

---

# Topology and Metric Spaces

---

Arjun Paul

Department of Mathematics and Statistics  
Indian Institute of Science Education and Research Kolkata,  
Mohanpur - 741 246, Nadia,  
West Bengal, India.  
Email: [arjun.paul@iiserkol.ac.in](mailto:arjun.paul@iiserkol.ac.in).

Version: October 7, 2022 at 11:09pm (IST).

*Disclaimer: This note is only for personal use,  
and is not a reference. It may have some potential mistakes.  
This note will be updated from time to time.  
If there are any potential mistakes, please bring it to my notice.*



# Contents

<b>List of Symbols</b>	<b>v</b>
<b>1 Metric Space</b>	<b>1</b>
1.1 Examples . . . . .	1
1.2 Topological properties . . . . .	4
1.3 Sequence . . . . .	6
1.4 Limits and Continuity . . . . .	7
1.5 Uniform continuity . . . . .	7
1.6 Extension of uniformly continuous functions . . . . .	7
<b>2 Point Set Topology</b>	<b>9</b>
2.1 Topological space . . . . .	9
2.1.1 Order topology . . . . .	13
2.1.2 Product topology . . . . .	14
2.1.3 Subspace topology . . . . .	16
2.2 Continuity . . . . .	17
2.3 Quotient space . . . . .	19
2.4 Projective space and Grassmannian . . . . .	31
2.4.1 Real and complex projective spaces . . . . .	31
2.4.2 Grassmannian $\text{Gr}(k, \mathbb{R}^n)$ . . . . .	34
2.5 Topological group . . . . .	34
2.6 Metric topology . . . . .	39
2.7 Connectedness . . . . .	40
2.7.1 Path-connectedness . . . . .	45
2.8 Compactness . . . . .	50

2.9	Separation axioms . . . . .	52
2.10	Metrization theorem . . . . .	52
2.11	Paracompactness . . . . .	52
2.11.1	Partition of unity . . . . .	52
2.12	Compactification . . . . .	52
<b>3</b>	<b>Appendix</b>	<b>53</b>
3.1	Category Theory . . . . .	53

# List of Symbols

$\emptyset$	Empty set
$\mathbb{Z}$	The set of all integers
$\mathbb{Z}_{\geq 0}$	The set of all non-negative integers
$\mathbb{N}$	The set of all natural numbers (i.e., positive integers)
$\mathbb{Q}$	The set of all rational numbers
$\mathbb{R}$	The set of all real numbers
$\mathbb{C}$	The set of all complex numbers
$<$	Less than
$\leq$	Less than or equal to
$>$	Greater than
$\geq$	Greater than or equal to
$\subset$	Proper subset
$\subseteq$	Subset or equal to
$\subsetneq$	Subset but not equal to (c.f. proper subset)
$\exists$	There exists
$\nexists$	Does not exist
$\forall$	For all
$\in$	Belongs to
$\notin$	Does not belong to
$\sum$	Sum
$\prod$	Product
$\pm$	Plus and/or minus
$\infty$	Infinity
$\sqrt{a}$	Square root of $a$
$\cup$	Union
$\sqcup$	Disjoint union
$\cap$	Intersection
$A \rightarrow B$	$A$ mapping into $B$
$a \mapsto b$	$a$ maps to $b$
$\hookrightarrow$	Inclusion map
$A \setminus B$	$A$ setminus $B$
$\cong$	Isomorphic to
$A := \dots$	$A$ is defined to be ...
$\square$	End of a proof

Symbol	Name	Symbol	Name
$\alpha$	alpha	$\beta$	beta
$\gamma$	gamma	$\delta$	delta
$\pi$	pi	$\phi$	phi
$\varphi$	var-phi	$\psi$	psi
$\epsilon$	epsilon	$\varepsilon$	var-epsilon
$\zeta$	zeta	$\eta$	eta
$\theta$	theta	$\iota$	iota
$\kappa$	kappa	$\lambda$	lambda
$\mu$	mu	$\nu$	nu
$\upsilon$	upsilon	$\rho$	rho
$\varrho$	var-rho	$\xi$	xi
$\sigma$	sigma	$\tau$	tau
$\chi$	chi	$\omega$	omega
$\Omega$	Capital omega	$\Gamma$	Capital gamma
$\Theta$	Capital theta	$\Delta$	Capital delta
$\Lambda$	Capital lambda	$\Xi$	Capital xi
$\Sigma$	Capital sigma	$\Pi$	Capital pi
$\Phi$	Capital phi	$\Psi$	Capital psi

Some of the useful Greek letters

## Chapter 1

# Metric Space

### 1.1 Examples

A *pseudo metric* on a set  $X$  is a map

$$d : X \times X \rightarrow [0, \infty) := \{t \in \mathbb{R} : t \geq 0\}$$

such that

- (i)  $d(x, x) = 0, \forall x \in X$ ,
- (ii)  $d(x_1, x_2) = d(x_2, x_1)$ , for all  $x_1, x_2 \in X$ , and
- (iii)  $d(x_1, x_2) \leq d(x_1, x_3) + d(x_3, x_2)$ , for all  $x_1, x_2, x_3 \in X$ .

A *pseudo metric space* is a pair  $(X, d)$  consisting of a set  $X$  and a pseudo metric  $d$  on it.

**Definition 1.1.1.** A *metric* on  $X$  is a pseudo metric  $d : X \times X \rightarrow \mathbb{R}$  on  $X$  such that if  $d(x_1, x_2) = 0$ , for some  $x_1, x_2 \in X$ , then  $x_1 = x_2$  in  $X$ . A *metric space* is a pair  $(X, d)$ , where  $X$  is a set and  $d : X \times X \rightarrow \mathbb{R}$  is a metric on  $X$ .

**Example 1.1.2.** The *absolute value* of a real number  $x \in \mathbb{R}$  is a non-negative real number  $|x|$ , defined by

$$|x| := \begin{cases} x, & \text{if } x \geq 0, \\ -x, & \text{if } x < 0. \end{cases}$$

Let  $d : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$  be defined by

$$d(x, y) = |x - y|, \forall x, y \in \mathbb{R}.$$

Then  $(\mathbb{R}, d)$  is a metric space.

**Example 1.1.3** (Pseudo metric that is not a metric). Let  $X = \mathbb{R}^2$ , the Cartesian product of  $\mathbb{R}$  with itself. Define  $d : X \times X \rightarrow \mathbb{R}$  by

$$d((x_1, x_2), (y_1, y_2)) = |x_1 - y_1|, \forall (x_1, x_2), (y_1, y_2) \in X.$$

Then  $d$  is a pseudo metric on  $X$ , and  $(X, d)$  is a pseudo metric space. Since  $d((1, 2), (1, 3)) = 0$  but  $(1, 2) \neq (1, 3)$  in  $\mathbb{R}^2$ ,  $d$  is not a metric on  $\mathbb{R}^2$ .

**Exercise 1.1.4.** Let  $C'[0, 1]$  be the set of all real-valued piece-wise continuous functions on  $[0, 1] \subset \mathbb{R}$ . Given  $f, g \in C'[0, 1]$ , we define

$$d(f, g) := \int_0^1 |f(t) - g(t)| dt.$$

Show that  $d$  is a pseudo metric on  $C'[0, 1]$  but not a metric. Let

$$C[0, 1] = \{f \in C'[0, 1] : f \text{ is continuous on } [0, 1]\}.$$

Show that the restriction of  $d$  gives a metric on  $C[0, 1]$ .

**Remark 1.1.5** (Construction of metric subspace from a pseudo metric space). Let  $(X, d)$  be a pseudo metric space. Define a relation  $\rho \subseteq X \times X$  on  $X$  by setting  $(x_1, x_2) \in \rho$  if  $d(x_1, x_2) = 0$ . Since  $d(x, x) = 0$ ,  $\forall x \in X$ ,  $\rho$  is reflexive. Since  $d(x, y) = d(y, x)$ ,  $\forall x, y \in X$ ,  $\rho$  is symmetric. If  $d(x, y) = 0$  and  $d(y, z) = 0$ , for some  $x, y, z \in X$ , then by triangular inequality we have  $0 \leq d(x, z) \leq d(x, y) + d(y, z) = 0$  and hence  $d(x, z) = 0$ . Therefore,  $\rho$  is transitive. Thus,  $\rho$  is an equivalence relation on  $X$ . Let  $\tilde{X} = X/\rho$  be the set of all  $\rho$ -equivalence classes of elements of  $X$ . We denote by

$$\bar{x} := \{y \in X : d(y, x) = 0\} \in \tilde{X}$$

the  $\rho$ -equivalence class of  $x \in X$  in  $X$ . Define

$$d' : \tilde{X} \times \tilde{X} \rightarrow \mathbb{R}$$

by

$$d'(\bar{x}, \bar{y}) := d(x, y), \forall \bar{x}, \bar{y} \in \tilde{X}.$$

Let  $x, x', y, y' \in X$  be such that  $\bar{x} = \bar{x'}$  and  $\bar{y} = \bar{y'}$ . Then  $d(x, x') = 0$  and  $d(y, y') = 0$ . Then  $d(x, y) \leq d(x, x') + d(x', y) = d(x', y) \leq d(x', x) + d(x, y) = d(x, y)$  implies  $d(x, y) = d(x', y)$ . Similarly,  $d(x', y) = d(x', y')$  since  $d(y, y') = 0$ . Therefore,  $d(x, y) = d(x', y')$ , and hence  $\tilde{d}$  is well-defined. Note that  $\tilde{d}(\tilde{x}, \tilde{y}) = d(x, y) = 0$  if and only if  $\tilde{x} = \tilde{y}$  in  $\tilde{X}$ . Clearly  $\tilde{d}(\tilde{x}, \tilde{y}) = d(x, y) = d(y, x) = \tilde{d}(\tilde{y}, \tilde{x})$ , and  $\tilde{d}(\tilde{x}, \tilde{y}) \leq \tilde{d}(\tilde{x}, \tilde{z}) + \tilde{d}(\tilde{z}, \tilde{y})$ , for all  $\tilde{x}, \tilde{y}, \tilde{z} \in \tilde{X}$ . Therefore,  $(\tilde{X}, \tilde{d})$  is a metric space. Note that, by choosing one element from each of the  $\rho$ -equivalence class in  $\tilde{X}$  (by axiom of choice), we get a subset  $Y \subseteq X$ . It is clear that  $d|_{Y \times Y} : Y \times Y \rightarrow [0, \infty)$  is a metric on  $Y$ .

**Example 1.1.6** (Euclidean metric on  $\mathbb{R}^n$ ). Fix an integer  $n \geq 1$ , and let

$$d : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}$$

be the map defined by

$$d((x_1, \dots, x_n), (y_1, \dots, y_n)) := \left( \sum_{j=1}^n |x_j - y_j|^2 \right)^{1/2},$$



for all  $(x_1, \dots, x_n), (y_1, \dots, y_n) \in \mathbb{R}^n$ . Then  $d$  is a metric on  $\mathbb{R}^n$ , called the *Euclidean metric* on  $\mathbb{R}^n$ .

**Example 1.1.7** (Euclidean metric on  $\mathbb{C}^n$ ). Fix an integer  $n \geq 1$ , and let

$$d : \mathbb{C}^n \times \mathbb{C}^n \rightarrow \mathbb{R}$$

be the map defined by

$$d((z_1, \dots, z_n), (w_1, \dots, w_n)) := \left( \sum_{j=1}^n |z_j - w_j|^2 \right)^{1/2},$$

for all  $(z_1, \dots, z_n), (w_1, \dots, w_n) \in \mathbb{C}^n$ . It is straight-forward to check that  $d$  is a metric on  $\mathbb{C}^n$ , called the *Euclidean metric* on  $\mathbb{C}^n$ .

**Example 1.1.8.** Given a non-empty set  $X$ , let  $d : X \times X \rightarrow \mathbb{R}$  be defined by

$$d(x, y) := \begin{cases} 1, & \text{if } x \neq y, \\ 0, & \text{if } x = y. \end{cases}$$

Then  $d$  is a metric on  $X$ , called the *discrete metric* on  $X$ .

**Exercise 1.1.9.** Let  $(X, d)$  be a metric space. Show that

$$d'(x, y) := \min\{1, d(x, y)\}, \quad \forall x, y \in X$$

defines a metric on  $X$ .

**Exercise 1.1.10.** Let  $(X, d)$  be a metric space. Show that the map  $d' : X \times X \rightarrow \mathbb{R}$  defined by

$$d'(x_1, x_2) := \frac{d(x_1, x_2)}{1 + d(x_1, x_2)}, \quad \forall x_1, x_2 \in X,$$

is a metric on  $X$ .

**Exercise 1.1.11.** Let  $(X, d_X)$  and  $(Y, d_Y)$  be two metric spaces. Show that the rule

$$d((x_1, y_1), (x_2, y_2)) := \max\{d_X(x_1, x_2), d_Y(y_1, y_2)\}, \quad \forall (x_1, y_1), (x_2, y_2) \in X \times Y$$

defines a metric on  $X \times Y$ , called the *product metric* on  $X \times Y$ .

**Definition 1.1.12.** Let  $\mathbb{k}$  be the field of real numbers or the field of complex numbers. A *norm* on a  $\mathbb{k}$ -vector space  $X$  is a map  $\|\cdot\| : X \rightarrow \mathbb{R}$  satisfying the following properties:

- (i)  $\|x\| \geq 0$ ,  $\forall x \in V$ , and  $\|x\| = 0$  if and only if  $x = 0$  in  $X$ .
- (ii)  $\|\alpha x\| = |\alpha| \|x\|$ ,  $\forall \alpha \in \mathbb{k}$ ,  $x \in X$ .
- (iii)  $\|x + y\| \leq \|x\| + \|y\|$ ,  $\forall x, y \in X$ .

The pair  $(X, \|\cdot\|)$  is called a *normed linear space*.

A normed linear space  $(X, \|\cdot\|)$  naturally admits a metric  $d$  defined by

$$d(x, y) := \|x - y\|, \quad \forall x, y \in X,$$

called the *norm-induced metric* on  $(X, \|\cdot\|)$ .

