(\Omega)$  be the set of all functions  $f : \Omega \rightarrow \mathbb{C}$  such that  $|f|^p$  is Lebesgue integrable.*

*The function  $\langle f, g \rangle = \int_{\Omega} f(x)g(x)dx$  is an inner product on  $L^2(\Omega)$ .*

**Proposition 10.0.9.** *Let  $E_1$  and  $E_2$  be inner product spaces. Then the function  $\langle (e_1, e_2), (e'_1, e'_2) \rangle = \langle e_1, e'_1 \rangle + \langle e_2, e'_2 \rangle$  is an inner product on  $E_1 \times E_2$ .*

**Definition 10.0.10** (Norm). In an inner product space, define  $\|x\| = \sqrt{\langle x, x \rangle}$ .

**Proposition 10.0.11** (Schwarz's Inequality). *In any inner product space,*

$$|\langle x, y \rangle| \leq \|x\| \|y\| .$$

*Equality holds iff  $x$  and  $y$  are linearly dependent.*

PROOF:

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

$\langle 1 \rangle 2$ .  $|\langle x, y \rangle| \leq \|x\| \|y\|$

$\langle 2 \rangle 1$ . For all  $\alpha \in \mathbb{C}$  we have  $\langle x, x \rangle + \bar{\alpha} \langle x, y \rangle + \alpha \langle y, x \rangle + |\alpha|^2 \langle y, y \rangle$

PROOF: The right-hand side is  $\langle x + \alpha y, x + \alpha y \rangle$ .

$\langle 2 \rangle 2$ .  $\langle x, x \rangle \langle y, y \rangle - |\langle x, y \rangle|^2 \geq 0$

PROOF: Taking  $\alpha = -\langle x, x \rangle / \langle y, y \rangle$  in  $\langle 2 \rangle 1$ .

$\langle 1 \rangle 3$ . If  $|\langle x, y \rangle| = \|x\| \|y\|$  then  $x$  and  $y$  are linearly dependent.

$\langle 2 \rangle 1$ . ASSUME:  $|\langle x, y \rangle| = \|x\| \|y\|$

$\langle 2 \rangle 2$ .  $\langle x, y \rangle \langle y, x \rangle = \langle x, x \rangle \langle y, y \rangle$

$\langle 2 \rangle 3$ .  $\langle y, y \rangle x - \langle x, x \rangle y = 0$

PROOF:

$$\begin{aligned} \langle \langle y, y \rangle x - \langle x, x \rangle y, \langle y, y \rangle x - \langle x, x \rangle y \rangle &= \langle y, y \rangle^2 \langle x, x \rangle - \langle y, y \rangle \langle y, x \rangle \langle x, y \rangle - \langle x, y \rangle \langle y, y \rangle \langle y, x \rangle + \langle x, y \rangle \langle y, x \rangle \langle x, x \rangle \\ &= 0 \end{aligned}$$

$\langle 1 \rangle 4$ . If  $x$  and  $y$  are linearly dependent then  $|\langle x, y \rangle| = \|x\| \|y\|$

$\langle 2 \rangle 1$ . ASSUME:  $x$  and  $y$  are linearly dependent.

$\langle 2 \rangle 2$ . LET:  $y = \alpha x$

$\langle 2 \rangle 3$ .  $|\langle x, y \rangle| = \|x\| \|y\|$

PROOF:

$$\begin{aligned} |\langle x, y \rangle| &= |\langle x, \alpha x \rangle| \\ &= |\alpha| |\langle x, x \rangle| \\ &= |\alpha| \|x\|^2 \\ &= \|x\| \|\alpha x\| \\ &= \|x\| \|y\| \end{aligned}$$

□

**Corollary 10.0.11.1** (Triangle Inequality). *In any inner product space,*

$$\|x + y\| \leq \|x\| + \|y\|$$

PROOF:

$$\begin{aligned}
\|x + y\|^2 &= \langle x + y, x + y \rangle \\
&= \langle x, x \rangle + \langle x, y \rangle + \langle y, x \rangle + \langle y, y \rangle \\
&\leq \langle x, x \rangle + 2|\langle x, y \rangle| + \langle y, y \rangle \\
&\leq \|x\|^2 + 2\|x\|\|y\| + \|y\|^2 && \text{(Schwarz's Inequality)} \\
&= (\|x\| + \|y\|)^2 && \square
\end{aligned}$$

**Corollary 10.0.11.2.** *The norm in an inner product space is a norm.*

**Theorem 10.0.12** (Parallelogram Law). *In any inner product space,*

$$\|x + y\|^2 + \|x - y\|^2 = 2(\|x\|^2 + \|y\|^2)$$

PROOF:

$$\begin{aligned}
\langle 1 \rangle 1. \quad &\|x + y\|^2 = \|x\|^2 + \langle x, y \rangle + \langle y, x \rangle + \|y\|^2 \\
\langle 1 \rangle 2. \quad &\|x - y\|^2 = \|x\|^2 - \langle x, y \rangle - \langle y, x \rangle + \|y\|^2 \\
\langle 1 \rangle 3. \quad &\text{Q.E.D.}
\end{aligned}$$

PROOF: Add  $\langle 1 \rangle 1$  and  $\langle 1 \rangle 2$ .

