

# Mathematics

Robin Adams

September 18, 2023



# Contents

<b>1</b>	<b>Primitive Terms and Axioms</b>	<b>5</b>
1.1	Primitive Terms . . . . .	5
1.2	Axioms . . . . .	5
1.3	Consequences of the Axioms . . . . .	6
1.3.1	Definitions Used in the Axioms . . . . .	6
1.3.2	Tabulations . . . . .	6
1.3.3	The Empty Set . . . . .	7
1.3.4	The Singleton . . . . .	8
1.3.5	Subsets . . . . .	9
1.4	Composition . . . . .	10
1.5	Axioms Part Two . . . . .	10
1.6	Cartesian Product . . . . .	11
<b>2</b>	<b>Topology</b>	<b>13</b>
2.1	Topological Spaces . . . . .	13
2.1.1	Subspaces . . . . .	15
2.1.2	Topological Disjoint Union . . . . .	15
2.1.3	Product Topology . . . . .	15
2.1.4	Bases . . . . .	15
2.1.5	Subbases . . . . .	15
2.2	Continuous Functions . . . . .	15
2.3	Convergence . . . . .	16
2.4	Connected Spaces . . . . .	16
2.5	Hausdorff Spaces . . . . .	16
2.6	Compactness . . . . .	17
2.7	Metric Spaces . . . . .	17
<b>3</b>	<b>Topological Vector Spaces</b>	<b>19</b>
3.1	Cauchy Sequences . . . . .	19
3.2	Seminorms . . . . .	19
3.3	Fréchet Spaces . . . . .	20
3.4	Normed Spaces . . . . .	20
3.5	Inner Product Spaces . . . . .	20
3.6	Banach Spaces . . . . .	20

3.7 Hilbert Spaces . . . . .	20
------------------------------	----

# Chapter 1

## Primitive Terms and Axioms

### 1.1 Primitive Terms

Let there be *sets*. We write  $A : \text{Set}$  for:  $A$  is a set.

For any set  $A$ , let there be *elements* of  $A$ . We write  $a : \text{El}(A)$  for:  $a$  is an element of  $A$ .

For any sets  $A$  and  $B$ , let there be *functions* from  $A$  to  $B$ . We write  $f : A \rightarrow B$  iff  $f$  is a function from  $A$  to  $B$ .

For any function  $f : A \rightarrow B$  and element  $a : \text{El}(A)$ , let there be an element  $f(a) : \text{El}(B)$ , the *value* of the function  $f$  at the *argument*  $a$ .

For any sets  $A$  and  $B$ , let there be a set  $A \times B$ , the *Cartesian product* of  $A$  and  $B$ , and functions  $\pi_1 : A \times B \rightarrow A$  and  $\pi_2 : A \times B \rightarrow B$ , the *projections*.

For any elements  $a : \text{El}(A)$  and  $b : \text{El}(B)$ , let there be an element  $(a, b) : \text{El}(A \times B)$ , the *ordered pair* of  $a$  and  $b$ .

### 1.2 Axioms

**Definition 1.1** (Function). Let  $A$  and  $B$  be sets and  $F : A \rightarrow B$ . Then  $F$  is a *function* from  $A$  to  $B$ ,  $F : A \rightarrow B$ , if and only if, for all  $x : \text{El}(A)$ , there exists a unique  $y : \text{El}(B)$  such that  $xFy$ . We denote this unique  $y$  by  $F(x)$ .

**Axiom Schema 1.2** (Comprehension). For any formula  $\phi[X, Y, x, y]$  where  $X$  and  $Y$  are set variables and  $x : \text{El}(X)$  and  $y : \text{El}(Y)$ , the following is an axiom:

For any sets  $A$  and  $B$ , there exists a relation  $R : A \rightarrow B$  such that, for all  $a : \text{El}(A)$  and  $b : \text{El}(B)$ , we have  $aRb$  if and only if  $\phi[A, B, a, b]$ .

**Axiom 1.3** (Tabulations). For any sets  $A$  and  $B$  and relation  $R : A \rightarrow B$ , there exists a set  $|R|$ , a tabulation of  $R$ , and functions  $p : |R| \rightarrow A$  and  $q : |R| \rightarrow B$  such that:

- For all  $x : \text{El}(A)$  and  $y : \text{El}(B)$ , we have  $xRy$  if and only if there exists  $r : \text{El}(|R|)$  such that  $p(r) = x$  and  $q(r) = y$
- For all  $r, s : \text{El}(|R|)$ , if  $p(r) = p(s)$  and  $q(r) = q(s)$  then  $r = s$ .

**Axiom 1.4** (Infinity). There exists a set  $\mathbb{N}$ , an element  $0 : \text{El}(\mathbb{N})$ , and a function  $s : \mathbb{N} \rightarrow \mathbb{N}$  such that:

- $\forall n : \text{El}(\mathbb{N}). s(n) \neq 0$
- $\forall m, n : \text{El}(\mathbb{N}). s(m) = s(n) \Rightarrow m = n$ .

