

Mathematics

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

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:

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

- ⟨1⟩1. LET: $x \in \text{fld } \mathbf{R}$
 PROVE: $(x, x) \in \mathbf{R}$
- ⟨1⟩2. PICK y such that either $(x, y) \in \mathbf{R}$ or $(y, x) \in \mathbf{R}$
- ⟨1⟩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* Π 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 Π have any common elements, and
2. each element of A is in some set in Π .

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:

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

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

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

□

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*

$$h(0) = a \text{ ,}$$

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

$$h(n^+) = F(h(n)) \text{ .}$$

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 $\forall m < n^+. m^+ < n^{++}$

- 1

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:

$$\begin{aligned} mp^+ &= mp + m \\ &< np + m && \text{(induction hypothesis. Theorem 4.4.7)} \\ &< np + n && (\langle 1 \rangle 2, \text{Theorem 4.4.7}) \\ &= np^+ \end{aligned}$$

□

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

Proposition 5.1.16. *For any integeres a and b , if $ab = 0$ then $a = 0$ or $b = 0$.*

PROOF:

$\langle 1 \rangle 1$. ASSUME: $[(m, n)][(p, q)] = [(0, 0)]$

$\langle 1 \rangle 2$. $mp + nq = mq + np$

$\langle 1 \rangle 3$. ASSUME: $[(m, n)] \neq [(0, 0)]$

$\langle 1 \rangle 4$. $m \neq n$

PROVE: $p = q$

$\langle 1 \rangle 5$. CASE: $m < n$

$\langle 2 \rangle 1$. $p \not< q$

PROOF: If $p < q$ then $mq + np < mp + nq$ by Proposition 4.4.10.

$\langle 2 \rangle 2$. $q \not< p$

PROOF: If $q < p$ then $mp + nq < mq + np$ by Proposition 4.4.10.

$\langle 2 \rangle 3$. $p = q$

PROOF: By trichotomy.

$\langle 1 \rangle 6$. CASE: $n < m$

PROOF: Similar.

\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, 5.1.8, 5.1.9. \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

Ring Theory

7.1 Integral Domains

Definition 7.1.1 (Integral Domain). An *integral domain* consists of a set D and two binary operations $+$, \cdot on D such that:

- D is an Abelian group under $+$. Let us write 0 for its identity element.
- \cdot is commutative and associative, and distributes over $+$.
- \cdot has an identity element that is different from 0 .
- For all $a, b \in D$, if $ab = 0$ then $a = 0$ or $b = 0$.

Proposition 7.1.2. *The integers \mathbb{Z} form an integral domain.*

PROOF: Propositions 5.1.12, 5.1.13, 5.1.14, 5.1.15, 5.1.16, 6.1.2. \square

Chapter 8

Complex Analysis

Definition 8.0.1. 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 8.0.2. 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 8.0.3 (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 8.0.4 (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 8.0.2)

⟨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 9

Vector Spaces

9.1 Vector Spaces

Definition 9.1.1 (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 9.1.2. *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 9.1.3. *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 9.1.4. *The set \mathbb{C} is a real vector space under complex addition and complex multiplication.*

PROOF: TODO

Proposition 9.1.5. *The set \mathbb{C} is a complex vector space under complex addition and complex multiplication.*

PROOF: TODO

Proposition 9.1.6. *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 9.1.6.1. *Let V be a vector space over K . For any set I , we have V^I is a vector space over K .*

Corollary 9.1.6.2. *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 9.1.7. *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 9.1.8. *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 $v + (-v) = u$

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:

$$x = x + 0 \quad (\text{Proposition 9.1.7})$$

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

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

$$= y \quad (\text{Proposition 9.1.7})$$

□

Proposition 9.1.9. *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:

$$v + u + (-v) = u + 0 \quad (\text{Proposition 9.1.8})$$

$$= u \quad (\text{Proposition 9.1.7})$$

$\langle 1 \rangle 3$. 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:

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

$$= x + 0 \quad (\text{Proposition 9.1.8})$$

$$= x \quad (\text{Proposition 9.1.7})$$

□

Proposition 9.1.10. *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:

$$v = v + 0 \quad (\text{Proposition 9.1.7})$$

$$= v + u + (-u) \quad (\text{Proposition 9.1.8})$$

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

$$= w + 0 \quad (\text{Proposition 9.1.8})$$

$$= w \quad (\text{Proposition 9.1.7})$$

Proposition 9.1.11. *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:

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

$$= \lambda 0 \quad (\text{Proposition 9.1.7})$$

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

PROOF: Proposition 9.1.10.