$\square$

**Proposition 10.0.13.** *Let  $E$  be a normed space over  $\mathbb{C}$ . Then there exists an inner product on  $E$  that induces the norm of  $E$  iff  $E$  satisfies the Parallelogram Law.*

PROOF: If  $E$  satisfies the parallelogram law, define

$$\langle x, y \rangle = \frac{1}{4}(\|x + y\|^2 - \|x - y\|^2 + i\|x + iy\|^2 - i\|x - iy\|^2) .$$

**Definition 10.0.14** (Orthogonal). Vectors  $x$  and  $y$  in an inner product space are *orthogonal*,  $x \perp y$ , iff  $\langle x, y \rangle = 0$ .

**Theorem 10.0.15** (Pythagorean Formula). *If  $x$  and  $y$  are orthogonal then*

$$\|x + y\|^2 = \|x\|^2 + \|y\|^2 .$$

**Definition 10.0.16** (Weak Convergence). Let  $E$  be an inner product space. Let  $(x_n)$  be a sequence in  $E$  and  $l \in E$ . Then  $(x_n)$  *weakly converges* to  $l$ ,  $x_n \xrightarrow{w} l$  as  $n \rightarrow \infty$ , iff  $\forall y \in E. \langle x_n, y \rangle \rightarrow \langle l, y \rangle$  as  $n \rightarrow \infty$ .

**Proposition 10.0.17.** *In any inner product space  $E$ , the inner product  $\langle \cdot, \cdot \rangle : E^2 \rightarrow \mathbb{C}$  is continuous.*

PROOF:

$\langle 1 \rangle 1.$  LET:  $x_n \rightarrow x$  and  $y_n \rightarrow y$  in  $E$ .

$\langle 1 \rangle 2.$   $\langle x_n, y_n \rangle \rightarrow \langle x, y \rangle$

PROOF:

$$\begin{aligned}
|\langle x_n, y_n \rangle - \langle x, y \rangle| &\leq |\langle x_n, y_n \rangle - \langle x_n, y \rangle| + |\langle x_n, y \rangle - \langle x, y \rangle| \\
&= |\langle x_n, y_n - y \rangle| + |\langle x_n - x, y \rangle| \\
&\leq \|x_n\| \|y_n - y\| + \|x_n - x\| \|y\| && \text{(Schwarz's Inequality)} \\
&\rightarrow 0
\end{aligned}$$

using the fact that  $(x_n)$  is bounded.

□

**Theorem 10.0.18.**  $x_n \rightarrow l$  if and only if  $x_n \xrightarrow{w} l$  and  $\|x_n\| \rightarrow \|l\|$ .

PROOF:

⟨1⟩1. If  $x_n \rightarrow l$  then  $x_n \xrightarrow{w} l$  and  $\|x_n\| \rightarrow \|l\|$ .

PROOF: Easy using the fact that the inner product is continuous.

⟨1⟩2. If  $x_n \xrightarrow{w} l$  and  $\|x_n\| \rightarrow \|l\|$  then  $x_n \rightarrow l$ .

⟨2⟩1. ASSUME:  $x_n \xrightarrow{w} l$  and  $\|x_n\| \rightarrow \|l\|$

⟨2⟩2.  $\langle x_n, l \rangle \rightarrow \|l\|^2$

⟨2⟩3.  $\|x_n - l\| \rightarrow 0$

PROOF:

$$\begin{aligned} \|x_n - l\|^2 &= \langle x_n - l, x_n - l \rangle \\ &= \langle x_n, x_n \rangle - \langle x_n, l \rangle - \langle l, x_n \rangle + \langle l, l \rangle \\ &= \|x_n\|^2 - \langle x_n, l \rangle - \overline{\langle x_n, l \rangle} + \|l\|^2 \\ &\rightarrow \|l\|^2 - 2\|l\|^2 + \|l\|^2 \\ &= 0 \end{aligned}$$

□

**Theorem 10.0.19.** Let  $S$  be a subset of an inner product space  $E$  such that  $\text{span } S$  is dense in  $E$ . If  $(x_n)$  is a bounded sequence in  $E$  and, for all  $y \in S$ , we have  $\langle x_n, y \rangle \rightarrow \langle x, y \rangle$  then  $x_n \xrightarrow{w} x$ .

PROOF:

⟨1⟩1. For all  $y \in \text{span } S$ , we have  $\langle x_n, y \rangle \rightarrow \langle x, y \rangle$

⟨1⟩2. LET:  $z \in E$

PROVE:  $\langle x_n, z \rangle \rightarrow \langle x, z \rangle$

⟨1⟩3. LET:  $\epsilon > 0$

PROVE: There exists  $n_0$  such that  $\forall n \geq n_0, |\langle x_n, z \rangle - \langle x, z \rangle| < \epsilon$

⟨1⟩4. PICK  $M > 0$  such that  $\|x\| \leq M$  and  $\forall n \in \mathbb{Z}_+, \|x_n\| \leq M$ .