**Axiom 1.5** (Choice). Let  $R : A \looparrowright B$  be a relation such that  $\forall a : \text{El}(A). \exists b : \text{El}(B). aRb$ . Then there exists a function  $f : A \rightarrow B$  such that  $\forall a : \text{El}(A). aRf(a)$ .

### 1.3 Consequences of the Axioms

#### 1.3.1 Definitions Used in the Axioms

**Definition 1.6** (Equality of Relations). Let  $R, S : A \looparrowright B$ . We say that  $R$  and  $S$  are equal,  $R = S$ , iff  $\forall a : \text{El}(A). \forall b : \text{El}(B). aRb \Leftrightarrow aSb$ .

**Proposition 1.7.** Let  $f, g : A \rightarrow B$ . If  $\forall x : \text{El}(A). f(x) = g(x)$  then  $f = g$ .

PROOF: Since  $xfy \Leftrightarrow y = f(x) \Leftrightarrow y = g(x) \Leftrightarrow xgy$ .  $\square$

**Definition 1.8** (Injective). A function  $f : A \rightarrow B$  is *injective* iff, for all  $x, y : \text{El}(A)$ , if  $f(x) = f(y)$  then  $x = y$ .

**Definition 1.9** (Surjective). A function  $f : A \rightarrow B$  is *surjective* iff, for all  $y : \text{El}(B)$ , there exists  $x : \text{El}(A)$  such that  $f(x) = y$ .

**Definition 1.10** (Bijective). A function  $f : A \rightarrow B$  is *bijective* or a *bijection* iff it is injective and surjective.

Sets  $A$  and  $B$  are *equinumerous*,  $A \approx B$ , iff there exists a bijection between them.

If we prove there exists a set  $X$  such that  $P(X)$ , and that any two sets that satisfy  $P$  are bijective, then we may introduce a constant  $C$  and define "Let  $C$  be the set such that  $P(C)$ ".

#### 1.3.2 Tabulations

**Theorem 1.11.** Let  $R : A \looparrowright B$ . Let  $p : T \rightarrow A$  and  $q : T \rightarrow B$  form a tabulation of  $R$ . Let  $p' : T' \rightarrow A$  and  $q' : T' \rightarrow B$  form a tabulation of  $R$ . Then there exists a unique bijection  $f : T \approx T'$  such that  $\forall t : \text{El}(T). p'(f(t)) = p(t)$  and  $\forall t : \text{El}(T). q'(f(t)) = q(t)$ .

PROOF:

$\langle 1 \rangle 1$ . LET:  $f : T \looparrowright T'$  be the relation such that  $tft'$  iff  $p(t) = p'(t')$  and  $q(t) = q'(t')$

PROOF: Axiom of Comprehension

$\langle 1 \rangle 2$ .  $f$  is a function.

$\langle 2 \rangle 1$ . LET:  $x : \text{El}(T)$

$\langle 2 \rangle 2$ .  $p(x)Rq(x)$

PROOF: Since  $T$  is a tabulation of  $R$ .

$\langle 2 \rangle 3$ . There exists a unique  $y : \text{El}(T')$  such that  $p'(y) = p(x)$  and  $q'(y) = q(x)$ .

PROOF: Since  $T'$  is a tabulation of  $R$ .

$\langle 1 \rangle 3$ .  $f$  is injective.

$\langle 2 \rangle 1$ . LET:  $x, y : \text{El}(T)$

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

$\langle 2 \rangle 3$ .  $p'(f(x)) = p'(f(y))$  and  $q'(f(x)) = q'(f(y))$

$\langle 2 \rangle 4$ .  $p(x) = p(y)$  and  $q(x) = q(y)$

$\langle 2 \rangle 5$ .  $x = y$

PROOF: Since  $T$  is a tabulation of  $R$ .

$\langle 1 \rangle 4$ .  $f$  is surjective.

$\langle 2 \rangle 1$ . LET:  $y : \text{El}(T')$

$\langle 2 \rangle 2$ .  $p'(y)Rq'(y)$

PROOF: Since  $T'$  is a tabulation of  $R$ .

$\langle 2 \rangle 3$ . There exists  $x : \text{El}(T)$  such that  $p(x) = p'(y)$  and  $q(x) = q'(y)$ .

PROOF: Since  $T$  is a tabulation of  $R$ .

$\langle 1 \rangle 5$ . If  $g : T \approx T'$  satisfies  $\forall t : \text{El}(T) . p'(g(t)) = p(t)$  and  $\forall t : \text{El}(T) . q'(g(t)) = q(t)$ .

$\langle 2 \rangle 1$ . LET:  $g : T \approx T'$  satisfy  $\forall t : \text{El}(T) . p'(g(t)) = p(t)$  and  $\forall t : \text{El}(T) . q'(g(t)) = q(t)$ .

$\langle 2 \rangle 2$ . For all  $t : \text{El}(T)$  we have  $p'(f(t)) = p'(g(t))$  and  $q'(f(t)) = q'(g(t))$ .