□

Proposition 9.1.12. *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 9.1.13. *Let V be a vector space over K . For all $v \in V$ we have $0v = 0$.*

PROOF:

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

$$\begin{aligned}
0v + 0 &= 0v && \text{(Proposition 9.1.7)} \\
&= (0 + 0)v \\
&= 0v + 0v && \text{(Axiom 5)}
\end{aligned}$$

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

PROOF: Proposition 9.1.10, $\langle 1 \rangle 1.$

□

Proposition 9.1.14. *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:

$$\begin{aligned}
v + (-1)v &= 1v + (-1)v && \text{(Axiom 7)} \\
&= (1 + (-1))v && \text{(Axiom 5)} \\
&= 0v \\
&= 0 && \text{(Proposition 9.1.13)}
\end{aligned}$$

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

PROOF: Proposition 9.1.8.

□

9.2 Subspaces

Definition 9.2.1 (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 9.2.2. *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 9.2.3. *Every vector space is a subspace of itself.*

PROOF: Trivial. □

Proposition 9.2.4. *Let Ω 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}^Ω .*

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

Proposition 9.2.5. *Let Ω 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}^Ω .*

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

Proposition 9.2.6. *Let Ω 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}^Ω .*

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

Proposition 9.2.7. *Let Ω 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}^Ω .*

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

Proposition 9.2.8. *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 9.2.9. *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: $\langle 1 \rangle 2, \langle 2 \rangle 1$.

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

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

\square

Proposition 9.2.10. *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 9.2.11. *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 9.2.12. *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 8.0.2, and it is easy to see that it is closed under scalar multiplication. \square

9.3 Linear Independence and Bases

Definition 9.3.1 (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 9.3.2 (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 9.3.3 (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 9.3.4. 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 9.3.5 (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 9.3.6 (Finite Dimensional). A vector space is *finite dimensional* iff there exists a finite basis; otherwise it is *infinite dimensional*.

Proposition 9.3.7. In a finite dimensional space, any two bases have the same size.

TODO

Definition 9.3.8 (Dimension). The *dimension* of a finite dimensional vector space V , $\dim V$, is the number of vectors in any basis.

Proposition 9.3.9. 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 9.3.10. 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 9.3.11. *Let Ω 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 9.3.12. *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

9.4 Linear Mappings

Definition 9.4.1 (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 9.4.2 (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 9.4.3. *Let U and V be vector spaces over K . The set of linear mappings from U to V is a subspace of V^U .*

9.5 Eigenvalues and Eigenvectors

Definition 9.5.1 (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* λ iff $A(v) = \lambda v$.

Chapter 10

Normed Spaces

Definition 10.0.1 (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 10.0.2. *In a normed space, $\|0\| = 0$.*

PROOF: $\|0\| = |0| \|0\| = 0$ by Axiom 2. \square

Proposition 10.0.3. *Let V be a normed vector space over K . For all $v \in V$ we have $\|v\| \geq 0$.*

PROOF:

$$\begin{aligned} 0 &= \|0\| && \text{(Proposition 10.0.2)} \\ &= \|v - v\| \\ &\leq \|v\| + \|-v\| && \text{(Triangle Inequality)} \\ &= 2\|v\| && \text{(Axiom 2)} \end{aligned}$$

Proposition 10.0.4. *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 10.0.5 (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 10.0.6. 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 10.0.6.1. The absolute value function $|\cdot|$ is a norm on K .