⟨1⟩5. PICK  $y_0 \in \text{span } S$  such that  $\|z - y_0\| < \epsilon/3M$

⟨1⟩6. PICK  $n_0 \in \mathbb{Z}_+$  such that, for all  $n \geq n_0$ , we have  $|\langle x_n, y_0 \rangle - \langle x, y_0 \rangle| < \epsilon/3$

⟨1⟩7. LET:  $n \geq n_0$

⟨1⟩8.  $|\langle x_n, z \rangle - \langle x, z \rangle| < \epsilon$

PROOF:

$$\begin{aligned} |\langle x_n, z \rangle - \langle x, z \rangle| &\leq |\langle x_n, z \rangle - \langle x_n, y_0 \rangle| + |\langle x_n, y_0 \rangle - \langle x, y_0 \rangle| + |\langle x, y_0 \rangle - \langle x, z \rangle| \\ &< \|x_n\| \|z - y_0\| + \epsilon/3 + \|x\| \|y_0 - z\| \\ &< M(\epsilon/3M) + \epsilon/3 + M(\epsilon/3M) \\ &= \epsilon \end{aligned}$$

□

## 10.1 Orthonormal Bases

**Definition 10.1.1** (Orthogonal). Let  $V$  be an inner product space and  $S \subseteq V$ . Then  $S$  is *orthogonal* iff any two distinct elements of  $S$  are orthogonal.

**Definition 10.1.2** (Orthonormal). Let  $V$  be an inner product space and  $S \subseteq V$ . Then  $S$  is *orthonormal* iff it is orthogonal and  $\forall x \in S, \|x\| = 1$ .

**Proposition 10.1.3.** *Orthonormal sets are linearly independent.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $S$  be orthonormal

$\langle 1 \rangle 2$ . ASSUME:  $\alpha_1 e_1 + \cdots + \alpha_n e_n = 0$  where  $e_1, \dots, e_n \in S$

$\langle 1 \rangle 3$ .  $|\alpha_1|^2 + \cdots + |\alpha_n|^2 = 0$

PROOF:

$$\begin{aligned} 0 &= \sum_{m=1}^n \langle 0, \alpha_m e_m \rangle \\ &= \sum_{m=1}^n \left\langle \sum_{k=1}^n \alpha_k e_k, \alpha_m e_m \right\rangle \\ &= \sum_{m=1}^n \sum_{k=1}^n \alpha_k \overline{\alpha_m} \langle e_k, e_m \rangle \\ &= \sum_{k=1}^n |\alpha_k|^2 \end{aligned}$$

$\langle 1 \rangle 4$ .  $\alpha_1 = \cdots = \alpha_n = 0$

□

**Proposition 10.1.4.** *In  $l^2$ , let  $e_n$  be the sequence whose  $n$ th element is 1 and whose other elements are 0. Then  $\{e_n \mid n \in \mathbb{Z}_+\}$  is orthonormal.*

**Proposition 10.1.5.** *In  $L^2([-\pi, \pi])$ , let  $\phi_n(x) = e^{inx}/\sqrt{2\pi}$  for  $n \in \mathbb{Z}$ . Then  $\{\phi_n \mid n \in \mathbb{Z}\}$  is orthonormal.*

**Definition 10.1.6** (Legendre Polynomials). The *Legendre polynomials*  $P_n \in \mathbb{Q}[x]$  for  $n \in \mathbb{N}$  are defined by

$$\begin{aligned} P_0 &= 1 \\ P_n &= \frac{1}{2^n n!} \frac{d^n}{dx^n} (x^2 - 1)^n \end{aligned}$$

**Proposition 10.1.7.** *Let  $P_n$  be the  $n$ th Legendre polynomial. Then  $\{P_n \mid n \in \mathbb{N}\}$  is orthogonal in  $L^2([-1, 1])$ .*

**Definition 10.1.8** (Hermite Polynomial). The *Hermite polynomials*  $H_n \in \mathbb{R}[x]$  for  $n \in \mathbb{N}$  are defined by

$$H_n(x) = (-1)^n e^{x^2} \frac{d^n}{dx^n} e^{-x^2}.$$

**Proposition 10.1.9.** *Let  $H_n$  be the  $n$ th Hermite polynomial. Then  $\{e^{-x^2/2} H_n(x) \mid n \in \mathbb{N}\}$  is orthogonal in  $L^2(\mathbb{R})$ .*

**Theorem 10.1.10.** *Let  $V$  be an inner product space. If  $x_1, \dots, x_n \in V$  are orthogonal then*

$$\left\| \sum_{i=1}^n x_i \right\|^2 = \sum_{i=1}^n \|x_i\|^2 .$$

**Theorem 10.1.11** (Bessel's Equality). *Let  $V$  be an inner product space. Let  $x_1, \dots, x_n \in V$  be orthonormal. Let  $x \in V$ . Then*

$$\left\| x - \sum_{k=1}^n \langle x, x_k \rangle x_k \right\|^2 = \|x\|^2 - \sum_{k=1}^n |\langle x, x_k \rangle|^2 .$$