$\langle 2 \rangle 3$ . For all  $t : \text{El}(T)$  we have  $f(t) = g(t)$ .

□

### 1.3.3 The Empty Set

**Theorem 1.12.** *There exists a set which has no elements.*

PROOF:

$\langle 1 \rangle 1$ . PICK a set  $A$

PROOF: By the Axiom of Infinity, a set exists.

$\langle 1 \rangle 2$ . LET:  $R : A \looparrowright A$  be the relation such that, for all  $x, y \in A$ , we have  $\neg(xRy)$

PROOF: By the Axiom of Comprehension.

$\langle 1 \rangle 3$ . LET:  $|R|$  be the tabulation of  $R$  with projections  $p, q : |R| \rightarrow A$ .

PROVE:  $|R|$  has no elements.

PROOF: By the Axiom of Tabulations.

$\langle 1 \rangle 4$ . ASSUME: for a contradiction  $r : \text{El}(|R|)$

$\langle 1 \rangle 5$ .  $p(r)Rq(r)$

$\langle 1 \rangle 6$ . Q.E.D.

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

□

**Theorem 1.13.** *If  $E$  and  $E'$  have no elements then  $E \approx E'$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $E$  and  $E'$  have no elements.

$\langle 1 \rangle 2$ . LET:  $F : E \rightarrowtail E'$  be the relation such that, for all  $x : \text{El}(E)$  and  $y : \text{El}(E')$ , we have  $x F y$ .

PROOF: Axiom of Comprehension.

$\langle 1 \rangle 3$ .  $F$  is a function.

PROOF: Vacuously, for all  $x : \text{El}(E)$ , there exists a unique  $y : \text{El}(E')$  such that  $x F y$ .

$\langle 1 \rangle 4$ .  $F$  is injective.

PROOF: Vacuously, for all  $x, y : \text{El}(E)$ , if  $F(x) = F(y)$  then  $x = y$ .

$\langle 1 \rangle 5$ .  $F$  is surjective.

PROOF: Vacuously, for all  $y : \text{El}(E')$ , there exists  $x : \text{El}(E)$  such that  $F(x) = y$ .

□

**Definition 1.14** (Empty Set). The *empty set*  $\emptyset$  is the set with no elements.

### 1.3.4 The Singleton

**Theorem 1.15.** *There exists a set that has exactly one element.*

PROOF:

$\langle 1 \rangle 1$ . PICK a set  $A$  that has an element.

PROOF: By the Axiom of Infinity, there exists a set that has an element.

$\langle 1 \rangle 2$ . PICK  $a : \text{El}(A)$

$\langle 1 \rangle 3$ . LET:  $R : A \rightarrowtail A$  be the relation such that, for all  $x, y : \text{El}(A)$ , we have  $x R y$  if and only if  $x = y = a$ .

PROOF: By the Axiom of Comprehension.

$\langle 1 \rangle 4$ . LET:  $|R|$  be the tabulation of  $R$  with projections  $p, q : |R| \rightarrow A$ .

PROVE:  $|R|$  has exactly one element.

PROOF: By the Axiom of Tabulations.

$\langle 1 \rangle 5$ . LET:  $r : \text{El}(|R|)$  be the element such that  $p(r) = q(r) = a$

PROOF: Since  $a R a$  by  $\langle 1 \rangle 3$ .

$\langle 1 \rangle 6$ . LET:  $s : \text{El}(|R|)$

PROVE:  $s = r$

$\langle 1 \rangle 7$ .  $p(s) R q(s)$

PROOF: By the Axiom of Tabulations.

$\langle 1 \rangle 8$ .  $p(s) = q(s) = a$

PROOF: By  $\langle 1 \rangle 3$ .

$\langle 1 \rangle 9$ .  $p(s) = p(r)$  and  $q(s) = q(r)$

PROOF: By  $\langle 1 \rangle 5$ .

$\langle 1 \rangle 10$ .  $s = r$



PROOF: By the Axiom of Tabulations.

□

**Theorem 1.16.** *If  $A$  and  $B$  both have exactly one element then  $A \approx B$ .*

PROOF:

⟨1⟩1. LET:  $A$  and  $B$  both have exactly one element.

⟨1⟩2. LET:  $F : A \rightarrow B$  be the relation such that, for all  $x : \text{El}(A)$  and  $y : \text{El}(B)$ , we have  $xFy$ .

⟨1⟩3.  $F$  is a function.

PROOF: If  $xFy$  and  $xFy'$  then  $y = y'$  because  $B$  has only one element.

⟨1⟩4.  $F$  is injective.

PROOF: If  $F(x) = F(x')$  then  $x = x'$  because  $A$  has only one element.

⟨1⟩5.  $F$  is surjective.

⟨2⟩1. LET:  $y : \text{El}(B)$

⟨2⟩2. LET:  $x$  be the element of  $A$ .