**Example 1.1.13.** Let  $\|\cdot\|_1, \|\cdot\|_2$  and  $\|\cdot\|_\infty : \mathbb{R}^n \rightarrow \mathbb{R}$  be defined by

$$(i) \quad \|(x_1, \dots, x_n)\|_1 := \sum_{j=1}^n |x_j|, \quad \forall (x_1, \dots, x_n) \in \mathbb{R}^n,$$

$$(ii) \quad \|(x_1, \dots, x_n)\|_2 := \left( \sum_{j=1}^n x_j^2 \right)^{1/2}, \quad \forall (x_1, \dots, x_n) \in \mathbb{R}^n, \text{ and}$$

$$(iii) \quad \|(x_1, \dots, x_n)\|_\infty := \max_{1 \leq j \leq n} |x_j|, \quad \forall (x_1, \dots, x_n) \in \mathbb{R}^n.$$

Then  $\|\cdot\|_1, \|\cdot\|_2$ , and  $\|\cdot\|_\infty$  are norms on  $\mathbb{R}^n$ .

**Example 1.1.14.** Let  $\mathbb{k}$  be the field of real numbers or the field of complex numbers. Let  $X$  be a non-empty set and let  $\mathcal{B}(X)$  be the set of all  $\mathbb{k}$ -valued bounded functions defined on  $X$ . Define

$$\|f\|_\infty := \sup\{|f(x)| : x \in X\}, \quad \forall f \in \mathcal{B}(X).$$

Then  $\|\cdot\|_\infty$  is a norm on  $\mathcal{B}(X)$ .

**Exercise 1.1.15** ( $\ell_p$  space). Let  $\mathbb{k}$  be the field of real numbers or the field of complex numbers. Fix a natural number  $p \geq 1$ . Let

$$\ell_p(\mathbb{k}) := \left\{ (a_n)_{n=1}^\infty : a_n \in \mathbb{k}, \forall n \in \mathbb{N}, \text{ and } \sum_{n=1}^\infty |a_n|^p < \infty \right\}.$$

Given  $a = (a_n)_{n=1}^\infty$  let

$$\|a\|_p := \left( \sum_{n=1}^\infty |a_n|^p \right)^{1/p}.$$

Show that  $\|\cdot\|_p$  is a norm on  $\ell_p(\mathbb{k})$ .

## 1.2 Topological properties

Let  $(X, d)$  be a pseudo metric space. Given a point  $x_0 \in X$  and a real number  $\delta > 0$ , the *open ball* in  $(X, d)$  with center at  $x_0$  and radius  $\delta$  is the subset

$$B_d(x_0, \delta) := \{x \in X : d(x, x_0) < \delta\}.$$

Let  $U \subseteq X$ . A point  $x \in X$  is said to be an *interior point* of  $U \subseteq X$  if there exists a real number  $\delta_x > 0$  such that  $B(x, \delta_x) \subseteq U$ . A subset  $U \subseteq X$  is said to be *open* in  $(X, d)$  if either  $U = \emptyset$  or each point of  $U$  is an interior point of  $U$ . A subset  $Z \subseteq X$  is said to be *closed* if its complement  $X \setminus Z$  is open in  $(X, d)$ .

**Example 1.2.1** (Open intervals). Given  $a, b \in \mathbb{R}$  with  $a \leq b$ , we define

$$\begin{aligned}(a, b) &:= \{t \in \mathbb{R} : a < t < b\}, \\ (-\infty, a) &:= \{t \in \mathbb{R} : t < a\}, \\ (a, \infty) &:= \{t \in \mathbb{R} : a < t\}, \\ (-\infty, \infty) &:= \mathbb{R}\end{aligned}$$

It is easy to see that each of the above intervals are open subsets of  $\mathbb{R}$ .

**Lemma 1.2.2.** Let  $(X, d)$  be a pseudo metric space.

- (i)  $X$  and  $\emptyset$  are both open and closed in  $(X, d)$ .
- (ii) Arbitrary union of open subsets of  $X$  is open.
- (iii) Finite intersection of open subsets of  $X$  is open.

*Proof.* (i) Clear.

- (ii) Let  $\{U_\alpha : \alpha \in I\}$  be an indexed family of open subsets of  $(X, d)$ . Let  $x \in \bigcup_{\alpha \in I} U_\alpha$ . Then there exists  $\alpha_0 \in I$  such that  $x \in U_{\alpha_0}$ . Then there exists a real number  $\delta > 0$  such that  $B(x, \delta) \subseteq U_{\alpha_0} \subseteq \bigcup_{\alpha \in I} U_\alpha$ . Thus  $\bigcup_{\alpha \in I} U_\alpha$  is open in  $(X, d)$ .

- (iii) Let  $U_1, \dots, U_n$  be a finite collection of open subsets of  $(X, d)$ . Let  $x_0 \in \bigcap_{j=1}^n U_j$ . Since  $x_0 \in U_j$  and  $U_j$  is open in  $(X, d)$ , there exists a  $\delta_j > 0$  such that  $B(x_0, \delta_j) \subseteq U_j$ , for each  $j = 1, \dots, n$ . Let  $\delta := \min\{\delta_1, \dots, \delta_n\} > 0$ . Then  $B(x_0, \delta) \subseteq \bigcap_{j=1}^n U_j$ .

□

**Corollary 1.2.3.** Let  $(X, d)$  be a pseudo metric space. Then arbitrary intersection of closed subsets are closed, and a finite union of closed subsets is closed.

**Example 1.2.4.** Given  $a, b \in \mathbb{R}$  with  $a \leq b$ , let

$$[a, b] := \{t \in \mathbb{R} : a \leq t \leq b\}.$$

Since  $[a, b] = \mathbb{R} \setminus ((-\infty, a) \cup (b, \infty))$ , it is closed in  $\mathbb{R}$ .

**Definition 1.2.5.** A point  $x_0 \in X$  is said to be a *limit point* of a subset  $A \subseteq X$  if for each real number  $\delta > 0$  we have

$$(B(x_0, \delta) \setminus \{x_0\}) \cap A \neq \emptyset.$$

**Proposition 1.2.6.** Let  $Z \subseteq X$ . Show that  $Z$  is closed in  $(X, d)$  if and only if  $Z$  contains all of its limit points.

*Proof.* Suppose that  $Z$  is closed in  $(X, d)$ . If  $x_0 \in U := X \setminus Z$ , then  $U$  being open in  $(X, d)$ , there exists a  $\delta > 0$  such that  $B(x_0, \delta) \subseteq U$ , and so  $B(x_0, \delta) \cap Z = \emptyset$ . Therefore,  $x_0$  cannot be a limit point of  $Z$ .

Conversely, suppose that  $Z$  contains all of its limit points in  $(X, d)$ . Let  $U := X \setminus Z$ , and  $x_0 \in U$ . Since  $x_0 \notin Z$  and  $x_0$  is not a limit point of  $Z$ , there exists a  $\delta > 0$  such that  $B(x_0, \delta) \cap Z = \emptyset$ . Therefore,  $B(x_0, \delta) \subseteq U$ . Since  $x_0 \in U$  is arbitrary,  $U$  is open in  $(X, d)$  and hence  $Z$  is closed.  $\square$

**Lemma 1.2.7.** Let  $(X, d)$  be a pseudo metric space and let  $A \subseteq X$ . Let  $\mathcal{C}_A$  be the collection of all closed subsets of  $(X, d)$  containing  $A$ . Then  $\bigcap_{Z \in \mathcal{C}_A} Z$  is the smallest closed subset of  $X$  containing  $A$ , called the closure of  $A$  in  $(X, d)$ .

*Proof.* It follows from Lemma 1.2.2 that  $\bar{A} := \bigcap_{Z \in \mathcal{C}_A} Z$  is a closed subset of  $X$ . Clearly  $A \subseteq \bar{A}$ . Let  $W$  be any closed subset of  $X$  containing  $A$ . Then  $W \in \mathcal{C}_A$ , and hence  $\bigcap_{Z \in \mathcal{C}_A} Z \subseteq W$ .  $\square$

**Proposition 1.2.8.** Let  $(X, d)$  be a pseudo metric space. A subset  $A \subseteq X$  is closed if and only if  $\bar{A} = A$ .

*Proof.* Suppose that  $A$  is closed. Let  $\mathcal{C}_A$  be the collection of all closed subsets of  $(X, d)$  containing  $A$ . If  $A$  is closed, then  $A \in \mathcal{C}_A$ , and hence  $A \subseteq \bar{A} = \bigcap_{Z \in \mathcal{C}_A} Z \subseteq A$  shows that  $A = \bar{A}$ .

Converse is obvious since  $\bar{A} = \bigcap_{Z \in \mathcal{C}_A} Z$  is closed.  $\square$

**Definition 1.2.9.** Two pseudo metrics  $d_1$  and  $d_2$  on a set  $X$  are said to be *equivalent* if for any subset  $U \subseteq X$ ,  $U$  is  $d_1$ -open if and only if  $U$  is  $d_2$ -open.

**Proposition 1.2.10.** Let  $(X, d)$  be a pseudo metric space. Then  $d$  is a metric on  $X$  if and only if given any two distinct points  $x, y \in X$ , there exist positive real numbers  $r_x, r_y > 0$  such that  $B_d(x, r_x) \cap B_d(y, r_y) = \emptyset$ . In other words, the metric topology on  $X$  generated by  $d$  is Hausdorff<sup>1</sup>.

*Proof.* Suppose that  $d$  be a metric on  $X$ . Let  $x, y \in X$  with  $x \neq y$ . Then  $r := d(x, y) > 0$ . Then the open  $d$ -balls  $B_d(x, r/2)$  and  $B_d(y, r/2)$  do not intersect each others. Indeed, if there were  $z \in B_d(x, r/2) \cap B_d(y, r/2)$ , then  $d(x, z) < r/2$  and  $d(z, y) < r/2$  gives  $r = d(x, y) \leq d(x, z) + d(z, y) < r/2 + r/2 = r$ , which is not possible.

To see the converse, note that if  $d$  is a pseudo metric but not a metric on  $X$ , then there exists  $x, y \in X$  with  $x \neq y$  such that  $d(x, y) = 0$ . Then for any positive real numbers  $\delta_x, \delta_y > 0$ , we have  $B_d(x, \delta_x) \cap B_d(y, \delta_y) \neq \emptyset$ .  $\square$

**Corollary 1.2.11.** Let  $d_1$  and  $d_2$  be two equivalent pseudo metrics on a non-empty set  $X$ . Then  $d_1$  is a metric on  $X$  if and only if  $d_2$  is a metric on  $X$ .

### 1.3 Sequence

Let  $(X, d)$  be a metric space. A sequence in  $X$  is a map  $f : \mathbb{N} \rightarrow X$ . We generally denote a sequence  $f : \mathbb{N} \rightarrow X$  by its image  $\{x_n\}_{n \in \mathbb{N}}$ , where  $x_n = f(n)$ ,  $\forall n \in \mathbb{N}$ . A sequence  $\{x_n\}$  in  $X$  is said to be *Cauchy* if given any real number  $\epsilon > 0$  there exists a natural number  $n_0 \in \mathbb{N}$  such that  $d(x_n, x_m) < \epsilon$ ,  $\forall m, n \geq n_0$ .

<sup>1</sup>A space  $X$  is said to be *Hausdorff* if any two distinct points of  $X$  can be separated by a pair of disjoint open subsets of  $X$  containing them.

A sequence  $\{x_n\}$  in  $(X, d)$  is said to be *convergent* if there exists  $x_0 \in X$  such that given any  $\epsilon > 0$  there exists a natural number  $n_0$  such that  $d(x_n, x) < \epsilon, \forall n \geq n_0$ . In this case, we say that  $x_0$  is a *limit point* of the sequence  $\{x_n\}$  and we denote this symbolically as  $x_0 = \lim_{n \rightarrow \infty} x_n$ .

**Definition 1.3.1.** A metric space  $(X, d)$  is said to be *complete* if every Cauchy sequence in  $(X, d)$  is convergent in  $(X, d)$ .

**Example 1.3.2.** The metric spaces  $\mathbb{R}^n$  is complete with respect to the Euclidean metric.

**Example 1.3.3.** Let  $C[0, 1]$  be the set of all real valued continuous functions defined on  $[0, 1]$ . Note that  $C[0, 1]$  is a metric space with respect to the metric defined by

$$d(f, g) := \int_0^1 |f(t) - g(t)| dt, \forall f, g \in C[0, 1].$$

Then

**Proposition 1.3.4.** Let  $d_1$  and  $d_2$  be two metrics on a non-empty set  $X$ . Then  $d_1$  and  $d_2$  induces the same metric topology on  $X$  if and only if given any point  $x \in X$  and real number  $r > 0$ , there exists a real number  $r_2 > 0$  such that  $B_{d_1}(x, r_1) \subseteq B_{d_2}(x, r_2)$ .

**Lemma 1.3.5.** Let  $d_1$  and  $d_2$  be two metrics on a non-empty set  $X$  inducing the same metric topology on  $X$ . Then  $(X, d_1)$  is complete if and only if  $(X, d_2)$  is complete.

*Proof.* Suppose that  $(X, d_1)$  is a complete metric space. Let  $\{x_n\}_{n \in \mathbb{N}}$  be a  $d_2$ -Cauchy sequence in  $X$ . Let  $\epsilon > 0$  be given. Then there exists a natural number  $n_\epsilon > 0$  such that

$$d_2(x_m, x_n) < \epsilon, \forall m, n \geq n_\epsilon.$$

□

## 1.4 Limits and Continuity

### 1.5 Uniform continuity

### 1.6 Extension of uniformly continuous functions



## Chapter 2

# Point Set Topology

In this chapter, we recall some topological preliminaries from basic topology course. **Star** marked exercises are difficult one and are not required for this course.

## 2.1 Topological space

A topology on a set  $X$  is given by specifying which subsets of  $X$  are ‘open’. Naturally those subsets should satisfies certain properties as we are familiar from basic analysis and metric space courses.

**Definition 2.1.1.** A *topology* is on a set  $X$  is a collection  $\tau$  of subsets of  $X$  satisfying the following properties:

- (i)  $\emptyset$  and  $X$  are in  $\tau$ ,
- (ii) for any collection  $\{U_\alpha\}_{\alpha \in \Lambda}$  of objects of  $\tau$ , their union  $\bigcup_{\alpha \in \Lambda} U_\alpha \in \tau$ ,
- (iii) for a finite collection of objects  $U_1, \dots, U_n \in \tau$ , their intersection  $\bigcap_{i=1}^n U_i \in \tau$ .

The pair  $(X, \tau)$  is called a *topological space*, and the objects of  $\tau$  are called *open subsets* of  $(X, \tau)$ . For notational simplicity, we suppress  $\tau$  and denote a topological space  $(X, \tau)$  simply by  $X$ .