PROOF:

$$\begin{aligned} \left\| x - \sum_{k=1}^n \langle x, x_k \rangle x_k \right\|^2 &= \left\langle x - \sum_{k=1}^n \langle x, x_k \rangle x_k, x - \sum_{k=1}^n \langle x, x_k \rangle x_k \right\rangle \\ &= \langle x, x \rangle - \left\langle x, \sum_{k=1}^n \langle x, x_k \rangle x_k \right\rangle - \left\langle \sum_{k=1}^n \langle x, x_k \rangle x_k, x \right\rangle \\ &\quad + \left\langle \sum_{k=1}^n \langle x, x_k \rangle x_k, \sum_{k=1}^n \langle x, x_k \rangle x_k \right\rangle \\ &= \langle x, x \rangle - 2 \sum_{k=1}^n \langle x, x_k \rangle \langle x_k, x \rangle + \sum_{i=1}^n \sum_{j=1}^n \langle x, x_i \rangle \langle x_j, x \rangle \langle x_i, x_j \rangle \\ &= \|x\|^2 - 2 \sum_{k=1}^n |\langle x, x_k \rangle|^2 + \sum_{i=1}^n \langle x, x_i \rangle \langle x_i, x \rangle \\ &= \|x\|^2 - \sum_{k=1}^n |\langle x, x_k \rangle|^2 \end{aligned} \quad \square$$

**Corollary 10.1.11.1** (Bessel's Inequality). *Let  $V$  be an inner product space. Let  $x_1, \dots, x_n \in V$  be orthonormal. Let  $x \in E$ . Then*

$$\sum_{k=1}^n |\langle x, x_k \rangle|^2 \leq \|x\|^2 .$$

**Corollary 10.1.11.2.** *Orthonormal sequences are weakly convergent to 0.*

PROOF: Let  $(x_n)$  be an orthonormal sequence. Taking the limit in Bessel's inequality we have  $\sum_{k=1}^{\infty} |\langle x, x_k \rangle|^2 \leq \|x\|^2 < \infty$  and so  $\langle x, x_k \rangle \rightarrow 0$  as  $k \rightarrow \infty$ .  $\square$

**Corollary 10.1.11.3** (Generalized Fourier Series). *Let  $V$  be an inner product space. Let  $(e_n)$  be an orthonormal sequence in  $V$ . For any  $x \in V$ , the generalized Fourier series of  $x$  is*

$$\sum_{n=1}^{\infty} \langle x, e_n \rangle e_n ,$$

and  $\langle x, e_n \rangle$  is called the  $n$ th generalized Fourier coefficient of  $x$  with respect to  $(e_n)$ . We have  $(\langle x, e_n \rangle e_n)_n \in l^2$ .

**Definition 10.1.12** (Complete Orthonormal Sequence). Let  $E$  be an inner product space. Let  $(x_n)$  be an orthonormal sequence in  $E$ . Then  $(x_n)$  is *complete* iff, for all  $x \in E$ , we have

$$\sum_{n=1}^{\infty} \langle x, x_n \rangle x_n = x \quad .$$





# Chapter 11

## Hilbert Spaces

**Definition 11.0.1** (Hilbert Space). A *Hilbert space* is a complete inner product space.

**Proposition 11.0.2.** For  $n \in \mathbb{N}$ ,  $\mathbb{C}^n$  is a Hilbert space.

**Proposition 11.0.3.**  $l^2$  is a Hilbert space.

**Proposition 11.0.4.**  $L^2(\mathbb{R})$  is a Hilbert space.

**Proposition 11.0.5.**  $L^2([a, b])$  is a Hilbert space.

**Proposition 11.0.6.** Let  $\rho$  be a measurable function on  $[a, b]$  such that  $\rho(x) > 0$  almost everywhere. Let  $L^{2\rho}([a, b])$  be the set of all measurable functions  $f : [a, b] \rightarrow \mathbb{C}$  such that

$$\int_a^b |f(x)|^2 \rho(x) dx < \infty .$$

Define an inner product on  $L^{2\rho}([a, b])$  by

$$\langle f, g \rangle = \int_a^b f(x) \overline{g(x)} \rho(x) dx .$$

Then  $L^{2\rho}([a, b])$  is a Hilbert space.

**Proposition 11.0.7.** Let  $m$  and  $N$  be positive integers. Let  $\Omega$  be an open set in  $\mathbb{R}^N$ . Let  $\tilde{H}^m(\Omega)$  be the set of all  $f \in C^m(\Omega)$  such that, for every  $\alpha = (\alpha_1, \dots, \alpha_N) \in \mathbb{Z}_+^N$  with  $|\alpha| := \alpha_1 + \dots + \alpha_N \leq m$ , we have

$$D^\alpha f := \frac{\partial^{|\alpha|} f}{\partial x_1^{\alpha_1} \partial x_2^{\alpha_2} \dots \partial x_N^{\alpha_N}} \in L^2(\Omega) .$$

Define an inner product on  $\tilde{H}^m(\Omega)$  by

$$\langle f, g \rangle := \int_\Omega \sum_\alpha D^\alpha f \overline{D^\alpha g} .$$

Let  $H^m(\Omega)$  be the completion of  $\tilde{H}^m(\Omega)$ . Then  $H^m(\Omega)$  is a Hilbert space.