⟨2⟩3.  $F(x) = y$

□

**Definition 1.17** (Singleton). Let  $1$  be the set that has exactly one element. Let  $*$  be its element.

### 1.3.5 Subsets

**Definition 1.18** (Subset). A *subset* of a set  $A$  is a relation  $1 \rightarrow A$ .

Given  $S : 1 \rightarrow A$  and  $a : \text{El}(A)$ , we write  $a \in S$  for  $*Sa$ .

**Theorem Schema 1.19.** *For any property  $P[X, x]$  where  $X$  is a set variable and  $x : \text{El}(X)$ , the following is a theorem:*

*For any set  $A$ , there exists a set  $B$  and injection  $i : B \rightarrow A$  such that, for all  $x : \text{El}(A)$ , we have  $P[A, x]$  if and only if there exists  $b : \text{El}(B)$  such that  $i(b) = x$ .*

PROOF:

⟨1⟩1. LET:  $S : 1 \rightarrow A$  be the relation such that, for all  $e : \text{El}(1)$  and  $a : \text{El}(A)$ , we have  $eSa$  if and only if  $P[A, a]$ .

PROOF: Axiom of Comprehension.

⟨1⟩2. LET:  $B$  be the tabulation of  $S$  with projections  $p : B \rightarrow 1$  and  $i : B \rightarrow A$ .

PROOF: Axiom of Tabulations.

⟨1⟩3.  $i$  is injective.

⟨2⟩1. LET:  $r, s : \text{El}(B)$

⟨2⟩2. ASSUME:  $i(r) = i(s)$

⟨2⟩3.  $p(r) = p(s)$

PROOF: Since  $1$  has only one element.

⟨2⟩4.  $r = s$

PROOF: Axiom of Tabulations.

⟨1⟩4. For all  $x : \text{El}(A)$ , we have  $P[A, x]$  if and only if there exists  $b : \text{El}(B)$  such that  $i(b) = x$ .

$\langle 2 \rangle 1$ . LET:  $x : \text{El}(A)$   
 $\langle 2 \rangle 2$ . If  $P[A, x]$  then there exists  $b : \text{El}(B)$  such that  $i(b) = x$   
 $\langle 3 \rangle 1$ . ASSUME:  $P[A, x]$   
 $\langle 3 \rangle 2$ .  $*Sx$   
 PROOF:  $\langle 1 \rangle 1$   
 $\langle 3 \rangle 3$ . There exists  $b : \text{El}(B)$  such that  $p(b) = *$  and  $i(b) = x$   
 PROOF: Axiom of Tabulations.  
 $\langle 2 \rangle 3$ . For all  $b : \text{El}(B)$  we have  $P[A, i(b)]$   
 $\langle 3 \rangle 1$ . LET:  $b : \text{El}(B)$   
 $\langle 3 \rangle 2$ .  $p(b)Si(b)$   
 PROOF: Axiom of Tabulations.  
 $\langle 3 \rangle 3$ .  $P[A, i(b)]$   
 PROOF:  $\langle 1 \rangle 1$

□

## 1.4 Composition

**Definition 1.20** (Composite). Let  $\phi : A \rightharpoonup B$  and  $\psi : B \rightharpoonup C$ . The *composite*  $\psi \circ \phi : A \rightharpoonup C$  is the relation such that  $a(\psi \circ \phi)c$  iff there exists  $b$  such that  $a\phi b$  and  $b\psi c$ .

**Definition 1.21** (Identity). For any set  $A$ , the *identity* function  $\text{id}_A : A \rightarrow A$  is the function defined by  $\text{id}_A(a) = a$ .

**Theorem 1.22.** *Composition of relations is associative, and the identity function is an identity for composition. The composite of functions is a function. The composite of injective functions is injective. The composite of surjective functions is surjective. The composite of bijections is a bijection. A function  $f : A \rightarrow B$  is a bijection iff there exists a function  $f^{-1} : B \rightarrow A$  such that  $f^{-1}f = \text{id}_A$  and  $ff^{-1} = \text{id}_B$ , in which case  $f^{-1}$  is unique.*

## 1.5 Axioms Part Two

**Axiom 1.23** (Power Set). For any set  $A$ , there exists a set  $\mathcal{P}A$ , the power set of  $A$ , and a relation  $\in : A \rightharpoonup \mathcal{P}A$ , called membership, such that, for any subset  $S$  of  $A$ , there exists a unique  $\bar{S} \in \mathcal{P}A$  such that, for all  $x \in A$ , we have  $x \in \bar{S}$  if and only if  $x \in S$ .

We usually write just  $S$  for  $\bar{S}$ .

**Axiom Schema 1.24** (Collection). Let  $P[X, Y, x]$  be a formula with set variables  $X$  and  $Y$  and an element variable  $x \in X$ . Then the following is an axiom.

For any set  $A$ , there exists a set  $B$ , a function  $p : B \rightarrow A$ , a set  $Y$  and a relation  $M : B \rightharpoonup Y$  such that:

- $\forall b \in B. P[A, \{y \in Y : bMy\}, p(b)]$
- For all  $a \in A$ , if  $\exists Y. P[A, Y, a]$ , then there exists  $b \in B$  such that  $a = p(b)$ .