*Joke: An empty set may contain some air since it is open!*

**Remark 2.1.2.** One can also define a topology on a set  $X$  by considering a collection  $\tau_c$  of subsets of  $X$  such that

- (a) both  $\emptyset$  and  $X$  are in  $\tau_c$ ,
- (b)  $\tau_c$  is closed under arbitrary intersections, and
- (c)  $\tau_c$  is closed under finite unions.

This is known as the *closed set axioms for a topology*. In this settings, the objects of  $\tau_c$  are called *closed subsets* of  $X$ . It is easy to switch between these two definitions by taking complements of

objects of  $\tau$  and  $\tau_c$  in  $X$ . However, unless explicitly mentioned, we usually work with open set axioms for topology.

**Example 2.1.3.** (i) If  $X = \emptyset$  then  $\tau = \{\emptyset\}$  is the only topology on  $\emptyset$ .

(ii) For any set  $X$ ,  $\tau_{\text{disc}} := \mathcal{P}(X)$  and  $\tau_{\text{triv}} := \{\emptyset, X\}$  are topologies on  $X$ , called the *discrete topology* and the *indiscrete topology* on  $X$ , respectively. Note that,  $\tau_{\text{disc}}(X)$  and  $\tau_{\text{triv}}(X)$  are different if  $X$  has at least two elements.

(iii) Let  $X \neq \emptyset$ , and let  $\tau = \{A \in \mathcal{P}(X) : X \setminus A \text{ is finite}\}$ . Then  $(X, \tau)$  is a topological space; such a topology is called the *cofinite topology* on  $X$ .

(iv) Consider the set  $\mathbb{R}^n$ . Let  $\tau_E(\mathbb{R}^n)$  be the set of all subsets  $U \subseteq \mathbb{R}^n$  such that given any  $x \in U$  there exists a real number  $r > 0$  such that

$$B(x, r) := \{y \in \mathbb{R}^n : \|x - y\| < r\} \subseteq U.$$

Then the set  $\tau_E(\mathbb{R}^n)$  is a topology on  $\mathbb{R}^n$  (verify!), called the *standard topology* or the *Euclidean topology* on  $\mathbb{R}^n$ .

(v) Any metric space  $(X, d)$  is a topological space where the topology on  $X$  is given by the collection of all open subsets of  $(X, d)$ .

**Exercise\* 2.1.4.** This exercise is for readers interested in commutative algebra. Let  $A$  be a commutative ring with identity. Let  $\text{Spec}(A)$  be the set of all prime ideals of  $A$ , known as the *spectrum* of  $A$ . For each subset  $E \subseteq A$ , let

$$V(E) := \{\mathfrak{p} \in \text{Spec}(A) : E \subseteq \mathfrak{p}\}.$$

Prove the following.

- (i)  $V(A) = \emptyset$  and  $V(0) = \text{Spec}(A)$ .
- (ii)  $V(E) = V(\mathfrak{a})$ , where  $\mathfrak{a} \subseteq A$  is the ideal generated by  $E \subseteq A$ .
- (iii)  $V(\mathfrak{a} \cup \mathfrak{b}) = V(\mathfrak{a}\mathfrak{b})$ , for all ideals  $\mathfrak{a}, \mathfrak{b}$  of  $A$ .
- (iv)  $\bigcap_{i \in I} V(\mathfrak{a}_i) = V(\sum_{i \in I} \mathfrak{a}_i)$ , for any collection of ideals  $\{\mathfrak{a}_i : i \in I\}$  of  $A$ .
- (v) Conclude that the collection  $\{V(\mathfrak{a}) : \mathfrak{a} \text{ is an ideal of } A\}$  satisfies axioms for closed subsets of a topological space. The resulting topology on  $\text{Spec}(A)$  is called the *Zariski topology* on  $\text{Spec}(A)$ .
- (vi) For any ideal  $\mathfrak{a}$  of  $A$ , show that  $\text{Spec}(A/\mathfrak{a})$  is homeomorphic to the closed subspace  $V(\mathfrak{a})$  of  $\text{Spec}(A)$ .
- (vii) Let  $X$  be a topological space. A point  $\xi \in X$  is said to be a
  - (a) *closed point* of  $X$  if  $\overline{\{\xi\}} = \{\xi\}$ , and
  - (b) *generic point* of  $X$  if  $\overline{\{\xi\}} = X$ .



If  $A$  is an integral domain, show that  $\text{Spec}(A)$  contains a unique generic point, which is precisely the zero ideal of  $A$ .

- (viii) Show that the Zariski topology on  $\text{Spec}(A)$  is not even T1 let alone be it Hausdorff.
- (ix) Show that, a point  $\mathfrak{m} \in \text{Spec}(A)$  is closed if and only if  $\mathfrak{m}$  is a maximal ideal of  $A$ .
- (x) Let  $k$  be an algebraically closed field, and let  $A = k[x_1, \dots, x_n]$ . Use Hilbert's Nullstellensatz to show that the set of all closed points of  $\text{Spec}(A)$  is in bijection with the set  $k^n := \{(a_1, \dots, a_n) : a_i \in k, \forall i \in \{1, \dots, n\}\}$ .
- (xi) Let  $k$  be an algebraically closed field. Fix a subset  $S \subseteq A := k[x_1, \dots, x_n]$ , and let  $\mathfrak{a}_S \subseteq A$  be the ideal generated by  $S$ . Show that the set

$$Z(S) := \{(a_1, \dots, a_n) \in k^n : f(a_1, \dots, a_n) = 0, \forall f \in S\}$$

is in bijection with the set of all closed points of  $V(\mathfrak{a}_S) \subseteq \text{Spec}(A)$ .

The space  $\text{Spec}(A)$  carries rich algebro-geometric structure. They are called *affine scheme*, and are building blocks of all schemes in the sense that any scheme is build up by suitably gluing affine schemes.

**Definition 2.1.5** (Basis). Let  $(X, \tau)$  be a topological space. A subset  $\mathcal{B} \subseteq \tau$  is said to be a *basis* for the topology  $\tau$  on  $X$  if given any  $U \in \tau$  and any  $x \in U$ , there exists an element  $V \in \mathcal{B}$  such that  $x \in V$  and  $V \subseteq U$ . The elements of  $\mathcal{B}$  are called *basic open subsets* of  $X$ .

- Example 2.1.6.** (i) If  $\tau$  is the discrete topology on  $X$ , then  $\mathcal{B} = \{\{x\} : x \in X\}$  is a basis for  $(X, \tau)$ .
- (ii) Let  $\mathcal{B}$  be the set of all open intervals  $(a, b) \subset \mathbb{R}$ , where  $a < b$ . Then  $\mathcal{B}$  is a basis for the Euclidean topology on  $\mathbb{R}$ .
- (iii) Let  $(X, d)$  be a metric space. Then  $\mathcal{B} = \{B(x, r) : x \in X, r > 0\}$  is a basis for the metric topology on  $(X, d)$ .

**Lemma 2.1.7.** Let  $\mathcal{B}$  be a basis for a topological space  $(X, \tau)$ . Then

- (i)  $\bigcup_{V \in \mathcal{B}} V = X$ , and
- (ii)  $\tau$  is the set of all unions of elements from  $\mathcal{B}$ .

*Proof.* (i) Follows from the Definition 2.1.5 by taking  $X = U \in \tau$ .

- (ii) Let  $U \in \tau$  be arbitrary. Since  $\mathcal{B}$  is a basis for the topology  $\tau$  on  $X$ , for each  $x \in U$  there is a basic open subset  $V_x \in \mathcal{B}$  with  $x \in V_x$  such that  $V_x \subseteq U$ . Then we have  $U = \bigcup_{x \in U} V_x$ .

□

**Proposition 2.1.8** (Topology generated by a basis). Let  $X$  be a set. Let  $\mathcal{B}$  be a collection of subsets of  $X$  satisfying the following properties.

- (i)  $\bigcup_{V \in \mathcal{B}} V = X$ , and
- (ii) given any  $V_1, V_2 \in \mathcal{B}$  and a point  $x \in V_1 \cap V_2$ , there exists a  $W \in \mathcal{B}$  such that  $x \in W$  and  $W \subseteq V_1 \cap V_2$ .

Then there is a unique topology  $\tau_{\mathcal{B}}$  on  $X$  such that  $\mathcal{B}$  is a basis for  $\tau_{\mathcal{B}}$ . Such a topology  $\tau_{\mathcal{B}}$  on  $X$  is called the topology generated by  $\mathcal{B}$ .

*Proof.* Take

$$\tau_{\mathcal{B}} := \{U \in \mathcal{P}(X) : \text{for each } x \in U, \exists V_x \in \mathcal{B} \text{ such that } x \in V_x \subseteq U\}.$$

Clearly  $\emptyset$  and  $X$  are in  $\tau_{\mathcal{B}}$ . Let  $\{U_{\alpha}\}_{\alpha \in \Lambda}$  be any collection of objects from  $\tau_{\mathcal{B}}$ , and let  $x \in \bigcup_{\alpha \in \Lambda} U_{\alpha}$ . Then  $x \in U_{\lambda}$ , for some  $\lambda \in \Lambda$ . Then by construction of  $\tau_{\mathcal{B}}$  there exists a  $V_x \in \mathcal{B}$  such that  $x \in V_x \subseteq U_{\lambda}$ , and hence  $x \in V_x \subseteq \bigcup_{\alpha \in \Lambda} U_{\alpha}$ . Thus  $\bigcup_{\alpha \in \Lambda} U_{\alpha} \in \tau_{\mathcal{B}}$ . Let  $U_1, U_2 \in \tau_{\mathcal{B}}$ . Let  $x \in U_1 \cap U_2$  be arbitrary. Then there exist  $V_1, V_2 \in \mathcal{B}$  such that  $x \in V_1 \subseteq U_1$  and  $x \in V_2 \subseteq U_2$ . Then by property (ii) of  $\mathcal{B}$ , there exists a  $W \in \mathcal{B}$  such that  $x \in W \subseteq V_1 \cap V_2 \subseteq U_1 \cap U_2$ . Therefore,  $U_1 \cap U_2 \in \tau_{\mathcal{B}}$ . Thus,  $\tau_{\mathcal{B}}$  is topology on  $X$ . It follows from the definition of  $\tau_{\mathcal{B}}$  that  $\mathcal{B}$  is a basis for  $(X, \tau_{\mathcal{B}})$ .

Let  $\tau$  be a topology on  $X$  such that  $\mathcal{B}$  is a basis for  $\tau$ . Let  $U \in \tau$  be arbitrary. Then given any  $x \in U$ , there exists a  $V \in \mathcal{B}$  such that  $x \in V \subseteq U$ . Then  $U \in \tau_{\mathcal{B}}$  by construction of  $\tau_{\mathcal{B}}$ . Therefore,  $\tau \subseteq \tau_{\mathcal{B}}$ . Conversely, let  $U \in \tau_{\mathcal{B}}$  be arbitrary. Then  $U = \bigcup_{x \in U} V_x$ , where  $V_x \in \mathcal{B}$  with  $x \in V_x \subseteq U$ , by Lemma 2.1.7. Since  $\mathcal{B} \subseteq \tau$  and  $\tau$  is closed under arbitrary union of its elements,  $U \in \tau$ . Therefore,  $\tau_{\mathcal{B}} \subseteq \tau$ , and hence  $\tau_{\mathcal{B}} = \tau$ . This proves uniqueness part.  $\square$

**Proposition 2.1.9.** Let  $\mathcal{B}$  and  $\mathcal{B}'$  be bases for the topologies  $\tau$  and  $\tau'$  on  $X$ . Then the following are equivalent.

- (i)  $\tau \subseteq \tau'$ ,
- (ii) given  $V \in \mathcal{B}$  and  $x \in V$ , there exists  $V' \in \mathcal{B}'$  such that  $x \in V' \subseteq V$ .

*Proof.* (i)  $\Rightarrow$  (ii): Suppose that  $\tau \subseteq \tau'$ . Let  $V \in \mathcal{B}$  and  $x \in V$  be given. Since  $\mathcal{B} \subseteq \tau \subseteq \tau'$  and  $\mathcal{B}'$  is a basis for  $\tau'$ , there exists a  $V' \in \mathcal{B}'$  such that  $x \in V' \subseteq V$ .

(ii)  $\Rightarrow$  (i): Let  $U \in \tau$  be arbitrary. Since  $\mathcal{B}$  is a basis for  $\tau$ , by Lemma 2.1.7 we have  $U = \bigcup_{x \in U} V_x$ , where  $V_x \in \mathcal{B}$  with  $x \in V_x \subseteq U$ . Then by (ii) there exists  $W_x \in \mathcal{B}'$  such that  $x \in W_x \subseteq V_x$ , for all  $x \in U$ . Then  $U = \bigcup_{x \in U} W_x \in \tau'$ .  $\square$

**Example 2.1.10.** Given  $a, b \in \mathbb{R}$  with  $a < b$ , let  $[a, b) := \{t \in \mathbb{R} : a \leq t < b\}$ . Let  $\mathcal{B}_{\ell} = \{[a, b) \subset \mathbb{R} : a, b \in \mathbb{R} \text{ with } a < b\}$ . Note that  $\mathcal{B}_{\ell}$  is a basis for a topology  $\tau_{\ell}$  on  $\mathbb{R}$ , called the lower limit topology on  $\mathbb{R}$ . We denote by  $\mathbb{R}_{\ell}$  the topological space  $(\mathbb{R}, \tau_{\ell})$ . Let  $a, b \in \mathbb{R}$  with  $a < b$  and let  $c \in (a, b)$ . Then  $c \in [c, b) \subset (a, b)$ . Then it follows from Proposition 2.1.9 that  $\tau_E \subseteq \tau_{\ell}$ , where  $\tau_E$  is the Euclidean topology on  $\mathbb{R}$ . Fix  $a, b \in \mathbb{R}$  with  $a < b$ . Then  $a \in [a, b)$ , but there is no open interval  $(c, d)$  in  $\mathbb{R}$  such that  $a \in (c, d) \subseteq [a, b)$ . Therefore,  $\tau_{\ell}$  is strictly finer than the Euclidean topology on  $\mathbb{R}$ .