Proposition 10.0.7. 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:

$$\begin{aligned}
 \|\lambda \vec{x}\| &= |\lambda x_1| + \cdots + |\lambda x_n| \\
 &= |\lambda|(|x_1| + \cdots + |x_n|) \\
 &= |\lambda| \|\vec{x}\|
 \end{aligned}$$

$\langle 1 \rangle 3. \|\vec{u} + \vec{v}\| \leq \|\vec{u}\| + \|\vec{v}\|$

PROOF:

$$\begin{aligned}
 \|\vec{u} + \vec{v}\|^2 &= |u_1 + v_1|^2 + \cdots + |u_n + v_n|^2 \\
 &\leq |u_1|^2 + |v_1|^2 + \cdots + |u_n|^2 + |v_n|^2 \\
 &= \|\vec{u}\|^2 + \|\vec{v}\|^2
 \end{aligned}$$

□

Proposition 10.0.8. *The function $\|\vec{x}\| = \max(|x_1|, \dots, |x_n|)$ is a norm on \mathbb{C}^n .*

PROOF:

$\langle 1 \rangle 1.$ If $\|\vec{x}\| = 0$ then $\vec{x} = \vec{0}$

PROOF: If $\max(|x_1|, \dots, |x_n|) = 0$ 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 10.0.9 (Uniform Convergence Norm). Let Ω 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 10.0.10. *Let Ω be a closed bounded subset of \mathbb{R}^n . The uniform convergence norm is a norm on $\mathcal{C}(\Omega)$.*

PROOF:

$\langle 1 \rangle 1.$ If $\|f\| = 0$ 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:

$$\begin{aligned}
 \|\lambda f\| &= \max_x |\lambda f(x)| \\
 &= |\lambda| \max_x |f(x)| \\
 &= |\lambda| \|f\|
 \end{aligned}$$

⟨1⟩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 10.0.11. *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 10.0.12. *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 10.0.13. *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

$$\langle 2 \rangle 4. \quad \|(\alpha_1 x_1 + \cdots + \alpha_n x_n) - (\beta_1 x_1 + \beta_n x_n)\| < \epsilon$$

PROOF:

$$\|(\alpha_1 x_1 + \cdots + \alpha_n x_n) - (\beta_1 x_1 + \beta_n x_n)\|$$

$$\leq |\alpha_1 - \beta_1| \|x_1\| + \cdots + |\alpha_n - \beta_n| \|x_n\| \quad (\text{Axioms 2 and 3})$$

$$< \delta(\|x_1\| + \cdots + \|x_n\|) \quad (\langle 2 \rangle 3)$$

$$= \epsilon \quad (\langle 2 \rangle 2)$$

$\langle 1 \rangle 3.$ 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 10.0.14. 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 10.0.3.

$\langle 1 \rangle 2.$ 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 10.0.2.

$\langle 1 \rangle 3.$ $\forall x, y \in V. d(x, y) = d(y, x)$

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.

10.1 Convergence

Proposition 10.1.1. 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. \square

Proposition 10.1.2. *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:

$$\begin{aligned} \|l - m\| &\leq \|x_N - l\| + \|x_N - m\| && \text{(Triangle Inequality)} \\ &< 2\epsilon && (\langle 1 \rangle 5) \\ &= \|l - m\| && (\langle 1 \rangle 4) \end{aligned}$$

$\langle 1 \rangle 7$. Q.E.D.

PROOF: This is a contradiction.

\square

Definition 10.1.3 (Bounded). Let V be a normed space over K . A sequence (x_n) in V is *bounded* iff there exists B such that $\forall n, \|x_n\| < B$.

Proposition 10.1.4. *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:

$$\begin{aligned} \|x_n\| &\leq \|l\| + \|x_n - l\| && \text{(Triangle Inequality)} \\ &< \|l\| + 1 && (\langle 1 \rangle 2) \\ &\leq B && (\langle 1 \rangle 3) \end{aligned}$$

\square

Proposition 10.1.5. *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 $n \rightarrow \infty$

(1)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:

$$\begin{aligned} \|\lambda_n x_n - \lambda l\| &\leq \|\lambda_n x_n - \lambda x_n\| + \|\lambda x_n - \lambda l\| && \text{(Triangle Inequality)} \\ &= |\lambda_n - \lambda| \|x_n\| + |\lambda| \|x_n - l\| && \text{(Axiom 2)} \\ &< \sqrt{\epsilon/2} \sqrt{\epsilon/2} + |\lambda| \epsilon/2|\lambda| && ((1)5) \\ &= \epsilon \end{aligned}$$

□

Proposition 10.1.6. *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:

$$\begin{aligned} \|(x_n + y_n) - (l + m)\| &\leq \|x_n - l\| + \|y_n - m\| && \text{(Triangle Inequality)} \\ &< \epsilon/2 + \epsilon/2 && ((1)2) \\ &= \epsilon \end{aligned}$$