**Definition 1.25** (Universe). Let  $E : U \multimap X$  be a relation. Let us say that a set  $A$  is *small* iff there exists  $u \in U$  such that  $A \approx \{x \in X : uEx\}$ .

Then  $(U, X, E)$  form a *universe* if and only if:

- $\mathbb{N}$  is  $U$ -small.
- For any  $U$ -small sets  $A$  and  $B$  and relation  $R : A \multimap B$ , the tabulation of  $R$  is  $U$ -small.
- If  $A$  is  $U$ -small then so is  $\mathcal{P}A$
- Let  $f : A \rightarrow B$  be a function. If  $B$  is  $U$ -small and  $f^{-1}(b)$  is  $U$ -small for all  $b \in B$ , then  $A$  is  $U$ -small.
- If  $p : B \twoheadrightarrow A$  is a surjective function such that  $A$  is  $U$ -small, then there exists a  $U$ -small set  $C$ , a surjection  $q : C \twoheadrightarrow A$ , and a function  $f : C \rightarrow B$  such that  $q = pf$ .

**Axiom 1.26** (Universe). *There exists a universe.*

Let  $E : U \multimap X$  be a universe. We shall say a set is *small* iff it is  $U$ -small, and *large* otherwise.

## 1.6 Cartesian Product

**Definition 1.27** (Cartesian Product). Let  $A$  and  $B$  be sets. The *Cartesian product* of  $A$  and  $B$ ,  $A \times B$ , is the tabulation of the relation  $A \multimap B$  that holds for all  $a \in A$  and  $b \in B$ . The associated functions  $\pi_1 : A \times B \rightarrow A$  and  $\pi_2 : A \times B \rightarrow B$  are called the *projections*.

Given  $a \in A$  and  $b \in B$ , we write  $(a, b)$  for the unique element of  $A \times B$  such that  $\pi_1(a, b) = a$  and  $\pi_2(a, b) = b$ .



## Chapter 2

# Topology

### 2.1 Topological Spaces

**Definition 2.1** (Topological Space). Let  $X$  be a set and  $\mathcal{O} \subseteq \mathcal{P}X$ . Then we say  $(X, \mathcal{O})$  is a *topological space* iff:

- For any  $\mathcal{U} \subseteq \mathcal{O}$  we have  $\bigcup \mathcal{U} \in \mathcal{O}$ .
- For any  $U, V \in \mathcal{O}$  we have  $U \cap V \in \mathcal{O}$ .
- $X \in \mathcal{O}$

We call  $\mathcal{O}$  the *topology* of the topological space, and call its elements *open* sets. We shall often write  $X$  for the topological space  $(X, \mathcal{O})$ .

**Definition 2.2** (Closed Set). Let  $X$  be a topological space and  $A \subseteq X$ . Then  $A$  is *closed* iff  $X - A$  is open.

**Proposition 2.3.** *A set  $B$  is open if and only if  $X - B$  is closed.*

**Proposition 2.4.** *Let  $X$  be a set and  $\mathcal{C} \subseteq \mathcal{P}X$ . Then there exists a topology  $\mathcal{O}$  on  $X$  such that  $\mathcal{C}$  is the set of closed sets if and only if:*

- For any  $\mathcal{D} \subseteq \mathcal{C}$  we have  $\bigcap \mathcal{D} \in \mathcal{C}$
- For any  $C, D \in \mathcal{C}$  we have  $C \cup D \in \mathcal{C}$ .
- $\emptyset \in \mathcal{C}$

*In this case,  $\mathcal{O}$  is unique and is given by  $\mathcal{O} = \{X - C : C \in \mathcal{C}\}$ .*

**Definition 2.5** (Neighbourhood). Let  $X$  be a topological space,  $x \in X$  and  $U \subseteq X$ . Then  $U$  is a *neighbourhood* of  $x$ , and  $x$  is an *interior* point of  $U$ , iff there exists an open set  $V$  such that  $x \in V \subseteq U$ .

**Proposition 2.6.** *A set  $B$  is open if and only if it is a neighbourhood of each of its points.*

**Proposition 2.7.** *Let  $X$  be a set and  $\mathcal{N} : X \rightarrow \mathcal{P}X$ . Then there exists a topology  $\mathcal{O}$  on  $X$  such that, for all  $x \in X$ , we have  $\mathcal{N}_x$  is the set of neighbourhoods of  $x$ , if and only if:*

- *For all  $x \in X$  and  $N \in \mathcal{N}_x$  we have  $x \in N$*
- *For all  $x \in X$  we have  $X \in \mathcal{N}_x$*
- *For all  $x \in X$ ,  $N \in \mathcal{N}_x$  and  $V \subseteq \mathcal{P}X$ , if  $N \subseteq V$  then  $V \in \mathcal{N}_x$*
- *For all  $x \in X$  and  $M, N \in \mathcal{N}_x$  we have  $M \cap N \in \mathcal{N}_x$*
- *For all  $x \in X$  and  $N \in \mathcal{N}_x$ , there exists  $M \in \mathcal{N}_x$  such that  $M \subseteq N$  and  $\forall y \in M. M \in \mathcal{N}_y$ .*

*In this case,  $\mathcal{O}$  is unique and is given by  $\mathcal{O} = \{U : \forall x \in U. U \in \mathcal{N}_x\}$ .*

**Definition 2.8** (Exterior Point). Let  $X$  be a topological space,  $x \in X$  and  $B \subseteq X$ . Then  $x$  is an *exterior point* of  $B$  iff  $B - X$  is a neighbourhood of  $x$ .