**Example 2.1.11** ( $K$ -topology). Let  $K = \{\frac{1}{n} : n \in \mathbb{N}\}$ . Let  $\mathcal{B}_K$  be the set of all open intervals in  $\mathbb{R}$  along with the subsets of the form  $(a, b) \setminus K$ , where  $a, b \in \mathbb{R}$  with  $a < b$ . It is easy to check that  $\mathcal{B}_K$  is a basis for a topology  $\tau_K$  on  $\mathbb{R}$  which is strictly finer than the Euclidean topology on  $\mathbb{R}$ . The topology  $\tau_K$  on  $\mathbb{R}$  generated by  $\mathcal{B}_K$  is called the  $K$ -topology on  $\mathbb{R}$ . Note that  $(-1, 1) \setminus K$  is open in the  $K$ -topology on  $\mathbb{R}$ , but not in the Euclidean topology on  $\mathbb{R}$  because there is no open interval  $(a, b)$  containing 0 and contained in  $(-1, 1) \setminus K$ .

**Exercise 2.1.12.** Show that the lower limit topology and the  $K$ -topology on  $\mathbb{R}$  are not comparable in the sense that neither  $\tau_\ell \subseteq \tau_K$  nor  $\tau_K \subseteq \tau_\ell$ .

**Definition 2.1.13.** Let  $X$  be a set. A set  $\mathcal{S} \subseteq \mathcal{P}(X)$  of subsets of  $X$  is said to be a *subbasis* for a topology on  $X$  if  $\bigcup_{V \in \mathcal{S}} V = X$ .

Let  $\mathcal{S} \subseteq \mathcal{P}(X)$  be such that  $\bigcup_{V \in \mathcal{S}} V = X$ . Let  $\mathcal{B} \subseteq \mathcal{P}(X)$  be the set of all finite intersections of elements from  $\mathcal{S}$ . Note that  $\mathcal{S} \subseteq \mathcal{B}$  and so  $\bigcup_{V \in \mathcal{B}} V = X$ . Let  $V, W \in \mathcal{B}$  be arbitrary. Then  $V = \bigcap_{j=1}^m V_j$  and  $W = \bigcap_{k=1}^n W_k$ , for some  $V_1, \dots, V_m, W_1, \dots, W_n \in \mathcal{S}$ . Then their intersection  $V \cap W = \left(\bigcap_{j=1}^m V_j\right) \cap \left(\bigcap_{k=1}^n W_k\right)$  is again a finite intersection of elements from  $\mathcal{S}$ , and hence is an element of  $\mathcal{B}$ . Therefore,  $\mathcal{B}$  is a basis for a topology  $\tau_{\mathcal{B}}$  on  $X$ , called the *topology generated by the subbasis*  $\mathcal{S}$ .

### 2.1.1 Order topology

Let  $(X, \leq)$  be a simply ordered (i.e., totally ordered) set. Given  $a, b \in X$  with  $a < b$ , there are four types of subset of  $X$  that are called intervals determined by  $a$  and  $b$ , namely

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

Let  $\mathcal{B}$  be the set of all subsets of  $X$  of the following forms

- (i) all open intervals  $(a, b)$  in  $X$ ,
- (ii) all intervals of the form  $[a_0, b)$ , where  $a_0$  is the smallest element, if exists, of  $X$ ,
- (iii) all intervals of the form  $(a, b_0]$ , where  $b_0$  is the largest element, if exists, of  $X$ .

Then the collection  $\mathcal{B}$  is a basis for a topology on  $X$ , called the *order topology* on  $(X, \leq)$ .

**Example 2.1.14.** The Euclidean topology on  $\mathbb{R}$  is the order topology on it.

**Exercise 2.1.15.** Consider the set  $\mathbb{R} \times \mathbb{R}$  and give a partial order relation on it by setting  $(a, b) < (c, d)$  if  $a < c$  or if  $a = c$  and  $b < d$ . Draw intervals  $((a, b), (c, d))$  in  $\mathbb{R} \times \mathbb{R}$ , for the case  $a < c$ , and the case  $a = c$  with  $b < d$ .

### 2.1.2 Product topology

Let  $\mathcal{C}$  be a category. For example, the category of topological spaces: objects are topological spaces and given two topological spaces  $X$  and  $Y$ ,  $\text{Mor}(X, Y)$  is the set of all continuous maps from  $X$  to  $Y$ .

**Definition 2.1.16.** The *product* of an indexed family of objects  $\{X_\alpha : \alpha \in \Lambda\}$  in  $\mathcal{C}$  is a pair  $(P, (\pi_\alpha : P \rightarrow X_\alpha)_{\alpha \in \Lambda})$ , consisting of an object  $P$  in  $\mathcal{C}$  and a family of morphisms  $\{\pi_\alpha : P \rightarrow X_\alpha\}_{\alpha \in \Lambda}$  in  $\mathcal{C}$ , satisfying the following universal property: given any object  $T$  of  $\mathcal{C}$  and a family of morphisms  $\{f_\alpha : T \rightarrow X_\alpha\}_{\alpha \in \Lambda}$  in  $\mathcal{C}$ , there exists a unique morphism  $f : T \rightarrow P$  in  $\mathcal{C}$  such that  $\pi_\alpha \circ f = f_\alpha$ , for all  $\alpha \in \Lambda$ .

$$\begin{array}{ccc} T & \xrightarrow{\quad f \quad} & P \\ & \searrow f_\alpha & \downarrow \pi_\alpha \\ & & X_\alpha \end{array}$$

It follows from the universal property of product that, if it exists, then it is unique upto a unique isomorphism making the above diagram commutative. Indeed, if  $(P, (\pi_\alpha : P \rightarrow X_\alpha)_{\alpha \in \Lambda})$  and  $(P', (\pi'_\alpha : P' \rightarrow X_\alpha)_{\alpha \in \Lambda})$  are two products of an indexed family of objects  $\{X_\alpha : \alpha \in \Lambda\}$  in  $\mathcal{C}$ , then applying universal property of  $(P, (\pi_\alpha : P \rightarrow X_\alpha)_{\alpha \in \Lambda})$  for the test object  $(P', (\pi'_\alpha : P' \rightarrow X_\alpha)_{\alpha \in \Lambda})$ , we get a unique morphism  $f : P' \rightarrow P$  such that  $\pi_\alpha \circ f = \pi'_\alpha$ ,  $\forall \alpha \in \Lambda$ . Similarly, applying universal property of  $(P', (\pi'_\alpha : P' \rightarrow X_\alpha)_{\alpha \in \Lambda})$  for the test object  $(P, (\pi_\alpha : P \rightarrow X_\alpha)_{\alpha \in \Lambda})$  we have a unique morphism  $g : P \rightarrow P'$  such that  $\pi'_\alpha \circ g = \pi_\alpha$ ,  $\forall \alpha \in \Lambda$ .

$$\begin{array}{ccccc} & & \text{Id}_{P'} & & \\ & \nearrow & & \searrow & \\ P' & \xrightarrow{\quad f \quad} & P & \xrightarrow{\quad g \quad} & P' \\ & \searrow \pi'_\alpha & \downarrow \pi_\alpha & \swarrow \pi'_\alpha & \\ & & X_\alpha & & \end{array}$$

Since both the morphisms  $g \circ f, \text{Id}_{P'} \in \text{Mor}_{\mathcal{C}}(P', P')$  makes the following diagram commutative,

$$\begin{array}{ccc} P' & \xrightarrow{\quad g \circ f \quad} & P' \\ & \searrow \pi'_\alpha & \swarrow \pi'_\alpha \\ & & X_\alpha \end{array}$$

for all  $\alpha \in \Lambda$ , it follows from the uniqueness assertion in Definition 2.1.16 that  $g \circ f = \text{Id}_{P'}$ . Similarly one can show that  $f \circ g = \text{Id}_P$ . Therefore, the product of  $\{X_\alpha\}_{\alpha \in \Lambda}$  in  $\mathcal{C}$ , if it exists, is unique upto a unique isomorphism making the diagram in Definition 2.1.16 commutative. We denote the product of  $\{X_\alpha\}_{\alpha \in \Lambda}$  in  $\mathcal{C}$  by  $\prod_{\alpha \in \Lambda} X_\alpha$ .

**Lemma 2.1.17.** The product  $\prod_{\alpha \in \Lambda} X_\alpha$  of a family of sets  $\{X_\alpha : \alpha \in \Lambda\}$  exists in the category of sets.

*Proof.* Let

$$\prod_{\alpha \in \Lambda} X_\alpha := \left\{ f : \Lambda \rightarrow \bigcup_{\alpha \in \Lambda} X_\alpha \mid f(\alpha) \in X_\alpha, \forall \alpha \in \Lambda \right\}.$$

Define a map  $\pi_\beta : \prod_{\alpha \in \Lambda} X_\alpha \rightarrow X_\beta$  by  $\pi_\beta(f) = f_\beta, \forall \beta \in \Lambda$ . Suppose that we are given a set  $T$  together with maps  $f_\alpha : T \rightarrow X_\alpha$ , for each  $\alpha \in \Lambda$ . Define a map  $F : T \rightarrow \prod_{\alpha \in \Lambda} X_\alpha$  which sends  $t \in T$  to  $F(t) \in \prod_{\alpha \in \Lambda} X_\alpha$  defined by  $F(t)(\alpha) = f_\alpha(t), \forall \alpha \in \Lambda$ . Then  $(\pi_\alpha \circ F)(t)(\alpha) = \pi_\alpha(F(t)) = F(t)(\alpha) = f_\alpha(t), \forall t \in T$ . Therefore,  $\pi_\alpha \circ F = f_\alpha, \forall \alpha \in \Lambda$ . Uniqueness of  $F$  is obvious.  $\square$

**Theorem 2.1.18.** *Let  $\mathcal{Top}$  be the category of topological spaces. The categorical product of a family of topological spaces  $\{X_\alpha : \alpha \in \Lambda\}$  exists in  $\mathcal{Top}$ .*

*Proof.* Uniqueness follows from the universal property of product in a category. We only prove existence. Let  $\{X_\alpha : \alpha \in \Lambda\}$  be an indexed family of topological spaces. Let  $\tau_\alpha$  be the topology on  $X_\alpha$ , for all  $\alpha \in \Lambda$ . Let  $\mathcal{B}$  be the family of products (in the category of sets)  $\prod_{\alpha \in \Lambda} U_\alpha$ , where  $U_\alpha \in \tau_\alpha$  such that  $U_\alpha = X_\alpha$  for all but finitely many  $\alpha \in \Lambda$ . In particular,  $\prod_{\alpha \in \Lambda} X_\alpha \in \mathcal{B}$ . Let  $U = \prod_{\alpha \in \Lambda} U_\alpha$  and  $V = \prod_{\alpha \in \Lambda} V_\alpha$  be any objects in  $\mathcal{B}$ , and let  $x \in U \cap V$  be given. Since  $x_\alpha := \pi_\alpha(x) \in U_\alpha \cap V_\alpha$ , and  $U_\alpha \cap V_\alpha$  is open in  $X_\alpha$ , we have

$\square$

Let  $(X, \tau_X)$  and  $(Y, \tau_Y)$  be two topological spaces. Let  $\mathcal{B} := \{U \times V : U \in \tau_X \text{ and } V \in \tau_Y\}$ . Given any  $(x, y) \in X \times Y$ , there exists  $U_x \in \tau_X$  and  $U_y \in \tau_Y$  such that  $x \in U_x$  and  $y \in U_y$ . Then  $(x, y) \in U_x \times U_y$ . Therefore, the union of all members of  $\mathcal{B}$  is  $X \times Y$ . Let  $U_1 \times V_1$  and  $U_2 \times V_2$  be any two elements from  $\mathcal{B}$ , and let  $(x, y) \in (U_1 \times V_1) \cap (U_2 \times V_2)$  be given. Since  $(U_1 \times V_1) \cap (U_2 \times V_2) = (U_1 \cap U_2) \times (V_1 \cap V_2)$ , we see that  $\mathcal{B}$  is a basis for a topology on  $X \times Y$ , called the *product topology* on  $X \times Y$ .

**Proposition 2.1.19.** *Let  $X$  and  $Y$  be two topological spaces. Let  $\mathcal{B}_X$  and  $\mathcal{B}_Y$  be bases for  $X$  and  $Y$ , respectively. Then the collection*

$$\mathcal{B} := \{U \times V : U \in \mathcal{B}_X \text{ and } V \in \mathcal{B}_Y\}$$

*is a basis for the product topological space  $X \times Y$ .*

*Proof.* Since  $\mathcal{B}_X$  and  $\mathcal{B}_Y$  are bases for  $X$  and  $Y$ , respectively, given any  $(x, y) \in X \times Y$ , there exist  $U \in \mathcal{B}_X$  and  $V \in \mathcal{B}_Y$  such that  $x \in U$  and  $y \in V$ , so that  $(x, y) \in U \times V$ . Let  $U_1 \times V_1, U_2 \times V_2 \in \mathcal{B}$  and  $(x, y) \in (U_1 \times V_1) \cap (U_2 \times V_2)$  be given. Since  $(U_1 \times V_1) \cap (U_2 \times V_2) = (U_1 \cap U_2) \times (V_1 \cap V_2)$ , there exist  $U \in \mathcal{B}_X$  and  $V \in \mathcal{B}_Y$  such that  $x \in U \subseteq U_1 \cap U_2$  and  $y \in V \subseteq V_1 \cap V_2$ . Then  $(x, y) \in U \times V \subseteq (U_1 \times V_1) \cap (U_2 \times V_2)$ . Therefore,  $\mathcal{B}$  is a basis for a topology on  $X \times Y$ . Let  $A \subseteq X \times Y$  be any non-empty open subset in the product topological space  $X \times Y$ . Let  $(x, y) \in A$  be given. Then there exist  $U \in \tau_X$  and  $V \in \tau_Y$  such that  $(x, y) \in U \times V \subseteq A$ . Since  $\mathcal{B}_X$  and  $\mathcal{B}_Y$  are bases for  $(X, \tau_X)$  and  $(Y, \tau_Y)$ , respectively, there exist  $U_1 \in \mathcal{B}_X$  and  $V_1 \in \mathcal{B}_Y$  such that  $x \in U_1 \subseteq U$  and  $y \in V_1 \subseteq V$ . Then  $(x, y) \in U_1 \times V_1 \subseteq A$ . Therefore,  $\mathcal{B}$  is a basis for the product topology on  $X \times Y$ .  $\square$

**Exercise 2.1.20.** Show that the product topology on  $\mathbb{R}^n$  coincides with the Euclidean topology on  $\mathbb{R}^n$ .

Let  $X$  and  $Y$  be two sets. Let  $\pi_X : X \times Y \rightarrow X$  and  $\pi_Y : X \times Y \rightarrow Y$  be the maps defined by

$$\begin{aligned}\pi_X(x, y) &= x, \forall (x, y) \in X \times Y, \\ \text{and } \pi_Y(x, y) &= y, \forall (x, y) \in X \times Y.\end{aligned}$$

The maps  $\pi_X$  and  $\pi_Y$  are called the projection maps onto  $X$  and  $Y$ , respectively. Note that,  $\pi_X^{-1}(U) = U \times Y$  and  $\pi_Y^{-1}(V) = X \times V$ , for any subsets  $U \subseteq X$  and  $V \subseteq Y$ , respectively.