**Theorem 11.0.8.** *Weakly convergent sequences in a Hilbert space are bounded.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $H$  be a Hilbert space.

$\langle 1 \rangle 2$ . LET:  $(x_n)$  be a weakly convergent sequence in  $H$ .

$\langle 1 \rangle 3$ . For  $n \in \mathbb{Z}_+$ ,

LET:  $f_n : H \rightarrow \mathbb{C}$ ,  $f_n(x) = \langle x, x_n \rangle$

$\langle 1 \rangle 4$ . For  $n \in \mathbb{Z}_+$ ,  $f_n$  is a bounded linear functional.

$\langle 1 \rangle 5$ . For every  $x \in H$ , the sequence  $(f_n(x))$  is bounded.

PROOF: Since it converges.

$\langle 1 \rangle 6$ . PICK  $M > 0$  such that, for all  $n \in \mathbb{Z}_+$ , we have  $\|f_n\| \leq M$ .

PROOF: Banach-Steinhaus Theorem,  $\langle 1 \rangle 4$ ,  $\langle 1 \rangle 5$ .

$\langle 1 \rangle 7$ .  $\forall n \in \mathbb{Z}_+$ .  $\|f_n\| = \|x_n\|$

$\langle 2 \rangle 1$ . LET:  $n \in \mathbb{Z}_+$

$\langle 2 \rangle 2$ .  $\|f_n\| \leq \|x_n\|$

PROOF: Since for all  $x \in H$  we have  $|f_n(x)| = |\langle x, x_n \rangle| \leq \|x\| \|x_n\|$  by Schwarz's Inequality.

$\langle 2 \rangle 3$ .  $\|x_n\| \leq \|f_n\|$

PROOF: Since  $\|x_n\|^2 = |\langle x_n, x_n \rangle| = |f_n(x_n)| \leq \|f_n\| \|x_n\|$ .

$\langle 1 \rangle 8$ .  $\forall n \in \mathbb{Z}_+$ .  $\|x_n\| \leq M$

PROOF:  $\langle 1 \rangle 6$ ,  $\langle 1 \rangle 7$

□

**Theorem 11.0.9.** *Let  $H$  be a Hilbert space. Let  $(x_n)$  be an orthonormal sequence in  $H$  and let  $(\alpha_n)$  be a sequence of complex numbers. Then the series  $\sum_{n=1}^{\infty} \alpha_n x_n$  converges in  $H$  if and only if  $\sum_{n=1}^{\infty} |\alpha_n|^2$  converges in  $\mathbb{R}$ , in which case*

$$\left\| \sum_{n=1}^{\infty} \alpha_n x_n \right\|^2 = \sum_{n=1}^{\infty} |\alpha_n|^2 .$$

PROOF:

$\langle 1 \rangle 1$ . For  $m > k > 0$  we have

$$\left\| \sum_{n=k}^m \alpha_n x_n \right\|^2 = \sum_{n=k}^m |\alpha_n|^2 .$$

PROOF: Theorem 10.1.10.

$\langle 1 \rangle 2$ . If  $\sum_{n=1}^{\infty} |\alpha_n|^2 < \infty$  then  $\sum_{n=1}^{\infty} \alpha_n x_n$  converges.

$\langle 2 \rangle 1$ . ASSUME:  $\sum_{n=1}^{\infty} |\alpha_n|^2 < \infty$

$\langle 2 \rangle 2$ .  $(\sum_{n=1}^m \alpha_n x_n)_m$  is Cauchy.

PROOF: From  $\langle 1 \rangle 1$ .

$\langle 2 \rangle 3$ .  $\sum_{n=1}^{\infty} \alpha_n x_n$  converges.

$\langle 1 \rangle 3$ . If  $\sum_{n=1}^{\infty} \alpha_n x_n$  converges then  $\sum_{n=1}^{\infty} |\alpha_n|^2 < \infty$ .

PROOF: From  $\langle 1 \rangle 1$ .

$\langle 1 \rangle 4$ . If  $\sum_{n=1}^{\infty} |\alpha_n|^2 < \infty$  then

$$\left\| \sum_{n=1}^{\infty} \alpha_n x_n \right\|^2 = \sum_{n=1}^{\infty} |\alpha_n|^2 .$$

PROOF: From  $\langle 1 \rangle 1$ .

□

**Proposition 11.0.10.** *Every complete orthonormal sequence in a Hilbert space is a basis.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $E$  be an inner product space.

$\langle 1 \rangle 2$ . LET:  $(e_n)$  be a complete orthonormal sequence in  $E$ .

$\langle 1 \rangle 3$ . For all  $x \in E$ , there exists a sequence  $(\alpha_n)$  in  $\mathbb{C}$  such that  $x = \sum_n \alpha_n e_n$ .

PROOF: Immediate from  $\langle 1 \rangle 2$ .

$\langle 1 \rangle 4$ . If  $\sum_n \alpha_n e_n = \sum_n \beta_n e_n$  then  $\alpha_n = \beta_n$  for all  $n$ .