□

Definition 10.1.7 (Uniform Convergence). Let Ω 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 10.1.8. *Let Ω 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:

(f_n) converges to f under the uniform convergence norm

$$\Leftrightarrow \forall \epsilon > 0. \exists N. \forall n \geq N. \|f_n - f\| < \epsilon$$

$$\Leftrightarrow \forall \epsilon > 0. \exists N. \forall n \geq N. \forall x \in X. |f_n(x) - f(x)| < \epsilon$$

□

Definition 10.1.9 (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 10.1.10. *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 10.1.11 (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 10.1.12. 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 α and β 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 α and β 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 α and β 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: α and β 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 10.1.13. *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 10.0.13, (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 10.1.12, $\langle 1 \rangle 5$, $\langle 2 \rangle 1$, $\langle 2 \rangle 2$, $\langle 2 \rangle 4$, $\langle 2 \rangle 5$.

□

Definition 10.1.14 (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 10.1.15 (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 10.1.16 (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 10.1.17 (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 10.1.18. *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: $\delta = \alpha \epsilon$

- ⟨2⟩5. $\{y \in V \mid \|x - y\|_2 < \delta\} \subseteq S$
 ⟨1⟩6. If S is open under $\|\cdot\|_2$ then S is open under $\|\cdot\|_1$.

PROOF: Similar.

□

Proposition 10.1.19. *Every open ball is open.*

PROOF:

⟨1⟩1. LET: V be a normed space over K .

⟨1⟩2. LET: $c \in V$ and $r > 0$

PROVE: $B(c, r)$ is open.

⟨1⟩3. LET: $x \in B(c, r)$

⟨1⟩4. LET: $\epsilon = r - \|x - c\|$

PROVE: $B(x, \epsilon) \subseteq B(c, r)$

⟨1⟩5. LET: $y \in B(x, \epsilon)$

PROVE: $y \in B(c, r)$

⟨1⟩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 10.1.20. *Let Ω 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:

⟨1⟩1. LET: $g \in U$

⟨1⟩2. LET: $\epsilon = \max_{x \in \Omega} (f(x) - g(x))$

PROVE: $B(g, \epsilon) \subseteq U$

⟨1⟩3. $\epsilon > 0$

⟨1⟩4. LET: $h \in B(g, \epsilon/2)$

PROVE: $h \in U$

⟨1⟩5. LET: $x \in \Omega$

⟨1⟩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 10.1.21. *Let Ω 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 10.1.22. *Let Ω 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 10.1.23. *Let Ω 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 10.1.24. *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 10.1.25. *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 10.1.26. *In any normed space, \emptyset is open.*

PROOF: Vacuous. \square

Proposition 10.1.27. *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 10.1.28 (Closed Set). Let V be a normed space over K . A set $S \subseteq V$ is *closed* iff $V - S$ is open.

Proposition 10.1.29. *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: $B(x, \epsilon) \subseteq V - \overline{B}(c, r)$

$\langle 1 \rangle 5. \epsilon > 0$

PROOF: Since $\|x - c\| > r$ by $\langle 1 \rangle 3$.

$\langle 1 \rangle 6. \text{ LET: } y \in B(x, \epsilon)$

$\langle 1 \rangle 7. \|y - c\| > r$

PROOF:

$$\begin{aligned} \|y - c\| &\geq \|x - c\| - \|x - y\| && \text{(Triangle Inequality)} \\ &> \|x - c\| - \epsilon && (\langle 1 \rangle 6) \\ &= r && (\langle 1 \rangle 4) \end{aligned}$$

□

Proposition 10.1.30. *The intersection of a set of closed sets is closed.*

PROOF: From Proposition 10.1.24. □

Proposition 10.1.31. *The union of two closed sets is closed.*

PROOF: From Proposition 10.1.25. □

Proposition 10.1.32. *Every sphere is closed.*

PROOF: $S(c, r) = \overline{B}(c, r) - B(c, r)$. □

Proposition 10.1.33. *Let Ω 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 10.1.34. *Let Ω 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 10.1.35. *Let Ω 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 10.1.36. *Let Ω 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 10.1.37. *Let Ω 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 10.1.38. *In any normed space V , we have \emptyset is closed.*

PROOF: Since $V - \emptyset = V$ is open. □

Proposition 10.1.39. *In any normed space V , the whole space V is closed.*

PROOF: Since $V - V = \emptyset$ is open. \square

Theorem 10.1.40. *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 10.1.41 (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 10.1.42. *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 10.1.30. \square

Theorem 10.1.43. *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 10.1.40.