**Theorem 2.1.21.** *Let  $(X, \tau_X)$  and  $(Y, \tau_Y)$  be two topological spaces. Then the collection*

$$\mathcal{S} := \{\pi_X^{-1}(U) : U \in \tau_X\} \cup \{\pi_Y^{-1}(V) : V \in \tau_Y\}$$

*is a subbasis for the product topology on  $X \times Y$ .*

*Proof.* Since  $\pi_X^{-1}(U) = U \times Y$  and  $\pi_Y^{-1}(V) = X \times V$ , for any subsets  $U \subseteq X$  and  $V \subseteq Y$ , respectively, we see that  $\mathcal{S} \subseteq \tau_{X \times Y}$ , where  $\tau_{X \times Y}$  is the product topology on  $X \times Y$ . Since the topology  $\tau_{\mathcal{S}}$  generated by  $\mathcal{S}$  consists of arbitrary unions of finite intersections of elements from  $\mathcal{S}$ , we have  $\tau_{\mathcal{S}} \subseteq \tau_{X \times Y}$ . On the other hand, every basic open subset  $U \times V$  for the product topology  $\tau_{X \times Y}$  can be written as finite intersection

$$U \times V = \pi_X^{-1}(U) \cap \pi_Y^{-1}(V).$$

Therefore, these two topologies coincide. □

### 2.1.3 Subspace topology

Let  $(X, \tau)$  be a topological space. Given a subset  $Y$  of  $X$ , let

$$\tau_Y := \{U \cap Y : U \in \tau\}.$$

Clearly  $\emptyset, Y \in \tau_Y$ . Let  $\{A_\alpha\}_{\alpha \in \Lambda}$  be a family of elements of  $\tau_Y$ . Then for each  $\alpha \in \Lambda$ , we have  $A_\alpha = U_\alpha \cap Y$ , for some  $U_\alpha \in \tau$ . Then  $\bigcup_{\alpha \in \Lambda} A_\alpha = \bigcup_{\alpha \in \Lambda} (U_\alpha \cap Y) = \left( \bigcup_{\alpha \in \Lambda} U_\alpha \right) \cap Y \in \tau_Y$ . If  $V_1, V_2 \in \tau_Y$ , then  $V_1 = U_1 \cap Y$  and  $V_2 = U_2 \cap Y$ , for some  $U_1, U_2 \in \tau$ . Then  $V_1 \cap V_2 = (U_1 \cap U_2) \cap Y \in \tau_Y$ . Therefore,  $\tau_Y$  is a topology on  $Y$ , called the *subspace topology* on  $Y$  induced from  $(X, \tau)$ .

**Proposition 2.1.22.** *Let  $\mathcal{B}$  be a basis for a topological space  $(X, \tau)$ . Let  $Y \subseteq X$ . Then  $\mathcal{B}_Y := \{V \cap Y : V \in \mathcal{B}\}$  is a basis for the subspace topology on  $Y$ .*

*Proof.* Since  $\mathcal{B}$  is a basis for  $(X, \tau)$ , we have  $\bigcup_{V \in \mathcal{B}} V = X$ . Then  $\bigcup_{V \in \mathcal{B}} (V \cap Y) = Y$ . Let  $U \cap Y \in \tau_Y$  and  $y \in U \cap Y$ . Then there exists  $V \in \mathcal{B}$  such that  $y \in V \subseteq U$ . Then  $y \in V \cap Y \subseteq U \cap Y$ . Therefore,  $\mathcal{B}_Y$  is a basis for the subspace topology  $\tau_Y$  on  $Y$ . □

**Proposition 2.1.23.** *Let  $Y$  be a subspace of a topological space  $X$ . If  $U \subseteq Y$  is open in  $Y$ , and  $Y$  is open in  $X$ , then  $U$  is open in  $X$ .*

*Proof.* Since  $U$  is open in  $Y$ ,  $U = Y \cap V$ , for some open subset  $V$  of  $X$ . Since  $Y$  is open in  $X$ ,  $U = Y \cap V$  is open in  $X$ .  $\square$

**Proposition 2.1.24.** *Let  $Y$  be a closed subspace of  $X$ . If  $Z \subseteq Y$  is closed in  $Y$ , then  $Z$  is closed in  $X$ .*

*Proof.* Note that,  $X \setminus Z = (X \setminus Y) \cup (Y \setminus Z)$ . Since  $Y$  is closed in  $X$ ,  $X \setminus Y$  is open in  $X$ . Since  $Z$  is closed in  $Y$ ,  $Y \setminus Z$  is open in  $Y$ , and hence  $Y \setminus Z = U \cap Y$ , for some open subset  $U$  of  $X$ . We claim that  $X \setminus Z = (X \setminus Y) \cup U$ . Since  $Y \setminus Z = U \cap Y \subseteq U$ , we have  $X \setminus Z \subseteq (X \setminus Y) \cup U$ . Again, since  $Z \subseteq Y$  and  $Y \setminus Z = U \cap Y$ , we must have  $U \subseteq X \setminus Z$ . Therefore,  $X \setminus Z = (X \setminus Y) \cup U$ , and hence  $X \setminus Z$  is open in  $X$ , which in turn gives that  $Z$  is closed in  $X$ .  $\square$

**Theorem 2.1.25.** *Let  $A$  be a subspace of  $X$  and  $B$  be a subspace of  $Y$ . Then the product topology on  $A \times B$  coincides with the subspace topology on  $A \times B$  induced from  $X \times Y$ .*

*Proof.* Let  $\mathcal{B}_X$  and  $\mathcal{B}_Y$  be bases for the topologies on  $X$  and  $Y$ , respectively. Then  $\mathcal{B}_A = \{U \cap A : U \in \mathcal{B}_X\}$  and  $\mathcal{B}_B = \{U \cap B : U \in \mathcal{B}_Y\}$  are bases for the subspace topologies on  $A$  and  $B$ , respectively. Then  $\mathcal{B} = \{(U \cap A) \times (V \cap B) : U \in \mathcal{B}_X \text{ and } V \in \mathcal{B}_Y\}$  is a basis for the product topology on  $A \times B$ . Note that  $\mathcal{B}_{X \times Y} = \{U \times V : U \in \mathcal{B}_X \text{ and } V \in \mathcal{B}_Y\}$  is a basis for the product topology on  $X \times Y$ . Then  $\mathcal{B}' = \{(U \times V) \cap (A \times B) : U \in \mathcal{B}_X \text{ and } V \in \mathcal{B}_Y\}$  is a basis for the subspace topology on  $A \times B$  induced from  $X \times Y$ . Since  $(U \cap A) \times (V \cap B) = (U \times V) \cap (A \times B)$ , for all  $U \in \mathcal{B}_X$  and  $V \in \mathcal{B}_Y$ , we have  $\mathcal{B} = \mathcal{B}'$ . Hence the result follows.  $\square$

## 2.2 Continuity

**Definition 2.2.1** (Continuous map). Let  $X$  and  $Y$  be topological spaces. A map  $f : X \rightarrow Y$  is said to be *continuous* if for each open subset  $V$  of  $Y$ , the subset  $f^{-1}(V)$  is open in  $X$ .

As an immediate consequence of the above definition, we get the following.

**Corollary 2.2.2.** *Let  $X$  be a non-empty set together with two topologies  $\tau_1$  and  $\tau_2$ . For each  $j = 1, 2$ , let  $X_j = (X, \tau_j)$  be the topological space whose underlying set is  $X$  and the topology is  $\tau_j$ . Then  $\tau_2$  is finer than  $\tau_1$  (i.e.,  $\tau_1 \subsetneq \tau_2$ ) if and only if the identity map  $\text{Id}_X : X_2 \rightarrow X_1$  is continuous.*

**Definition 2.2.3.** A topological space  $X$  is said to be *Hausdorff* or, *T2* or, *separated* if each pair of distinct points of  $X$  can be separated by a pair of disjoint open neighbourhoods of them. In other words, give  $x_1, x_2 \in X$  with  $x_1 \neq x_2$ , there exist open subsets  $V_1, V_2$  of  $X$  with  $x_1 \in V_1$ ,  $x_2 \in V_2$  and  $V_1 \cap V_2 = \emptyset$ .

**Lemma 2.2.4.** *A topological space is Hausdorff if and only if the image of the diagonal map*

$$\Delta_X : X \rightarrow X \times X, \quad x \mapsto (x, x)$$

*is closed in  $X \times X$ .*

*Proof.* Suppose that  $X$  is Hausdorff. It is enough to show that  $U := (X \times X) \setminus \Delta_X(X)$  is open in  $X \times X$ . Since any point of  $U$  is of the form  $(x_1, x_2) \in X \times X$  with  $x_1 \neq x_2$ , there are open

neighbourhoods  $x_j \in V_j \subset X$ ,  $j = 1, 2$ , such that  $V_1 \cap V_2 = \emptyset$ . Then  $(x_1, x_2) \in V_1 \times V_2 \subseteq U$ , and hence  $U$  is open.

Conversely suppose that  $X$  is separated. If  $x_1, x_2 \in X$  with  $x_1 \neq x_2$ , then  $(x_1, x_2) \in U := (X \times X) \setminus \Delta_X(X)$ . Since  $U$  is open in  $X \times X$ , there exist open subsets  $V_1, V_2 \subset X$  with  $x_j \in V_j$ ,  $j = 1, 2$ , such that  $(x_1, x_2) \in V_1 \times V_2 \subseteq U = (X \times X) \setminus \Delta_X(X)$ . Then  $(V_1 \times V_2) \cap \Delta_X(X) = \emptyset$ , and hence  $V_1 \cap V_2 = \emptyset$ .  $\square$

**Exercise 2.2.5.** Let  $f, g : X \rightarrow Y$  be continuous maps of topological spaces. If  $Y$  is Hausdorff, show that the subset  $\{x \in X : f(x) = g(x)\}$  is closed in  $X$ . (*Hint:* Look at the inverse image of  $\Delta_Y(Y) \subset Y \times Y$  under the map  $(f, g) : X \rightarrow Y \times Y$  given by  $x \mapsto (f(x), g(x))$ .)

**Exercise 2.2.6.** Let  $f : X \rightarrow Z$  and  $g : Y \rightarrow Z$  be continuous maps of topological spaces. If  $Z$  is Hausdorff, show that the subset

$$\text{Eq}(f, g) := \{(x, y) \in X \times Y : f(x) = g(y)\}$$

is closed in the product topological space  $X \times Y$ . (*Hint:* Note that  $\text{Eq}(f, g) = (f \times g)^{-1}(\Delta_Z(Z))$ , where  $f \times g : X \times Y \rightarrow Z \times Z$  is the continuous map defined by  $(f \times g)(x, y) = (f(x), g(y))$ , for all  $(x, y) \in X \times Y$ .)

**Exercise 2.2.7.** Let  $\{f_k : X_k \rightarrow Z \mid k = 1, \dots, n\}$  be a finite set of continuous maps of topological spaces. If  $Z$  is Hausdorff, show that the subset

$$\text{Eq}(f_1, \dots, f_n) := \{(x_1, \dots, x_n) \in X_1 \times \dots \times X_n : f_1(x_1) = \dots = f_n(x_n)\}$$

is closed in the product topological space  $X_1 \times \dots \times X_n$ .

(*Hint:* We only prove for the case  $n = 3$ ; general case is similar. For  $n = 3$ , we have  $\text{Eq}(f_1, f_2, f_3) = (\text{Eq}(f_1, f_2) \times X_3) \cap (X_1 \times \text{Eq}(f_2, f_3))$ . Since both  $\text{Eq}(f_1, f_2)$  and  $\text{Eq}(f_2, f_3)$  are closed in  $X_1 \times X_2$  and  $X_2 \times X_3$ , respectively, by previous exercise, the result follows.)

**Definition 2.2.8.** A continuous map  $f : X \rightarrow Y$  is said to be *separated* if the image of the induced map  $\Delta_f : X \rightarrow X \times_Y X$  is closed in  $X \times_Y X$ .

**Exercise 2.2.9.** Let  $X$  be a non-empty set together with a pseudo metric  $d$  on it. Show that the topology on  $X$  generated by  $d$  is Hausdorff if and only if  $d$  is a metric on  $X$ .

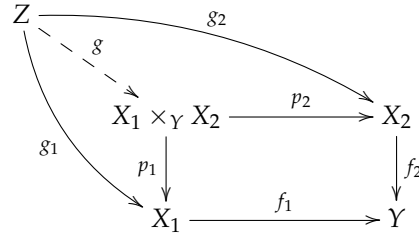
**Exercise\* 2.2.10.** Given continuous maps  $f_1 : X_1 \rightarrow Y$  and  $f_2 : X_2 \rightarrow Y$  of topological spaces, we define their *fiber product* to be a topological space  $X \times_Z Y$  together with continuous maps  $p_1 : X \times_Z Y \rightarrow X_1$  and  $p_2 : X \times_Z Y \rightarrow X_2$  such that

$$(i) \quad f_1 \circ p_1 = f_2 \circ p_2, \text{ and}$$

$$(ii) \quad \text{given any topological space } Z, \text{ and continuous maps } g_1 : Z \rightarrow X_1 \text{ and } g_2 : Z \rightarrow X_2 \text{ satisfying } f_1 \circ g_1 = f_2 \circ g_2, \text{ there is a unique continuous map } g : Z \rightarrow X \times_Z Y \text{ such that}$$



$$p_1 \circ g = g_1 \text{ and } p_2 \circ g = g_2.$$



Prove the following.