$\langle 2 \rangle 1$ . LET:  $x = \sum_n \alpha_n e_n = \sum_n \beta_n e_n$

$\langle 2 \rangle 2$ .  $\sum_n |\alpha_n - \beta_n|^2 = 0$

PROOF:

$$\begin{aligned}
 0 &= \|x - x\|^2 \\
 &= \left\| \sum_{n=1}^{\infty} \alpha_n e_n - \sum_{n=1}^{\infty} \beta_n e_n \right\|^2 && (\langle 2 \rangle 1) \\
 &= \left\| \sum_{n=1}^{\infty} (\alpha_n - \beta_n) e_n \right\|^2 \\
 &= \sum_{n=1}^{\infty} |\alpha_n - \beta_n|^2 && (\text{Theorem 11.0.9})
 \end{aligned}$$

$\langle 2 \rangle 3$ .  $\alpha_n = \beta_n$  for all  $n$ .

□

**Theorem 11.0.11.** *An orthonormal sequence  $(x_n)$  in a Hilbert space  $H$  is complete if and only if, for all  $x \in H$ , if  $\forall n. \langle x, x_n \rangle = 0$  then  $x = 0$ .*

PROOF:

$\langle 1 \rangle 1$ . If  $(x_n)$  is complete then, for all  $x \in H$ , if  $\forall n. \langle x, x_n \rangle = 0$  then  $x = 0$ .

$\langle 2 \rangle 1$ . ASSUME:  $(x_n)$  is complete.

$\langle 2 \rangle 2$ . LET:  $x \in H$

$\langle 2 \rangle 3$ . ASSUME:  $\forall n. \langle x, x_n \rangle = 0$

$\langle 2 \rangle 4$ .  $x = \sum_{n=1}^{\infty} \langle x, x_n \rangle x_n = 0$

$\langle 1 \rangle 2$ . If, for all  $x \in H$ , if  $\forall n. \langle x, x_n \rangle = 0$  then  $x = 0$ , then  $(x_n)$  is complete.

$\langle 2 \rangle 1$ . ASSUME: For all  $x \in H$ , if  $\forall n. \langle x, x_n \rangle = 0$ , then  $x = 0$ .

$\langle 2 \rangle 2$ . LET:  $y = x - \sum_{n=1}^{\infty} \langle x, x_n \rangle x_n$

$\langle 2 \rangle 3$ . For all  $n$ ,  $\langle y, x_n \rangle = 0$

$\langle 3 \rangle 1$ . LET:  $n \in \mathbb{Z}_+$

$\langle 3 \rangle 2$ .  $\langle y, x_n \rangle = 0$

PROOF:

$$\begin{aligned}
 \langle y, x_n \rangle &= \left\langle x - \sum_{m=1}^{\infty} \langle x, x_m \rangle x_m, x_n \right\rangle \\
 &= \langle x, x_n \rangle - \sum_{m=1}^{\infty} \langle x, x_m \rangle \langle x_m, x_n \rangle \\
 &= \langle x, x_n \rangle - \langle x, x_n \rangle \\
 &= 0
 \end{aligned}$$

$\langle 2 \rangle 4. y = 0$

$\langle 2 \rangle 5. x = \sum_{n=1}^{\infty} \langle x, x_n \rangle x_n$

□

**Theorem 11.0.12** (Parseval's Formula). *Let  $H$  be a Hilbert space. Let  $(x_n)$  be an orthonormal sequence in  $H$ . Then  $(x_n)$  is complete if and only if, for all  $x \in H$ ,*

$$\|x\|^2 = \sum_{n=1}^{\infty} |\langle x, x_n \rangle|^2.$$

PROOF:

$\langle 1 \rangle 1.$  If  $(x_n)$  is complete then for all  $x \in H$  we have  $\|x\|^2 = \sum_{n=1}^{\infty} |\langle x, x_n \rangle|^2$ .

$\langle 2 \rangle 1.$  ASSUME:  $(x_n)$  is complete.

$\langle 2 \rangle 2.$  LET:  $x \in H$

$\langle 2 \rangle 3.$   $\|x\|^2 = \sum_{n=1}^{\infty} |\langle x, x_n \rangle|^2$

PROOF:

$$\begin{aligned}
 \|x\|^2 &= \left\| \sum_{n=1}^{\infty} \langle x, x_n \rangle x_n \right\|^2 && (\langle 2 \rangle 1) \\
 &= \sum_{n=1}^{\infty} |\langle x, x_n \rangle|^2 && (\text{Theorem 11.0.9})
 \end{aligned}$$

$\langle 1 \rangle 2.$  If, for all  $x \in H$ , we have  $\|x\|^2 = \sum_{n=1}^{\infty} |\langle x, x_n \rangle|^2$ , then  $(x_n)$  is complete.