□

Definition 10.1.44 (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 10.1.45 (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 10.1.46. 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 10.1.47. 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 10.1.43.
 ⟨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 10.1.48 (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 10.1.49. *In K^n , a set is compact if and only if it is bounded and closed.*

PROOF: TODO

Definition 10.1.50 (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 10.1.51. *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 10.1.2.

$\langle 2 \rangle 5$. $l \in S$

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

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

PROOF: Theorem 10.1.40.

$\langle 1 \rangle 4$. 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 10.1.52. *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 10.1.53 (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/ϵ 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 10.1.54. *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 (α_{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 10.1.55. *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. $\alpha x + \beta y \in \text{cl}U$

□

10.2 Continuous Linear Mappings

Definition 10.2.1 (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 10.2.2. *Let V be a normed space. Then the norm is a continuous function $V \rightarrow \mathbb{R}$.*

PROOF: From Proposition 10.0.4. □

Proposition 10.2.3. *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 10.2.4. *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 10.2.5 (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 10.2.6. *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 10.2.4.

□

Proposition 10.2.7. *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 10.1.13.

- ⟨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:

$$\begin{aligned}
 \|T(x)\| &= \|\alpha_1 T(e_1) + \dots + \alpha_n T(e_n)\| && (T \text{ linear}) \\
 &\leq |\alpha_1| \|T(e_1)\| + \dots + |\alpha_n| \|T(e_n)\| && (\text{Triangle inequality}) \\
 &\leq M(|\alpha_1| + \dots + |\alpha_n|) && (\langle 1 \rangle 2) \\
 &\leq CM\|x\| && (\langle 1 \rangle 3)
 \end{aligned}$$

□

Corollary 10.2.7.1. *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 10.2.8. *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:

$$\begin{aligned}
 \|T(x) - T(y)\| &= \|T(x - y)\| && (T \text{ linear}) \\
 &\leq B\|x - y\| && (\langle 1 \rangle 2) \\
 &< B\delta && (\langle 1 \rangle 6) \\
 &= \epsilon && (\langle 1 \rangle 4)
 \end{aligned}$$

□

Proposition 10.2.9. *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 10.2.10. *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 10.2.11. *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 α 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 10.2.12. *Let V be a normed space. Then id_V is a bounded linear function $V \rightarrow V$, and $\|\text{id}_V\| = 1$.*

Proposition 10.2.13. *Let U and V be normed spaces. The constant zero function $U \rightarrow V$ is a bounded linear transformation with norm 0.*

Proposition 10.2.14. *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 10.2.15 (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 10.2.16. *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 10.2.17. *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 10.2.18 (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:

$$\begin{aligned}\left\| \sum_{j=1}^{\infty} x_{s_i s_j} \right\| &= \left\| x_{s_i s_i} + \sum_{i \neq j} x_{s_i s_j} \right\| \\ &\geq \left| \|x_{s_i s_i}\| - \left\| \sum_{i \neq j} x_{s_i s_j} \right\| \right| && \text{(Proposition 10.0.4)} \\ &\geq \left| \|x_{s_i s_i}\| - \sum_{i \neq j} \|x_{s_i s_j}\| \right| \\ &\geq \epsilon/2 && ((1)2, (1)8)\end{aligned}$$

(1)11. Q.E.D.

PROOF: (1)9 and (1)10 form a contradiction.

□

10.3 Banach Spaces

Definition 10.3.1 (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 10.3.2. 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 10.3.3. 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 $\|x_m - x_n\| < \epsilon$.
 \square

Proposition 10.3.4. *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. \square

Proposition 10.3.5. *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 10.0.4.

⟨1⟩2. Q.E.D.

PROOF: Since every Cauchy sequence in \mathbb{R} converges.

\square

Proposition 10.3.6. *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. $\forall n. \|x_n\| \leq B$

\square

Definition 10.3.7 (Banach Space). A normed space V over K is *complete* or a *Banach space* iff every Cauchy sequence converges.

Proposition 10.3.8. *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 $k \in \mathbb{Z}_+$, (α_{nk}) is Cauchy in \mathbb{C} .