**Definition 2.9** (Boundary Point). Let  $X$  be a topological space,  $x \in X$  and  $B \subseteq X$ . Then  $x$  is a *boundary point* of  $B$  iff it is neither an interior point nor an exterior point of  $B$ .

**Definition 2.10** (Interior). Let  $X$  be a topological space and  $B \subseteq X$ . The *interior* of  $B$ ,  $B^\circ$ , is the set of all interior points of  $B$ .

**Proposition 2.11.** *The interior of  $B$  is the union of all the open sets included in  $B$ .*

**Definition 2.12** (Closure). Let  $X$  be a topological space and  $B \subseteq X$ . The *closure* of  $B$ ,  $\overline{B}$ , is the set of all points that are not exterior points of  $B$ .

**Proposition 2.13.** *The closure of  $B$  is the intersection of all the closed sets that include  $B$ .*

**Proposition 2.14.** *A set  $B$  is open iff  $X - B = \overline{X - B}$ .*

**Proposition 2.15** (Kuratowski Closure Axioms). *Let  $X$  be a set and  $- : \mathcal{P}X \rightarrow \mathcal{P}X$ . Then there exists a topology  $\mathcal{O}$  such that, for all  $B \subseteq X$ ,  $\overline{B}$  is the closure of  $B$ , if and only if:*

- $\overline{\emptyset} = \emptyset$
- *For all  $A \subseteq X$  we have  $A \subseteq \overline{A}$*
- *For all  $A \subseteq X$  we have  $\overline{\overline{A}} = \overline{A}$*
- *For all  $A, B \subseteq X$  we have  $\overline{A \cup B} = \overline{A} \cup \overline{B}$*

*In this case,  $\mathcal{O}$  is unique and is defined by  $\mathcal{O} = \{U : X - U = \overline{X - U}\}$ .*

### 2.1.1 Subspaces

**Definition 2.16** (Subspace). Let  $X$  be a topological space and  $X_0 \subseteq X$ . The *subspace topology* on  $X_0$  is  $\{U \cap X_0 : U \text{ is open in } X\}$ .

### 2.1.2 Topological Disjoint Union

**Definition 2.17.** Let  $X$  and  $Y$  be topological spaces. The *disjoint union* is  $X + Y$  where  $U \subseteq X + Y$  is open if and only if  $\kappa_1^{-1}(U)$  is open in  $X$  and  $\kappa_2^{-1}(U)$  is open in  $Y$ .

### 2.1.3 Product Topology

**Definition 2.18.** Let  $X$  and  $Y$  be topological spaces. The *product topology* on  $X \times Y$  is the set of all subsets  $W \subseteq X \times Y$  such that, for all  $(x, y) \in W$ , there exist neighbourhoods  $U$  of  $x$  in  $X$  and  $V$  of  $y$  in  $Y$  such that  $U \times V \subseteq W$ .

### 2.1.4 Bases

**Definition 2.19** (Basis). Let  $X$  be a topological space. A *basis* for the topology on  $X$  is a set of open sets  $\mathcal{B}$  such that every open set is the union of a subset of  $\mathcal{B}$ .

### 2.1.5 Subbases

**Definition 2.20** (Subbasis). Let  $X$  be a topological space. A *subbasis* for the topology on  $X$  is a subset  $\mathcal{S} \subseteq \mathcal{P}X$  such that every open set is a union of finite intersections of  $\mathcal{S}$ .

## 2.2 Continuous Functions

**Definition 2.21** (Continuous). Let  $X$  and  $Y$  be topological spaces. A function  $f : X \rightarrow Y$  is *continuous* iff, for every open set  $V$  in  $Y$ , the inverse image  $f^{-1}(V)$  is open in  $X$ .

- Proposition 2.22.**
1.  $\text{id}_X$  is continuous
  2. The composite of two continuous functions is continuous.
  3. If  $f : X \rightarrow Y$  is continuous and  $X_0 \subseteq X$  then  $f|_{X_0} : X_0 \rightarrow Y$  is continuous.
  4. If  $f : X + Y \rightarrow Z$ , then  $f$  is continuous iff  $f \circ \kappa_1 : X \rightarrow Z$  and  $f \circ \kappa_2 : Y \rightarrow Z$  are continuous.
  5. If  $f : Z \rightarrow X \times Y$ , then  $f$  is continuous iff  $\pi_1 \circ f$  and  $\pi_2 \circ f$  are continuous.