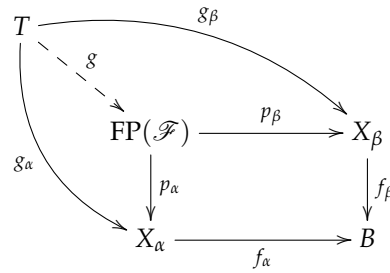
- (a) The fiber product  $X_1 \times_Y X_2$  exists and is unique up to a unique homeomorphism. (*Hint:  $X^I \times^I X^J := \{(x^I, x^J) \in X^I \times X^J : \downarrow^I(x^I) = \downarrow^J(x^J)\}$ .*)
- (b) If  $X_2 \subseteq Y$  and  $f_2 : X_2 \hookrightarrow Y$  is the inclusion map, show that  $f_1^{-1}(X_2)$  is homeomorphic to the fiber product  $X_1 \times_Y X_2$ . (*Hint: Verify properties (i) and (ii) for  $f_1^{-1}(X_2)$ .*)

**Exercise 2.2.11** (Fiber product of arbitrary family). Fix a base topological space  $B$ , and let

$$\mathcal{F} = \{f_\alpha : X_\alpha \rightarrow B : \alpha \in \Lambda\}$$

be an indexed family of continuous maps of topological spaces. The *fiber product* of  $\mathcal{F}$  is a pair  $(\text{FP}(\mathcal{F}), (p_\alpha)_{\alpha \in \Lambda})$  consisting of a topological space  $\text{FP}(\mathcal{F})$  and a continuous map  $p_\alpha : \text{FP}(\mathcal{F}) \rightarrow X_\alpha$ , for each  $\alpha \in \Lambda$  satisfying the following universal property:

- Given any topological space  $T$  and a family of continuous maps  $\{g_\alpha : T \rightarrow X_\alpha\}_{\alpha \in \Lambda}$ , there exists a unique continuous map  $g : T \rightarrow \text{FP}(\mathcal{F})$  such that  $p_\alpha \circ g = g_\alpha$ , for all  $\alpha \in \Lambda$ .



Show that the fiber product of a family of topological spaces exists, and is unique upto a unique homeomorphism making the above diagram commutative.

## 2.3 Quotient space

Let's recall the notion of quotients from algebra course. Let  $G$  be a group and  $H$  a normal subgroup of  $G$ . Then we have a relation  $\sim$  on  $G$  defined by

$$g_1 \sim g_2 \text{ if } g_1^{-1}g_2 \in H.$$

Clearly this is an equivalence relation on  $G$ , and we have a partition of  $G$  into a disjoint union of its subsets (equivalence classes)

$$G = \bigcup_{g \in G} gH,$$

where  $gH = \{g' \in G : g \sim g'\}$  is the equivalence class of  $g$  in  $G$ , for all  $g \in G$ .

Now question is does there exists a pair  $(Q, q)$  consisting of a group  $Q$  and a map  $q : G \rightarrow Q$  such that

(QG1)  $q : G \rightarrow Q$  is a surjective group homomorphism satisfying  $q(g) = q(g')$  whenever  $g \sim g'$ , and

(QG2) given any group  $G'$  and a group homomorphism  $f : G \rightarrow G'$  with  $H \subseteq \text{Ker}(f)$ , there should exists a unique group homomorphism  $\tilde{f} : Q \rightarrow G'$  such that  $\tilde{f} \circ q = f$ ?

$$\begin{array}{ccc} G & \xrightarrow{f} & G' \\ q \downarrow & \nearrow \tilde{f} & \\ Q & & \end{array} \quad (2.3.1)$$

Interesting point is that, without knowing existence of such a pair  $(Q, q)$ , it follows immediately from the properties (QG1) and (QG2) that such a pair  $(Q, q)$ , if it exists, must be unique up to a unique isomorphism of groups in the sense that, **given another such pair  $(Q', q')$  satisfying the above two conditions, there is a unique group isomorphism  $\phi : Q \rightarrow Q'$  such that  $\phi \circ q = q'$** .

**Exercise 2.3.2.** Prove the above mentioned **uniqueness statement**.

Now question is about its existence. The condition (QG1) suggests that the elements of  $Q$  should be the fibers of the map  $q$ , which are nothing but the  $\sim$ -equivalence classes

$$[g]_{\sim} = \{g' \in G : g' \sim g\} = gH, \quad \forall g \in G.$$

This suggests us to consider  $\{gH : g \in G\}$  as a possible candidate for the set  $Q$ . Now question is what should be the appropriate group structure on it? Take any group homomorphism  $f : G \rightarrow G'$  such that  $H \subseteq \text{Ker}(f)$ . This says that  $f(g_1) = f(g_2)$  if  $g_1 \sim g_2$  (equivalently,  $g_1^{-1}g_2 \in H$ ). The commutativity of the diagram (2.3.1) tells us to send  $gH \in Q$  to  $f(g) \in G'$  to define the map  $\tilde{f} : Q \rightarrow G'$  (note that this is well-defined!), and since we want  $\tilde{f} : Q \rightarrow G'$  to be a group homomorphism, we should define a binary operation on  $Q = \{gH : g \in G\}$  in such a way that  $(g_1H) * (g_2H) \xrightarrow{\tilde{f}} f(g_1)f(g_2) = f(g_1g_2)$ , for all  $g_1, g_2 \in G$ . So the obvious choice is to define

$$(g_1H) * (g_2H) := (g_1g_2)H, \quad \forall g_1, g_2 \in G. \quad (2.3.3)$$

Clearly this is a well-defined binary operation on  $Q = \{gH : g \in G\}$ , since  $H$  is normal.

**Exercise 2.3.4.** Verify that (2.3.3) makes  $Q$  a group such that the pair  $(Q, q)$  satisfies the condition (QG1) and (QG2).

**Exercise 2.3.5.** Verify analogous stories for the cases rings and vector spaces.

We are going to witness the same phenomenon in topology! Let  $X$  be a topological space.

**Definition 2.3.6.** Given an equivalence relation  $\sim$  on  $X$ , the associated *quotient topological space* (or, *identification space*)  $X/\sim$  is a pair  $(Q, q)$  consisting of a topological space  $Q$  and a continuous map  $q : X \rightarrow Q$  such that

- (QT1)  $q$  is surjective and satisfies  $q(x) = q(x')$  whenever  $x \sim x'$  in  $(X, \sim)$ ; and
- (QT2) given any topological space  $Y$  and a continuous map  $f : X \rightarrow Y$  satisfying  $f(x) = f(x')$  whenever  $x \sim x'$  in  $(X, \sim)$ , there is a unique continuous map  $\tilde{f} : Q \rightarrow Y$  such that  $\tilde{f} \circ q = f$ .

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ q \downarrow & \nearrow \tilde{f} & \\ Q & & \end{array}$$

The map  $q$  is called the *quotient map* (or, *identification map*) for  $(X, \sim)$ .

As an immediate corollary to the Definition 2.3.6, we have the following.

**Corollary 2.3.7.** If  $(Q, q)$  is a quotient space for  $(X, \sim)$ , then the topology on  $Q$  is the largest topology on the set  $Q$  such that the map  $q : X \rightarrow Q$  is continuous.

*Proof.* By a topology on a set  $S$  we mean a collection  $\tau$  of subsets of  $S$  that satisfies axioms for open subsets in  $S$ . Suppose on the contrary that the statement in Corollary 2.3.7 is false. Then there is a topology  $\tau'$  on the set  $Q$  finer than the quotient topology on  $Q$  such that the set map  $q : X \rightarrow Q' := (Q, \tau')$  is continuous. Then by property (QT2) of  $(Q, q)$  in Definition 2.3.6, there is a unique (continuous) map  $f : Q \rightarrow Q'$  such that  $f \circ q = q$ . Since  $q : X \rightarrow Q$  is surjective, it admits a right inverse (set theoretically). This forces  $f : Q \rightarrow Q'$  to be the identity map. This is not possible because  $f$  is continuous and the topology on  $Q'$  is finer than that of  $Q$  by our assumption (see Corollary 2.2.2). Hence the result follows.  $\square$

**Remark 2.3.8.** In Definition 2.3.6, the first condition suggests what should be the underlying set of points of  $Q$  and the map  $q : X \rightarrow Q$ , and the second condition suggests what should be the topology on the set  $Q$ .

**Theorem 2.3.9.** Given a topological space  $X$  and an equivalence relation  $\sim$  on  $X$ , the associated quotient space  $(Q, q)$  for  $(X, \sim)$  exists, and is *unique up to a unique homeomorphism* (i.e., if  $(Q, q)$  and  $(Q', q')$  are two quotient spaces for  $(X, \sim)$ , then there is a unique homeomorphism  $\varphi : Q \rightarrow Q'$  such that  $\varphi \circ q = q'$ ).

*Proof.* We first prove uniqueness of the pair  $(Q, q)$ , up to a unique homeomorphism. Let  $(Q', q')$  be another quotient space for the pair  $(X, \sim)$ . Since  $q'$  is continuous and  $q'(x) = q'(y)$  whenever  $x \sim y$  in  $(X, \sim)$ , we have a unique continuous map  $\tilde{q} : Q' \rightarrow Q$  such that  $\tilde{q} \circ q' = q$ .

$$\begin{array}{ccccc} & & X & & \\ & q' \swarrow & \downarrow q & \searrow q' & \\ Q' & \xleftarrow{\tilde{q}} & Q & \xrightarrow{\tilde{q}'} & Q' \end{array} \quad (2.3.10)$$

Similarly, interchanging the role of  $(Q, q)$  and  $(Q', q')$  we get a unique continuous map  $\tilde{q}' : Q \rightarrow Q'$  such that  $\tilde{q}' \circ q = q'$ . Then we have  $(\tilde{q}' \circ \tilde{q}) \circ q' = q'$ . Since the identity map  $\text{Id}_{Q'} : Q' \rightarrow Q'$  is continuous and satisfies  $\text{Id}_{Q'} \circ q' = q'$ , we must have  $\tilde{q}' \circ \tilde{q} = \text{Id}_{Q'}$ . Similarly, we have  $\tilde{q} \circ \tilde{q}' = \text{Id}_Q$ . Therefore, both  $\tilde{q}$  and  $\tilde{q}'$  are homeomorphisms. Thus the pair  $(Q, q)$  is unique, up to a unique homeomorphism.

Now (following Remark 2.3.8) we give an explicit construction of  $(Q, \sim)$ . For each  $x \in X$ , the *equivalence class* of  $x$  in  $(X, \sim)$  is the subset

$$[x] := \{x' \in X : x \sim x'\} \subseteq X.$$

Let  $Q$  be the set of all distinct equivalence classes of elements of  $X$ . Consider the map  $q : X \rightarrow Q$  defined by sending each point  $x \in X$  to its equivalence class  $[x] \in Q$ . Note that, the map  $q$  is surjective. As suggested in Corollary 2.3.7, we define a topology on  $Q$  by declaring a subset  $U \subseteq Q$  to be *open* if its inverse image  $q^{-1}(U) \subseteq X$  is open in  $X$ . Clearly this makes  $q : X \rightarrow Q$  continuous. It remains to check property (QT2) as in Definition 2.3.6. Let  $Y$  be any topological space and  $f : X \rightarrow Y$  any continuous map satisfying  $f(x) = f(x')$  for  $x \sim x'$  in  $(X, \sim)$ . Define a map  $\tilde{f} : Q \rightarrow Y$  by  $\tilde{f}([x]) = f(x)$ , for all  $[x] \in Q$ . Clearly  $\tilde{f}$  is well-defined, and by its construction it satisfies

$$\tilde{f} \circ q = f. \quad (2.3.11)$$

Since  $f$  is continuous, for any open subset  $V \subseteq Y$ , the subset

$$q^{-1}(\tilde{f}^{-1}(V)) = (\tilde{f} \circ q)^{-1}(V) = f^{-1}(V)$$

is open in  $X$ , and hence  $\tilde{f}^{-1}(V)$  is open in  $Q$  by definition of the topology on  $Q$ . Therefore,  $\tilde{f}$  is continuous. If  $g : Q \rightarrow Y$  is any continuous map satisfying  $g \circ q = f$ , then  $g([x]) = (g \circ q)(x) = f(x)$ , for all  $[x] \in Q$ , and hence  $g = \tilde{f}$ .  $\square$

**Theorem 2.3.12.** *Let  $X$  and  $Y$  be topological spaces, and let  $p : X \rightarrow Y$  be a surjective continuous map. Then the following are equivalent.*

- (i) *The pair  $(Y, p)$  is a quotient space for some equivalence relation  $\sim$  on  $X$ .*
- (ii) *A subset  $U \subseteq Y$  is open in  $Y$  if and only if  $p^{-1}(U)$  is open in  $X$ .*
- (iii) *A subset  $Z \subseteq Y$  is closed in  $Y$  if and only if  $p^{-1}(Z)$  is closed in  $X$ .*

*Proof.* (i)  $\Rightarrow$  (ii) and (i)  $\Rightarrow$  (iii): Follow from Corollary 2.3.7.

We show (ii)  $\Rightarrow$  (i) and (iii)  $\Rightarrow$  (i) together. Consider the relation  $\sim$  on  $X$  defined by

$$x_1 \sim x_2 \text{ in } X, \text{ if } p(x_1) = p(x_2).$$

It is easy to see that  $\sim$  is an equivalence relation on  $X$ . Clearly  $p(x) = p(x')$  whenever  $x \sim x'$  in  $X$ . Let  $T$  be a topological space and let  $f : X \rightarrow T$  be a continuous map such that  $f(x) = f(x')$  if  $x \sim x'$  in  $X$ . Since  $p : X \rightarrow Y$  is surjective, for each  $y \in Y$  we can choose a point  $x_y \in p^{-1}(y) \subseteq X$  by axiom of choice. Since  $f(x) = f(x')$  for all  $x, x' \in p^{-1}(y)$ , we get a well-defined map

$\tilde{f} : Y \rightarrow T$  defined by

$$\tilde{f}(y) = f(x_y), \forall y \in Y.$$

$$\begin{array}{ccc} X & \xrightarrow{f} & T \\ p \downarrow & \nearrow \tilde{f} & \\ Y & & \end{array}$$

Clearly  $\tilde{f} \circ p = f$ . Let  $V \subseteq T$  be an open (resp., closed) subset of  $T$ . Since  $f$  is continuous,  $p^{-1}(\tilde{f}^{-1}(V)) = f^{-1}(V)$  is open (resp., closed) in  $X$ . Then it follows from the assumption (ii) (resp., (iii)) that  $\tilde{f}^{-1}(V)$  is open (resp., closed) in  $Y$ . Therefore,  $\tilde{f} : Y \rightarrow T$  is continuous. If  $g : Y \rightarrow T$  is any continuous map such that  $g \circ p = f$ , then  $g(p(x)) = f(x)$ ,  $\forall x \in X$  gives  $g(y) = \tilde{f}(y)$ , for all  $y \in Y$ . Therefore,  $\tilde{f}$  is the unique continuous map such that  $\tilde{f} \circ p = f$ . Thus  $(Y, p)$  is the quotient space of  $X$  by the equivalence relation  $\sim$  on  $X$  (see Definition 2.3.6).  $\square$

**Remark 2.3.13.** It follows from construction of quotient space in Theorem 2.3.9, and the proof of Theorem 2.3.12 that if  $f : X \rightarrow Y$  is a quotient map then the set of all fibers  $\{f^{-1}(y) : y \in Y\}$  of  $f$  gives a partition of  $X$ , and hence defines an equivalence relation  $\sim$  on  $X$  such that the associated quotient space  $X/\sim$  is homeomorphic to  $(Y, f)$ .