⟨1⟩5. For every $k \in \mathbb{Z}_+$, (α_{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 (α_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 8.0.2.
- $\langle 1 \rangle 10$. $a_n \rightarrow a$ 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 10.3.9. *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:
- $$\begin{aligned}
 |f(x) - f(x_0)| &\leq |f(x) - f_{n_0}(x)| + |f_{n_0}(x) - f_{n_0}(x_0)| + |f_{n_0}(x_0) - f(x_0)| \quad (\text{Triangle Inequality}) \\
 &< \epsilon/3 + \epsilon/3 + \epsilon/3 \quad (\langle 2 \rangle 3, \langle 2 \rangle 4) \\
 &= \epsilon
 \end{aligned}$$
- $\langle 1 \rangle 9$. (f_n) converges to f uniformly.
- PROOF: From $\langle 1 \rangle 7$
-

Definition 10.3.10 (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 10.3.11 (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 10.3.12. In $\mathcal{P}([0, 1])$, the series $\sum_{n=0}^{\infty} x^n/n!$ is absolutely convergent but not convergent.

PROOF: Proposition 10.3.4. \square

Theorem 10.3.13. 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:

$$\sum_{k=1}^{\infty} \|x_{p_{k+1}} - x_{p_k}\| < \sum_{k=1}^{\infty} 2^{-k} \quad (\langle 2 \rangle 3)$$

$$< \infty$$

$\langle 2 \rangle 5$. $\sum_{k=1}^{\infty} (x_{p_{k+1}} - x_{p_k})$ 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 10.3.14. *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 10.1.40.

$\langle 1 \rangle 7$. $a_n \rightarrow l$ as $n \rightarrow \infty$ in U .

□

Definition 10.3.15 (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 10.3.16. *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. ϕ 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 10.3.17. *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:

$$\|T_m(u) - T_n(u)\| \leq \|T_m - T_n\| \|u\| \quad (\text{Proposition 10.2.11})$$

$$< \epsilon$$

$\langle 1 \rangle 3$. 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:

$$\begin{aligned} \|T(x)\| &\leq \|T_N(x) - T(x)\| + \|T_N(x)\| && (\text{Triangle inequality}) \\ &\leq \|T_N - T\| \|x\| + \|T_N\| \|x\| && (\text{Proposition 10.2.11}) \\ &< \|x\| + B\|x\| && (\langle 3 \rangle 1, \langle 3 \rangle 2) \\ &= (B + 1)\|x\| \end{aligned}$$

$\langle 1 \rangle 5$. $T_n \rightarrow T$ 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 10.3.17.1. *For any normed space V over K , the space $\mathcal{B}(V, K)$ is a Banach space.*

Theorem 10.3.18. *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 10.1.43.
- (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 10.3.18.1. *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 10.3.19 (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 10.3.20 (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 10.3.13.
- ⟨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.

□

10.4 Contraction Mappings

Definition 10.4.1 (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 α such that $0 < \alpha < 1$ and

$$\forall x, y \in A. \|f(x) - f(y)\| \leq \alpha \|x - y\| .$$

Proposition 10.4.2. *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 α 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 10.4.3 (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 α such that $0 < \alpha < 1$ and

$$\forall x, y \in F. \|f(x) - f(y)\| \leq \alpha \|x - y\| .$$

 $\langle 1 \rangle 2$. PICK $x_0 \in F$

$\langle 1 \rangle 3$. For $n \in \mathbb{Z}_+$,

LET: $x_n = f^n(x_0)$.

$\langle 1 \rangle 4$. (x_n) is a Cauchy sequence.

$\langle 2 \rangle 1$. For all $n \in \mathbb{Z}_+$ we have $\|x_{n+1} - x_n\| \leq \alpha^n \|x_1 - x_0\|$.