$\langle 2 \rangle 1.$  ASSUME: For all  $x \in H$ , we have  $\|x\|^2 = \sum_{n=1}^{\infty} |\langle x, x_n \rangle|^2$

$\langle 2 \rangle 2.$  LET:  $x \in H$

$\langle 2 \rangle 3.$   $x = \sum_{n=1}^{\infty} \langle x, x_n \rangle x_n$

□

**Proposition 11.0.13.** *For  $n \in \mathbb{Z}$ , let  $\pi_n(x) = e^{inx}/\sqrt{2\pi}$ . Then  $\{\pi_n \mid n \in \mathbb{Z}\}$  is a complete orthonormal set in  $L^2([-\pi, \pi])$ .*

TODO

**Proposition 11.0.14.**  $B = \{1/\sqrt{2\pi}\} \cup \{\cos nx/\sqrt{\pi} \mid n \in \mathbb{Z}_+\} \cup \{\sin nx/\sqrt{\pi} \mid n \in \mathbb{Z}_+\}$  is a complete orthonormal set in  $L^2([-\pi, \pi])$ .

PROOF:

$\langle 1 \rangle 1.$  For all  $f \in B$  we have  $\|f\| = 1$

$\langle 2 \rangle 1.$   $\|1/\sqrt{2\pi}\| = 1$

PROOF:

$$\begin{aligned}\|1/\sqrt{2\pi}\| &= \int_{-\pi}^{\pi} dx/2\pi \\ &= 1\end{aligned}$$

$\langle 2 \rangle 2$ . For all  $n \in \mathbb{Z}_+$  we have  $\|\cos nx/\sqrt{\pi}\| = 1$

PROOF:

$$\begin{aligned}\|\cos nx/\sqrt{\pi}\| &= 1/\pi \int_{-\pi}^{\pi} \cos^2 nx \, dx \\ &= 1/2\pi \int_{-\pi}^{\pi} (\cos 2nx + 1) dx \\ &= 1/2\pi [1/2n \sin 2nx + x]_{-\pi}^{\pi} \\ &= (1/2\pi)(2\pi) \\ &= 1\end{aligned}$$

$\langle 2 \rangle 3$ . For all  $n \in \mathbb{Z}_+$  we have  $\|\sin nx/\sqrt{\pi}\| = 1$

PROOF:

$$\begin{aligned}\|\sin nx/\sqrt{\pi}\| &= 1/\pi \int_{-\pi}^{\pi} \sin^2 nx \, dx \\ &= -1/2\pi \int_{-\pi}^{\pi} (\cos 2nx - 1) dx \\ &= -1/2\pi [1/2n \sin 2nx - x]_{-\pi}^{\pi} \\ &= (-1/2\pi)(-2\pi) \\ &= 1\end{aligned}$$

$\langle 1 \rangle 2$ . For all  $f, g \in B$  with  $f \neq g$  we have  $\langle f, g \rangle = 0$

$\langle 2 \rangle 1$ .  $\langle 1, \cos nx \rangle = 0$

PROOF:

$$\begin{aligned}\int_{-\pi}^{\pi} \cos nx \, dx &= [1/n \sin nx]_{-\pi}^{\pi} \\ &= 0\end{aligned}$$

$\langle 2 \rangle 2$ .  $\langle 1, \sin nx \rangle = 0$

PROOF:

$$\begin{aligned}\int_{-\pi}^{\pi} \sin nx \, dx &= [-1/n \cos nx]_{-\pi}^{\pi} \\ &= -1/n \cos n\pi + 1/n \cos n\pi \\ &= 0\end{aligned}$$

$\langle 2 \rangle 3$ . If  $m \neq n$  then  $\langle \cos mx, \cos nx \rangle = 0$

PROOF:

$$\begin{aligned}\int_{-\pi}^{\pi} \cos mx \cos nx \, dx &= 1/2 \int_{-\pi}^{\pi} (\cos(n+m)x - \cos(n-m)x) dx \\ &= 1/2 \left[ \frac{1}{n+m} \sin(n+m)x - \frac{1}{n-m} \sin(n-m)x \right]_{-\pi}^{\pi} \\ &= 0\end{aligned}$$

$\langle 2 \rangle 4$ .  $\langle \cos mx, \sin nx \rangle = 0$

PROOF:

$$\begin{aligned} \int_{-\pi}^{\pi} \cos mx \sin nx \, dx &= 1/2 \int_{-\pi}^{\pi} (\sin(n+m)x - \sin(n-m)x) \, dx \\ &= 1/2 \left[ -\frac{1}{n+m} \cos(n+m)x + \frac{1}{n-m} \cos(n-m)x \right]_{-\pi}^{\pi} \\ &= 0 \end{aligned} \quad (\cos \text{ is odd})$$

$\langle 2 \rangle 5$ . If  $m \neq n$  then  $\langle \sin mx, \sin nx \rangle = 0$

PROOF:

$$\begin{aligned} \int_{-\pi}^{\pi} \sin mx \sin nx \, dx &= 1/2 \int_{-\pi}^{\pi} (\cos(n-m)x - \cos(n+m)x) \, dx \\ &= 1/2 \left[ \frac{1}{n-m} \sin(n-m)x - \frac{1}{n+m} \sin(n+m)x \right]_{-\pi}^{\pi} \\ &= 0 \end{aligned}$$

$\langle 1 \rangle 3$ . For all  $f \in L^2([-\pi, \pi])$ , if  $\forall g \in B. \langle f, g \rangle = 0$  then  $f = 0$

$\langle 2 \rangle 1$ . LET:  $f \in L^2([-\pi, \pi])$

$\langle 2 \rangle 2$ . ASSUME:  $\forall g \in B. \langle f, g \rangle = 0$

$\langle 2 \rangle 3$ . For all  $n \in \mathbb{Z}$ ,  $\langle f, e^{inx} \rangle = 0$

PROOF: Since  $e^{inx} = \cos nx + i \sin nx$ .