**Definition 2.3.14.** A map  $f : X \rightarrow Y$  is said to be *open* (resp., *closed*) if  $f(U)$  is open (resp., closed) in  $Y$  for any open (resp., closed) subset  $U$  of  $X$ .

**Exercise 2.3.15.** Let  $f_1 : X_1 \rightarrow Y_1$  and  $f_2 : X_2 \rightarrow Y_2$  be two open maps of topological spaces. Show that the product map  $f_1 \times f_2 : X_1 \times X_2 \rightarrow Y_1 \times Y_2$  defined by

$$(f_1 \times f_2)(x_1, x_2) = (f_1(x_1), f_2(x_2)), \forall (x_1, x_2) \in X_1 \times X_2,$$

is an open map.

**Corollary 2.3.16.** A surjective continuous open (or, closed) map is a quotient map.

*Proof.* Let  $f : X \rightarrow Y$  be a surjective map. Then for any  $V \subseteq Y$  we have  $f(f^{-1}(V)) = V$ . Suppose that  $f$  is also continuous and open (resp., closed). Then for any  $V \subseteq Y$  with  $f^{-1}(V)$  open (resp., closed) in  $X$ ,  $V = f(f^{-1}(V))$  is open (resp., closed) in  $Y$ . Hence the result follows from Theorem 2.3.12.  $\square$

**Remark 2.3.17.** Corollary 2.3.16 fails without continuity assumption on  $f$ . For example, take a set  $X$  with at least two elements. Let  $\tau_0$  and  $\tau_1$  be the trivial topology and the discrete topology on  $X$ , respectively. Then the identity map  $\text{Id}_X : (X, \tau_0) \rightarrow (X, \tau_1)$  is a surjective open map, which is not continuous let alone be a quotient map.

**Exercise 2.3.18.** Let  $q : X \rightarrow Q$  be a quotient map, and let  $Z \subseteq Q$ . Show by an example that the restriction map  $q|_{q^{-1}(Z)} : q^{-1}(Z) \rightarrow Z$  need not be a quotient map, in general. If  $Z$  is open or  $q$  is an open map, show that the above restriction map become a quotient map.

**Corollary 2.3.19.** Let  $f : X \rightarrow Y$  be a continuous surjective map. If  $X$  is compact and  $Y$  is Hausdorff, then  $f$  is a quotient map.

*Proof.* Let  $Z$  be a closed subset of  $X$ . Since  $X$  is compact,  $Z$  is compact. Since  $f$  is continuous,  $f(Z)$  is a compact subset of  $Y$ . Since  $Y$  is Hausdorff,  $f(Z)$  is closed in  $Y$ . Hence the result follows from Corollary 2.3.16.  $\square$

**Proposition 2.3.20.** *Let  $\sim$  be an equivalence relation on a topological space  $X$ , and let  $(Q, q)$  be the associated quotient space. Given a topological space  $Y$ , a map  $\phi : Q \rightarrow Y$  is continuous if and only if the composite map  $\phi \circ q : X \rightarrow Y$  is continuous.*

$$\begin{array}{ccc} X & \xrightarrow{\phi \circ q} & Y \\ q \downarrow & \nearrow \phi & \\ Q & & \end{array}$$

*Proof.* Since the quotient map  $q$  is continuous, the composite map  $\phi \circ q$  is continuous whenever  $\phi$  is continuous. Conversely, let  $\phi \circ q$  be continuous. Since for any open subset  $V \subseteq Y$ , we have  $q^{-1}(\phi^{-1}(V)) = (\phi \circ q)^{-1}(V)$  is open in  $X$ , by construction of topology of  $Q$ , the subset  $\phi^{-1}(V)$  is open in  $Q$ . Thus  $\phi$  is continuous.  $\square$

**Example 2.3.21.** (i) **Circle:** Let  $I = [0, 1] \subset \mathbb{R}$  be the unit closed interval in  $\mathbb{R}$ . Define a map

$$f : [0, 1] \rightarrow S^1 := \{(x, y) \in \mathbb{R}^2 : x^2 + y^2 = 1\}$$

by

$$f(t) = (\cos 2\pi t, \sin 2\pi t), \quad \forall t \in [0, 1].$$

Clearly  $f$  is a surjective continuous map. Since  $[0, 1]$  is compact and  $S^1$  is Hausdorff, it follows from Corollary 2.3.19 that  $f : I \rightarrow S^1$  is a quotient map. Note that  $f^{-1}(1, 0) = \{0, 1\}$  and  $f^{-1}(x, y)$  is singleton for  $(x, y) \in S^1 \setminus \{(1, 0)\}$ . Therefore,  $S^1$  is the quotient space of  $[0, 1]$  for the equivalence relation on  $[0, 1]$  which only identifies the end points of  $[0, 1]$  to a single point.

(ii) **Cylinder:** Let  $I = [0, 1] \subset \mathbb{R}$ . Consider the unit square

$$I \times I = \{(x, y) \in \mathbb{R}^2 : 0 \leq x, y \leq 1\}$$

in  $\mathbb{R}^2$ . Define an equivalence relation  $\sim_1$  on  $I \times I$  by setting

$$(x, y) \sim_1 (x', y'), \quad \text{if } x' = x + 1 = 1 \text{ and } y = y'.$$

This identifies points of two vertical sides of  $I \times I$  (see Figure 2.1 below), and the associated quotient space  $(I \times I)/\sim_1$  is homeomorphic to the cylinder

$$S^1 \times [0, 1] = \{(x, y, z) \in \mathbb{R}^3 : x^2 + y^2 = 1, 0 \leq z \leq 1\}.$$

Indeed, we can define a (continuous) map

$$\phi : I \times I \rightarrow S^1 \times [0, 1]$$

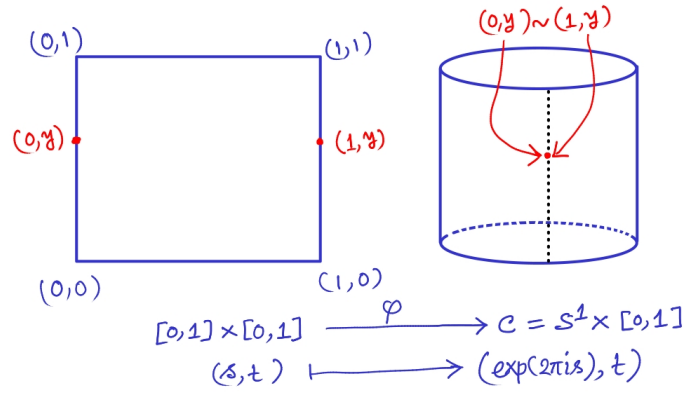


FIGURE 2.1

by  $\phi(s, t) = (\exp(2\pi is), t)$ , for all  $(s, t) \in I \times I$ . Then the set  $\{\phi^{-1}(z, t) : (z, t) \in S^1 \times [0, 1]\}$  of all fibers of  $\phi$  is precisely the partition of  $I \times I$  given by the equivalence relation  $\sim_1$  on  $I \times I$ . It follows from Corollary 2.3.19 that  $\phi$  is a quotient map, and by Remark 2.3.13 the associated quotient space  $(I \times I)/\sim$  is homeomorphic to  $S^1 \times I$ .

(iii) **Torus:** Consider an equivalence relation  $\sim_2$  on the cylinder  $S^1 \times I$  defined by

$$(z, t) \sim_2 (z', t') \text{ if } z = z', \text{ and } t' = t + 1 = 1.$$

This identifies each point of the bottom circle of  $S^1 \times I$  with the corresponding point of the top circle on  $S^1 \times I$  (see Figure 2.2 below).



FIGURE 2.2

Then the associated quotient space  $(S^1 \times I)/\sim_2$  is homeomorphic to the torus  $T := S^1 \times S^1$  in  $\mathbb{R}^3$ . Indeed, we can define a (continuous) map

$$\psi : S^1 \times I \rightarrow S^1 \times S^1$$

by  $\psi(z, t) = (z, \exp(2\pi it))$ , for all  $(z, t) \in S^1 \times I$ . As before, it is easy to see that the set of all fibers of the map  $\psi$  is precisely the partition of  $S^1 \times I$  defined by the equivalence relation  $\sim_2$  on the cylinder  $S^1 \times I$ . As before, it follows from Corollary 2.3.19 that  $\psi$

is a quotient map, and by Remark 2.3.13 the associated quotient space  $(S^1 \times I)/\sim$  is homeomorphic to  $S^1 \times S^1$ .

- (iv) Define a relation  $\rho \subset \mathbb{R} \times \mathbb{R}$  on  $\mathbb{R}$  by  $(x, y) \in \rho$  if  $x - y \in \mathbb{Z}$ . Note that this is an equivalence relation on  $\mathbb{R}$ . Let  $S^1 := \{(x, y) \in \mathbb{R}^2 : x^2 + y^2 = 1\} \subset \mathbb{R}^2$ . Define a map  $f : \mathbb{R} \rightarrow S^1$  by

$$f(t) = (\cos 2\pi t, \sin 2\pi t), \quad \forall t \in \mathbb{R}.$$

Clearly  $f$  is a surjective continuous map. We show that  $f$  is an open map. For this, it suffices to show that image of an open interval  $(a, b) \subset \mathbb{R}$  is open in  $S^1$ . Let  $a, b \in \mathbb{R}$  with  $a < b$ . Since  $f(t+1) = f(t)$ ,  $\forall t \in \mathbb{R}$ , it follows that  $f((a, b)) = S^1$  if  $b - a \geq 1$ . Suppose that  $b - a < 1$ . Let  $p := (x, y) \in f((a, b))$  be arbitrary. Then  $(x, y) = (\cos 2\pi t, \sin 2\pi t)$ , for some  $t \in (a, b)$ . Taking  $r = \min\{t - a, b - t\} > 0$ , we see that  $B(p, r) \cap S^1 \subseteq f((a, b))$  (verify). Thus,  $f((a, b))$  is open in  $S^1$ , and hence  $f$  is an open map. Then by Corollary 2.3.16  $f$  is a quotient map. Since the fibers of  $f$  can be identified with  $\mathbb{Z}$  (verify!), we may denote the associated quotient space by  $\mathbb{R}/\mathbb{Z}$ . Then  $f$  induces a homeomorphism of  $\mathbb{R}/\mathbb{Z}$  onto  $S^1$ .

- (v) **Cone:** Let  $I = [0, 1] \subseteq \mathbb{R}$ . The *cone* of a topological space  $X$  is the quotient space  $CX := (X \times I)/\sim$  of  $X \times I$  for the equivalence relation  $\sim$  on  $X \times I$  defined by

$$(x, t) \sim (x', t'), \quad \text{if } t = t' = 1. \quad (2.3.22)$$

The associated set of all partitions of  $X \times I$  is the set

$$\{X \times \{1\}, \{(x, t) : x \in X, 0 \leq t < 1\}.$$

Thus we identify all points of  $X \times \{1\} \subseteq X \times I$  into a single point, called the *vertex* of the

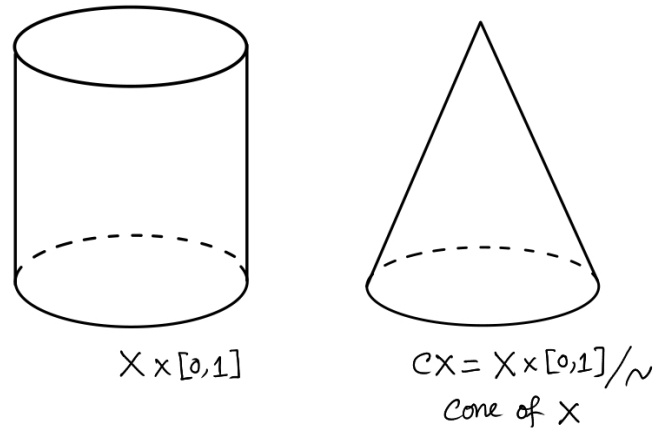


FIGURE 2.3

cone  $CX$ , and the remaining points of  $X \times [0, 1)$  remain as they are.

If  $X$  is a compact subset of an Euclidean space  $\mathbb{R}^n$ , then we can construct  $CX$  more geometrically as follows. Embed  $\mathbb{R}^n$  into  $\mathbb{R}^{n+1}$  by the map  $(x_1, \dots, x_n) \mapsto (x_1, \dots, x_n, 0)$ , and fix a point  $v \in \mathbb{R}^{n+1}$  which lies outside the image of this embedding; for example take



$v = (0, \dots, 0, 1) \in \mathbb{R}^{n+1}$ . Note that  $\ell_{[v,x]} := \{tv + (1-t)x : 0 \leq t \leq 1\} \subseteq \mathbb{R}^{n+1}$  is the straight line segment in  $\mathbb{R}^{n+1}$  joining  $v$  and  $x \in X$ . The subset

$$\bigcup_{x \in X} \ell_{[v,x]} \subseteq \mathbb{R}^{n+1}$$

with the subspace topology induced from  $\mathbb{R}^{n+1}$  is called the *geometric cone* of  $X$ . We show that the geometric cone of  $X$  is homeomorphic to the cone of  $X$ , i.e.,

$$CX \cong \bigcup_{x \in X} \ell_{[v,x]}.$$

Define a map

$$f : X \times I \rightarrow \bigcup_{x \in X} \ell_{[v,x]}$$

by  $f(x, t) = tv + (1-t)x$ , for all  $(x, t) \in X \times I$ . Clearly  $f$  is a surjective continuous map, and  $f(x, t) = f(x, t')$  if and only if either  $x = x'$  and  $t = t'$ , or  $t = t' = 1$ . Since  $X$  is compact and its image is Hausdorff (being a subspace of  $\mathbb{R}^{n+1}$ ), it follows from Corollary 2.3.19 that  $f$  is a quotient map. Since the fibers of the map  $f$  are precisely the equivalence classes for the equivalence relation on  $X \times I$  defined in (2.3.22), it follows from Remark 2.3.13 that  $CX = (X \times I) / \sim$  is homeomorphic to the geometric cone of  $X$ .