$\langle 2 \rangle 2$. 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:

$$\begin{aligned} \|x_n - x_m\| &\leq \|x_n - x_{n-1}\| + \|x_{n-1} - x_{n-2}\| + \cdots + \|x_{m+1} - x_m\| \quad (\text{Triangle inequality}) \\ &\leq (\alpha^{n-1} + \alpha^{n-2} + \cdots + \alpha^m) \|x_1 - x_0\| \quad (\langle 2 \rangle 1) \\ &< \frac{\|x_1 - x_0\|}{1 - \alpha} \alpha^m \end{aligned}$$

$\langle 2 \rangle 3$. LET: $\epsilon > 0$

$\langle 2 \rangle 4$. PICK N such that $\alpha^N \|x_1 - x_0\| / (1 - \alpha) < \epsilon$

$\langle 2 \rangle 5$. For all $m, n \geq N$, we have $\|x_n - x_m\| < \epsilon$

$\langle 1 \rangle 5$. LET: $z = \lim_{n \rightarrow \infty} x_n$

$\langle 1 \rangle 6$. $f(z) = z$

PROOF:

$$\begin{aligned} f(z) &= f\left(\lim_{n \rightarrow \infty} x_n\right) \\ &= \lim_{n \rightarrow \infty} f(x_n) \quad (\text{Proposition 10.4.2}) \\ &= \lim_{n \rightarrow \infty} x_{n+1} \\ &= z \end{aligned}$$

$\langle 1 \rangle 7$. For any $w \in F$, if $f(w) = w$ then $w = z$.

$\langle 2 \rangle 1$. LET: $w \in F$

$\langle 2 \rangle 2$. ASSUME: $f(w) = w$

$\langle 2 \rangle 3$. $\|z - w\| \leq \alpha \|z - w\|$

PROOF: $\|z - w\| = \|f(z) - f(w)\| \leq \alpha \|z - w\|$

$\langle 2 \rangle 4$. $\|z - w\| = 0$

$\langle 2 \rangle 5$. $z = w$

□

Chapter 11

Inner Product Spaces

Definition 11.0.1 (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 11.0.2. 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 11.0.3.

$$\langle x, \alpha y + \beta z \rangle = \overline{\alpha} \langle x, y \rangle + \overline{\beta} \langle x, z \rangle$$

Proposition 11.0.4.

$$\langle 0, y \rangle = \langle x, 0 \rangle = 0$$

Proposition 11.0.5. 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 11.0.6. 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 11.0.7. 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 11.0.8. *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 11.0.9. *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 11.0.10 (Norm). In an inner product space, define $\|x\| = \sqrt{\langle x, x \rangle}$.

Proposition 11.0.11 (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 11.0.11.1 (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 11.0.11.2. *The norm in an inner product space is a norm.*

Theorem 11.0.12 (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 11.0.13. *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 11.0.14 (Orthogonal). Vectors x and y in an inner product space are *orthogonal*, $x \perp y$, iff $\langle x, y \rangle = 0$.

Theorem 11.0.15 (Pythagorean Formula). *If x and y are orthogonal then*

$$\|x + y\|^2 = \|x\|^2 + \|y\|^2 .$$

Definition 11.0.16 (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 11.0.17. *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 11.0.18. $x_n \rightarrow l$ 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 11.0.19. 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:

$$\begin{aligned} |\langle x_n, z \rangle - \langle x, z \rangle| &\leq |\langle x_n, z \rangle - \langle x_n, y_0 \rangle| + |\langle x_n, y_0 \rangle - \langle x, y_0 \rangle| + |\langle x, y_0 \rangle - \langle x, z \rangle| \\ &< \|x_n\| \|z - y_0\| + \epsilon/3 + \|x\| \|y_0 - z\| \\ &< M(\epsilon/3M) + \epsilon/3 + M(\epsilon/3M) \\ &= \epsilon \end{aligned}$$

□

11.1 Orthonormal Bases

Definition 11.1.1 (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 11.1.2 (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 11.1.3. *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 11.1.4. *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 11.1.5. *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 11.1.6 (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 11.1.7. *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 11.1.8 (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 11.1.9. *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 11.1.10. *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 11.1.11 (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 11.1.11.1 (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 11.1.11.2. *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 11.1.11.3 (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 11.1.12 (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 12

Hilbert Spaces

Definition 12.0.1 (Hilbert Space). A *Hilbert space* is a complete inner product space.

Proposition 12.0.2. For $n \in \mathbb{N}$, \mathbb{C}^n is a Hilbert space.

Proposition 12.0.3. l^2 is a Hilbert space.

Proposition 12.0.4. $L^2(\mathbb{R})$ is a Hilbert space.

Proposition 12.0.5. $L^2([a, b])$ is a Hilbert space.