**Definition 2.23** (Homeomorphism). Let  $X$  and  $Y$  be topological spaces. A *homeomorphism* between  $X$  and  $Y$  is a bijection  $f : X \approx Y$  such that  $f$  and  $f^{-1}$  are continuous.

## 2.3 Convergence

**Definition 2.24** (Convergence). Let  $X$  be a topological space. Let  $(x_n)$  be a sequence in  $X$ . A point  $a \in \text{El}(X)$  is a *limit* of the sequence iff, for every neighbourhood  $U$  of  $a$ , there exists  $n_0$  such that  $\forall n \geq n_0. x_n \in U$ .

## 2.4 Connected Spaces

**Definition 2.25** (Connected). A topological space is *connected* iff it is not the union of two nonempty open disjoint subsets.

**Proposition 2.26.** *The continuous image of a connected space is connected.*

**Proposition 2.27.** *Let  $X$  be a topological space and  $A, B \subseteq X$ . If  $X = A \cup B$ ,  $A \cap B \neq \emptyset$ , and  $A$  and  $B$  are connected, then  $X$  is connected.*

**Proposition 2.28.** *If  $X$  and  $Y$  are nonempty topological spaces, then  $X \times Y$  is connected if and only if  $X$  and  $Y$  are connected.*

**Definition 2.29** (Path-connected). A topological space  $X$  is *path-connected* iff, for any points  $a, b \in X$ , there exists a continuous function  $\alpha : [0, 1] \rightarrow X$ , called a *path*, such that  $\alpha(0) = a$  and  $\alpha(1) = b$ .

**Proposition 2.30.** *The continuous image of a path connected space is path connected.*

**Proposition 2.31.** *Let  $X$  be a topological space and  $A, B \subseteq X$ . If  $X = A \cup B$ ,  $A \cap B \neq \emptyset$ , and  $A$  and  $B$  are path connected, then  $X$  is path connected.*

**Proposition 2.32.** *If  $X$  and  $Y$  are nonempty topological spaces, then  $X \times Y$  is path connected if and only if  $X$  and  $Y$  are path connected.*

## 2.5 Hausdorff Spaces

**Definition 2.33** (Hausdorff). A topological space is a *Hausdorff* space or a  $T_2$  space iff any two distinct points have disjoint neighbourhoods.

**Proposition 2.34.** *In a Hausdorff space, a sequence has at most one limit.*

**Proposition 2.35.** 1. *Every subspace of a Hausdorff space is Hausdorff.*

2. *The disjoint union of two Hausdorff spaces is Hausdorff.*

3. *The product of two Hausdorff spaces is Hausdorff.*



## 2.6 Compactness

**Definition 2.36** (Compact). A topological space is *compact* iff every open cover has a finite subcover.

**Proposition 2.37.** *Let  $X$  be a compact topological space. Let  $P$  be a set of open sets such that, for all  $U, V \in P$ , we have  $U \cup V \in P$ . Assume that every point has an open neighbourhood in  $P$ . Then  $X \in P$ .*

PROOF:

- $\langle 1 \rangle$ 1.  $P$  is an open cover of  $X$
  - $\langle 1 \rangle$ 2. PICK a finite subcover  $U_1, \dots, U_n \in P$
  - $\langle 1 \rangle$ 3.  $X = U_1 \cup \dots \cup U_n \in P$
- 

**Corollary 2.37.1.** *Let  $f$  be a compact space and  $f : X \rightarrow \mathbb{R}$  be locally bounded. Then  $f$  is bounded.*

PROOF: Take  $P = \{U \text{ open in } X : f \text{ is bounded on } U\}$ . □

**Proposition 2.38.** *The continuous image of a compact space is compact.*

**Proposition 2.39.** *A closed subspace of a compact space is compact.*

**Proposition 2.40.** *Let  $X$  and  $Y$  be nonempty spaces. Then the following are equivalent.*

1.  $X$  and  $Y$  are compact.
2.  $X + Y$  is compact.
3.  $X \times Y$  is compact.

**Proposition 2.41.** *A compact subspace of a Hausdorff space is closed.*

**Proposition 2.42.** *A continuous bijection from a compact space to a Hausdorff space is a homeomorphism.*

## 2.7 Metric Spaces

**Definition 2.43** (Metric Space). Let  $X$  be a set and  $d : X^2 \rightarrow \mathbb{R}$ . We say  $(X, d)$  is a *metric space* iff:

- For all  $x, y \in X$  we have  $d(x, y) \geq 0$
- For all  $x, y \in X$  we have  $d(x, y) = 0$  iff  $x = y$
- For all  $x, y \in X$  we have  $d(x, y) = d(y, x)$
- (*Triangle Inequality*) For all  $x, y, z \in X$  we have  $d(x, z) \leq d(x, y) + d(y, z)$

We call  $d$  the *metric* of the metric space  $(X, d)$ . We often write  $X$  for the metric space  $(X, d)$ .