$\langle 2 \rangle 4$ .  $f = 0$

PROOF: From Proposition 11.0.13.

□

**Proposition 11.0.15.**  $\{\frac{1}{\sqrt{\pi}}\} \cup \{\sqrt{\frac{2}{\pi}} \cos nx \mid n \in \mathbb{Z}_+\}$  is a complete orthonormal set in  $L^2([0, \pi])$ .

**Proposition 11.0.16.**  $\{\sqrt{\frac{2}{\pi}} \sin nx \mid n \in \mathbb{Z}_+\}$  is a complete orthonormal set in  $L^2([0, \pi])$ .

**Definition 11.0.17** (Signum). The *signum* function  $\text{sgn} : \mathbb{R} \rightarrow \mathbb{R}$  is defined by

$$\text{sgn } x = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{if } x = 0 \\ -1 & \text{if } x < 0 \end{cases}$$

**Definition 11.0.18** (Rademacher Functions). The *Rademacher functions*  $R : \mathbb{N} \times [0, 1] \rightarrow \{-1, 0, 1\}$  are defined by

$$R(m, x) = \text{sgn}(\sin(2^m \pi x)) \quad .$$

**Proposition 11.0.19.** The Rademacher functions  $\{R(m, -) \mid m \in \mathbb{N}\}$  are orthonormal in  $L^2([0, 1])$ .

PROOF:

$\langle 1 \rangle 1$ .  $\forall m \in \mathbb{N}. \|R(m, -)\| = 1$

PROOF:  $\int_0^1 \text{sgn}(\sin(2^m \pi x))^2 \, dx = 1$  since the integrand is 1 except for finitely many points in  $[0, 1]$ .

$\langle 1 \rangle 2$ . Given natural numbers  $m \neq n$ , we have  $\langle R(m, -), R(n, -) \rangle = 0$

$\langle 2 \rangle 1$ . Given reals  $a, b$  and a natural number  $m$ , we have  $\int_a^b R(m, x) dx = 0$  whenever  $2^m(b - a)$  is an even integer.

PROOF: If  $m > 0$ , or if  $m = 0$  and  $b - a$  is an even integer, then the regions where  $R(m, x) = 1$  are isometric with the regions where  $R(m, x) = -1$ .

$\langle 2 \rangle 2$ . LET:  $m$  and  $n$  be natural numbers with  $n < m$ .

$\langle 2 \rangle 3$ .  $\langle R(m, -), R(n, -) \rangle = 0$

PROOF:

$$\begin{aligned} \int_0^1 R(m, x) R(n, x) dx &= \sum_{k=1}^{2^n} \int_{\frac{k-1}{2^n}}^{\frac{k}{2^n}} R(m, x) R(n, x) dx \\ &= \sum_{k=1}^{2^n} (-i)^{k+1} \int_{\frac{k-1}{2^n}}^{\frac{k}{2^n}} R(m, x) dx \end{aligned}$$

$$= 0$$

$$(\langle 2 \rangle 1, 2^m \left( \frac{k}{2^n} - \frac{k-1}{2^n} \right) = 2^{m-n} \text{ is an even integer})$$

□

**Proposition 11.0.20.** *The set of Rademacher functions is not complete.*

PROOF:

$\langle 1 \rangle 1$ . Define  $f : [0, 1] \rightarrow \mathbb{C}$  by  $f(x) = 0$  if  $0 \leq x < 1/4$ ,  $f(x) = 1$  if  $1/4 \leq x \leq 3/4$ ,  $f(x) = 0$  if  $3/4 < x \leq 1$ .

$\langle 1 \rangle 2$ .  $f \in L^2([0, 1])$

$\langle 1 \rangle 3$ .  $\langle R(0, -), f \rangle = 1/2$

$\langle 1 \rangle 4$ .  $\langle R(m, -), f \rangle = 0$  for  $m \geq 1$

$\langle 1 \rangle 5$ .  $f \neq 1/2 R(0, -)$

□

**Definition 11.0.21** (Walsh Functions). Define the *Walsh functions*  $W : \mathbb{N} \times [0, 1] \rightarrow \{-1, 0, 1\}$  as follows. Given  $m \in \mathbb{N}$ , let  $m = \sum_{k=1}^n 2^{k-1} a_k$  where each  $a_k$  is either 0 or 1. Then

$$W(m, x) = \prod_{k=1}^n R(k, x)^{a_k} .$$

**Proposition 11.0.22.** *The set of Walsh functions  $\{W(m, -) \mid m \in \mathbb{N}\}$  is a complete orthonormal set.*

TODO