Proposition 12.0.6. Let ρ 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 12.0.7. Let m and N be positive integers. Let Ω 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 12.0.8. *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 12.0.9. *Let H be a Hilbert space. Let (x_n) be an orthonormal sequence in H and let (α_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 11.1.10.

$\langle 1 \rangle 2$. 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 12.0.10. *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 (α_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:

$$\begin{aligned}
 0 &= \|x - x\|^2 \\
 &= \left\| \sum_{n=1}^{\infty} \alpha_n e_n - \sum_{n=1}^{\infty} \beta_n e_n \right\|^2 && (\langle 2 \rangle 1) \\
 &= \left\| \sum_{n=1}^{\infty} (\alpha_n - \beta_n) e_n \right\|^2 \\
 &= \sum_{n=1}^{\infty} |\alpha_n - \beta_n|^2 && (\text{Theorem 12.0.9})
 \end{aligned}$$

$\langle 2 \rangle 3$. $\alpha_n = \beta_n$ for all n .

□

Theorem 12.0.11. *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 12.0.12 (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:

$$\begin{aligned}
 \|x\|^2 &= \left\| \sum_{n=1}^{\infty} \langle x, x_n \rangle x_n \right\|^2 && (\langle 2 \rangle 1) \\
 &= \sum_{n=1}^{\infty} |\langle x, x_n \rangle|^2 && (\text{Theorem 12.0.9})
 \end{aligned}$$

$\langle 1 \rangle 2.$ 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 12.0.13. *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 12.0.14. *$B = \{1/\sqrt{2\pi}\} \cup \{\cos nx/\sqrt{\pi} \mid n \in \mathbb{Z}_+\} \cup \{\sin nx/\sqrt{\pi} \mid n \in \mathbb{Z}_+\}$ 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:

$$\begin{aligned}
\int_{-\pi}^{\pi} \cos mx \sin nx \, dx &= 1/2 \int_{-\pi}^{\pi} (\sin(n+m)x - \sin(n-m)x) \, dx \\
&= 1/2 \left[-\frac{1}{n+m} \cos(n+m)x + \frac{1}{n-m} \cos(n-m)x \right]_{-\pi}^{\pi} \\
&= 0
\end{aligned}$$

(cos is odd)

⟨2⟩5. If $m \neq n$ then $\langle \sin mx, \sin nx \rangle = 0$

PROOF:

$$\begin{aligned}
\int_{-\pi}^{\pi} \sin mx \sin nx \, dx &= 1/2 \int_{-\pi}^{\pi} (\cos(n-m)x - \cos(n+m)x) \, dx \\
&= 1/2 \left[\frac{1}{n-m} \sin(n-m)x - \frac{1}{n+m} \sin(n+m)x \right]_{-\pi}^{\pi} \\
&= 0
\end{aligned}$$

⟨1⟩3. For all $f \in L^2([-\pi, \pi])$, if $\forall g \in B. \langle f, g \rangle = 0$ then $f = 0$

⟨2⟩1. LET: $f \in L^2([-\pi, \pi])$

⟨2⟩2. ASSUME: $\forall g \in B. \langle f, g \rangle = 0$

⟨2⟩3. For all $n \in \mathbb{Z}$, $\langle f, e^{inx} \rangle = 0$

PROOF: Since $e^{inx} = \cos nx + i \sin nx$.

⟨2⟩4. $f = 0$

PROOF: From Proposition 12.0.13.

□

Proposition 12.0.15. $\{\frac{1}{\sqrt{\pi}}\} \cup \{\sqrt{\frac{2}{\pi}} \cos nx \mid n \in \mathbb{Z}_+\}$ is a complete orthonormal set in $L^2([0, \pi])$.

Proposition 12.0.16. $\{\sqrt{\frac{2}{\pi}} \sin nx \mid n \in \mathbb{Z}_+\}$ is a complete orthonormal set in $L^2([0, \pi])$.

Definition 12.0.17 (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 12.0.18 (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 12.0.19. The Rademacher functions $\{R(m, -) \mid m \in \mathbb{N}\}$ are orthonormal in $L^2([0, 1])$.

PROOF:

⟨1⟩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 12.0.20. *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 12.0.21 (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 12.0.22. *The set of Walsh functions $\{W(m, -) \mid m \in \mathbb{N}\}$ is a complete orthonormal set.*

TODO