**Definition 2.44** (Topology of a Metric Space). Let  $(X, d)$  be a metric space. The topology *induced* by the metric  $d$  is defined by: for  $V \subseteq X$ , we have  $V$  is open if and only if, for all  $x \in V$ , there exists  $\epsilon > 0$  such that  $\{y \in X : d(x, y) < \epsilon\} \subseteq V$ .

**Definition 2.45** (Metrizable). A topological space is *metrizable* iff there exists a metric that induces its topology.

**Proposition 2.46.** *Every metrizable space is Hausdorff.*

## Chapter 3

# Topological Vector Spaces

**Definition 3.1** (Topological Vector Space). Let  $K$  be either  $\mathbb{R}$  or  $\mathbb{C}$ . A *topological vector space* over  $K$  consists of a vector space  $E$  over  $K$  and a topology on  $E$  such that:

- Substraction is a continuous function  $E^2 \rightarrow E$
- Multiplication is a continuous function  $K \times E \rightarrow E$

**Theorem 3.2.** *The usual topology on a finite dimensional vector space over  $K$  is the only one that makes it into a Hausdorff topological vector space.*

PROOF: See Bourbaki. Elements de Mathematique, Livre V: Espaces Vectoriels Topologiques, Th. 2, p. 18  $\square$

### 3.1 Cauchy Sequences

**Definition 3.3** (Cauchy Sequence). Let  $E$  be a topological vector space. A sequence  $(x_n)$  in  $E$  is a *Cauchy sequence* iff, for every neighbourhood  $U$  of 0, there exists  $n_0$  such that  $\forall m, n \geq n_0. x_n - x_m \in U$ .

**Definition 3.4** (Complete Topological Vector Space). A topological vector space is *complete* iff every Cauchy sequence converges.

### 3.2 Seminorms

**Definition 3.5** (Seminorm). Let  $E$  be a vector space over  $K$ . A *seminorm* on  $E$  is a function  $\| \cdot \| : E \rightarrow \mathbb{R}$  such that:

1.  $\forall x : \text{El}(E). \|x\| \geq 0$
2.  $\forall \alpha : \text{El}(K). \forall x : \text{El}(E). \|\alpha x\| = |\alpha| \|x\|$
3. *Triangle Inequality*  $\forall x, y : \text{El}(E). \|x + y\| \leq \|x\| + \|y\|$

**Example 3.6.** The function that maps  $(x_1, \dots, x_n)$  to  $|x_i|$  is a seminorm on  $\mathbb{R}^n$ .

**Definition 3.7.** Let  $E$  be a vector space over  $K$ . Let  $\Lambda$  be a set of seminorms on  $E$ . The topology *generated* by  $\Lambda$  is the topology generated by the subbasis consisting of all sets of the form  $B_\epsilon^\lambda(x) = \{y \in E : \lambda(y - x) < \epsilon\}$  for  $\epsilon > 0$ ,  $\lambda \in \Lambda$  and  $x \in E$ .

**Proposition 3.8.**  $E$  is a topological vector space under this topology. It is Hausdorff iff, for all  $x \in E$ , if  $\forall \lambda \in \Lambda. \lambda(x) = 0$  then  $x = 0$ .

### 3.3 Fréchet Spaces

**Definition 3.9** (Pre-Fréchet Space). A *pre-Fréchet space* is a Hausdorff topological vector space whose topology is generated by a countable set of seminorms.

**Proposition 3.10.** Let  $E$  be a pre-Fréchet space whose topology is generated by the family of seminorms  $\{\|\cdot\|_n : n \in \mathbb{Z}^+\}$ . Then

$$d(x, y) = \sum_{n=1}^{\infty} \frac{1}{2^n} \frac{\|x - y\|_n}{1 + \|x - y\|_n}$$

is a metric that induces the same topology. The two definitions of Cauchy sequence agree.

**Definition 3.11** (Fréchet Space). A *Fréchet space* is a complete pre-Fréchet space.

### 3.4 Normed Spaces

**Definition 3.12** (Normed Space). Let  $E$  be a vector space over  $K$ . A *norm* on  $E$  is a function  $\|\cdot\| : E \rightarrow \mathbb{R}$  is a seminorm such that,  $\forall x \in E. \|x\| = 0 \Leftrightarrow x = 0$ .

A *normed space* consists of a vector space with a norm.

**Proposition 3.13.** If  $E$  is a normed space then  $d(x, y) = \|x - y\|$  is a metric on  $E$  that makes  $E$  into a topological vector space. The two definitions of Cauchy sequence agree on  $E$ .

### 3.5 Inner Product Spaces

**Proposition 3.14.** If  $E$  is an inner product space then  $\|x\| = \sqrt{\langle x, x \rangle}$  is a norm on  $E$ .

### 3.6 Banach Spaces

**Definition 3.15** (Banach Space). A *Banach space* is a complete normed space.

## 3.7 Hilbert Spaces

**Definition 3.16** (Hilbert Space). A *Hilbert space* is a complete inner product space.