- (vi) **The space  $X/A$ :** Let  $A$  be a subset of a topological space  $X$ . Define an equivalence relation  $\sim$  on  $X$  by

$$x \sim x' \text{ if both } x \text{ and } x' \text{ are in } A.$$

We denote by  $X/A$  the associated quotient space  $X/\sim$ . Here we collapse the subspace  $A$  into a single point, and the remaining points of  $X \setminus A$  remains as they were. For example,  $CX = (X \times I) / (X \times \{1\})$ .

- (vii) **The space  $B^n / S^{n-1}$ :** Consider the closed unit ball

$$B^n := \{(x_1, \dots, x_n) \in \mathbb{R}^n : \sum_{j=1}^n x_j^2 \leq 1\}$$

in  $\mathbb{R}^n$ , and its boundary

$$\partial B^n = \{(x_1, \dots, x_n) \in \mathbb{R}^n : \sum_{j=1}^n x_j^2 = 1\} = S^{n-1}.$$

Then the associated quotient space is denoted by  $B^n / S^{n-1}$  is homeomorphic to  $S^n$ . This is quite easy to visualize for  $n = 1$  and  $2$ . For  $n = 1$ ,  $B^1 = [-1, 1] \subseteq \mathbb{R}$ , and  $S^0 = \{-1, 1\}$  is its boundary. If we identify all points of  $S^0 = \{-1, 1\}$  into a single point and keep all other points of  $B^1$  as they were, we get a circle  $S^1$  in  $\mathbb{R}^2$ ; see Figure 2.4 below.

The case  $n = 2$  is explained in the Figure 2.5 below.

In general, it suffices to construct a surjective continuous map

$$f : B^n \rightarrow S^n$$

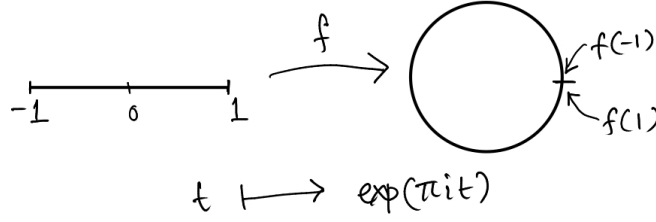


FIGURE 2.4

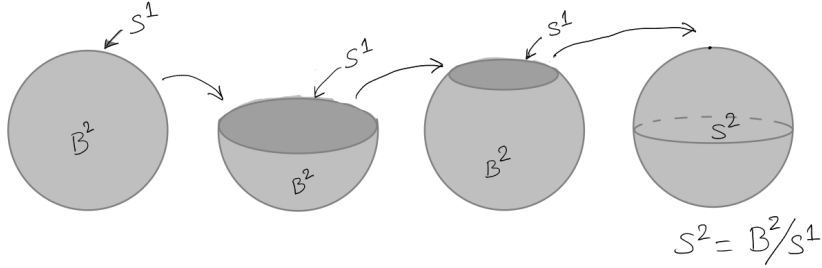


FIGURE 2.5

such that  $f|_{B^n \setminus S^{n-1}}$  is injective and  $f(S^{n-1})$  is a singleton subset of  $S^n$ . Then by Corollary 2.3.19,  $f$  becomes a quotient map producing a homeomorphism of  $B^n/S^{n-1}$  onto  $S^n$ . To construct such a map  $f$ , note that  $\mathbb{R}^n$  is homeomorphic to  $B^n \setminus S^{n-1}$  and  $S^n \setminus \{p\}$ , for any  $p \in S^n$ . Fix two homeomorphisms  $h_1 : B^n \setminus S^{n-1} \rightarrow \mathbb{R}^n$  and  $h_2 : \mathbb{R}^n \rightarrow S^n \setminus \{p\}$ , and define

$$f(x) := \begin{cases} h_2(h_1(x)), & \text{if } x \in B^n \setminus S^{n-1}, \\ p, & \text{if } x \in S^{n-1}. \end{cases} \quad (2.3.23)$$

It is easy to check that  $f$  has desired properties (verify).

**Example 2.3.24** (Attaching spaces along a map). Let  $X$  and  $Y$  be two topological spaces. Suppose we wish to attach  $X$  by identifying points of a subspace  $A \subseteq X$  with points of  $Y$  in a continuous way. This can be done by using a continuous map  $f : A \rightarrow Y$ . Indeed, we identify  $x \in A$  with its image  $f(x) \in Y$ . This defines an equivalence relation on  $X \sqcup Y$ , and we denote the associated quotient space by  $X \sqcup_f Y$ , and call it the *space  $Y$  with  $X$  attached along  $A$  via  $f$* . Let us discuss some examples.

- (i) Let  $I = [0, 1] \subset \mathbb{R}$ . Given a space  $X$ , we call  $X \times I$  the *cylinder over  $X$* . Let  $f : X \rightarrow Y$  be a continuous map of topological spaces. Then  $f$  induces a continuous map  $\tilde{f} : X \times \{0\} \rightarrow Y$  given by

$$\tilde{f}(x, 0) = f(x), \quad \forall (x, 0) \in X \times \{0\}.$$

If we attach  $Y$  with the cylinder  $X \times I$  of  $X$  along its base  $X \times \{0\} \subset X \times I$  via the map  $\tilde{f}$ , by identifying  $(x, 0) \sim f(x)$ , then the associated quotient space  $M_f = (X \times I) \sqcup_{\tilde{f}} Y$  is called the *mapping cylinder of  $f$*  (see Figure 2.6).

- (ii) Let  $CX = (X \times I)/(X \times \{1\})$  be the *cone over  $X$*  obtained by collapsing the subspace  $X \times \{1\}$  of the cylinder  $X \times I$  over  $X$  to a single point. Let  $f : X \rightarrow Y$  be a continuous map. If we attach this cone  $CX$  with  $Y$  along its base  $X \times \{0\} \subset CX$  by identifying



FIGURE 2.6: Mapping Cylinder

$(x, 0) \in X \times \{0\}$  with  $f(x) \in Y$ , then the resulting quotient space  $C_f = Y \sqcup_f CX$  is called the *mapping cone of  $f$*  (see Figure 2.7). Note that, the mapping cone  $C_f$  can also be obtained



FIGURE 2.7: Mapping Cone

as a quotient space of the mapping cylinder  $M_f$  by collapsing  $X \times \{1\} \subset M_f$  to a point.

- (iii) Let  $X$  be a topological space. The *suspension*  $SX$  of  $X$  is the quotient space of  $X \times I$  obtained by collapsing  $X \times \{0\}$  to one point and  $X \times \{1\}$  to another point.



FIGURE 2.8: Suspension

For example, if we take  $X$  to be the unit circle  $S^1 = \{(x, y) \in \mathbb{R}^2 : x^2 + y^2 = 1\}$ , then  $X \times I$  is a cylinder  $C = \{(x, y, z) \in \mathbb{R}^3 : x^2 + y^2 = 1, 0 \leq z \leq 1\}$ , and then we collapse two circular edges of  $C$  to two points to get  $SX$ , which is homeomorphic to the 2-sphere  $S^2 = \{(x, y, z) \in \mathbb{R}^3 : x^2 + y^2 + z^2 = 1\}$ .

We can think of  $SX$  as a *double cone on  $X$* : take disjoint union of two cones  $C_1 := (X \times I)/(X \times \{1\})$  and  $C_2 := (X \times I)/(X \times \{0\})$ , and then attach  $C_1$  with  $C_2$  via the continuous map  $f : X \times \{0\} \rightarrow C_2$  given by  $f(x, 0) = (x, 0) \in C_2$ ,  $\forall (x, 0) \in X \times \{0\} \subset C_1$ .

The following exercise shows that a quotient of a Hausdorff space need not be Hausdorff in general.

**Exercise 2.3.25.** Consider the double real line  $X = \mathbb{R} \times \{0, 1\} \subset \mathbb{R}^2$ , and the equivalence relation  $\sim$  on  $X$  defined by  $(t, 0) \sim (t, 1)$ , for all  $t \in \mathbb{R} \setminus \{0\}$ . The associated quotient space  $X/\sim$  is called the *real line with double origin*. Show that  $X/\sim$  is not Hausdorff.

**Proposition 2.3.26.** Let  $\rho \subseteq X \times X$  be an equivalence relation on a topological space  $X$ , and let  $q : X \rightarrow Q := X/\rho$  be the quotient map. Then we have the following.

- (i)  $Q$  is a T1 space if and only if every  $\rho$ -equivalence class is closed in  $X$ .
- (ii) If  $Q$  is Hausdorff then  $\rho$  is a closed subspace of the product space  $X \times X$ . The converse holds if  $q : X \rightarrow Q$  is an open map.

*Proof.* (i) Let  $Q$  be T1. Let  $x \in X$ . Choose a  $y \in X \setminus [x]$ . Then  $[x] \neq [y]$  in  $Q$ . Since  $Q$  is T1, there is an open subset  $V_y \subseteq Q$  such that  $[y] \in V_y$  and  $[x] \notin V_y$ . Then  $q^{-1}(V_y)$  is an open neighbourhood of  $y$  with  $q^{-1}(V_y) \cap [x] = \emptyset$ . Therefore,  $y$  is an interior point of  $X \setminus [x]$ . Therefore,  $X \setminus [x]$  is open, and hence  $[x] \subseteq X$  is closed.

Conversely, suppose that  $[x] \subseteq X$  is closed, for all  $x \in X$ . To show  $Q$  is T1, we need to show that  $\{[x]\}$  is closed in  $Q$ , for all  $x \in X$ . Since  $q^{-1}(Q \setminus \{[x]\}) = \{y \in X : q(y) \neq [x]\} = X \setminus [x]$  is open,  $Q \setminus \{[x]\}$  is open in  $Q$ , for all  $[x] \in Q$ . Therefore,  $Q$  is a T1 space.

- (ii) Consider the commutative diagram of continuous maps

$$\begin{array}{ccc} X & \xrightarrow{q} & Q \\ \Delta_X \downarrow & & \downarrow \Delta_Q \\ X \times X & \xrightarrow{q \times q} & Q \times Q, \end{array}$$

where  $q \times q : X \times X \rightarrow Q \times Q$  is the product map given by

$$(q \times q)(x, y) = (q(x), q(y)), \quad \forall (x, y) \in X \times X.$$

Note that,  $(q \times q)^{-1}(\Delta_Q(Q)) = \{(x, y) \in X \times X : q(x) = q(y)\} = \rho$ . If  $Q$  is Hausdorff, then  $\Delta_Q(Q)$  is closed by Lemma 2.2.4. Since  $q \times q$  is continuous,  $\rho$  is closed in  $X \times X$ .

Now we assume that  $q$  is an open map, and that  $\rho$  is closed in  $X \times X$ . Since  $q \times q$  is a continuous surjective open map (verify!), it is a quotient map by Corollary 2.3.16. Since  $(q \times q)^{-1}(\Delta_Q(Q)) = \rho$  is closed in  $X \times X$ , the diagonal  $\Delta_Q(Q)$  is closed in  $Q \times Q$  by Theorem 2.3.12 (iii). Therefore,  $Q$  is Hausdorff by Lemma 2.2.4.

□

Now we give an example to show that even if  $X$  is Hausdorff and the equivalence relation  $\rho$  is closed in  $X \times X$ , the associated quotient space  $Q = X/\rho$  need not be Hausdorff without the assumption that  $q$  is an open map. For this, we first recall the following.

**Definition 2.3.27.** A topological space  $X$  is said to be *normal* if any two disjoint closed subsets can be separated by a pair of disjoint open subsets containing them. In other words, given two closed subsets  $A, B \subset X$  with  $A \cap B = \emptyset$ , there are open subsets  $U, V \subset X$  such that  $A \subset U$ ,  $B \subset V$  and  $U \cap V = \emptyset$ .

Most of the familiar examples of topological spaces are generally normal (e.g.,  $\mathbb{R}^n$ ), and a closed subspace of a normal space is normal. The following example shows that a Hausdorff space need not be normal.

**Example 2.3.28.** Let  $K = \{\frac{1}{n} : n \in \mathbb{Z}^+\}$ . Consider the topology  $\tau_K$  on  $\mathbb{R}$  whose basis for open subsets is given by the collection

$$\mathcal{B} = \{(a, b) : a, b \in \mathbb{R} \text{ with } a < b\} \cup \{(a, b) \setminus K : a, b \in \mathbb{R} \text{ with } a < b\}.$$

Clearly this topology on  $\mathbb{R}$  is strictly finer than the Euclidean topology on  $\mathbb{R}$ , and hence  $(\mathbb{R}, \tau_K)$  is a Hausdorff space. Note that in this topology,  $K$  and  $\{0\}$  are disjoint closed subsets that cannot be separated by a pair of disjoint open subsets containing them. Therefore,  $(\mathbb{R}, \tau_K)$  is not normal.

**Exercise 2.3.29.** Start with a Hausdorff space  $X$  that is not normal. Choose two disjoint closed subsets  $A, B \subset X$  that cannot be separated by two disjoint open subsets containing them. Take  $\rho = \Delta_X(X) \cup (A \times A) \cup (B \times B)$ . Note that  $\rho$  is an equivalence relation on  $X$ , and is closed in  $X \times X$  (why?). Show that the associated quotient space  $X/\rho$  is T1 but not Hausdorff.

## 2.4 Projective space and Grassmannian

### 2.4.1 Real and complex projective spaces

Fix an integer  $n \geq 0$ . Define an equivalence relation  $\sim$  on  $\mathbb{R}^{n+1} \setminus \{0\}$  by

$$v \sim v' \text{ if } v' = \lambda \cdot v, \text{ for some } \lambda \in \mathbb{R} \setminus \{0\}. \quad (2.4.1)$$

In other words, identify all points lying on the same straight-line in  $\mathbb{R}^{n+1}$  passing through the origin  $0 \in \mathbb{R}^{n+1}$ . Then the associated quotient space

$$\mathbb{RP}^n := (\mathbb{R}^{n+1} \setminus \{0\}) / \sim$$

is called the *real projective  $n$ -space*. As a set,  $\mathbb{RP}^n$  consists of all straight-lines in  $\mathbb{R}^{n+1}$  passing through the origin  $0 \in \mathbb{R}^{n+1}$ . So an element of  $\mathbb{RP}^n$  is of the form

$$[a_0 : \cdots : a_n] := \{\lambda \cdot (a_0, \dots, a_n) \in \mathbb{R}^{n+1} \setminus \{0\} : \lambda \in \mathbb{R} \setminus \{0\}\}. \quad (2.4.2)$$

Let  $q : \mathbb{R}^{n+1} \setminus \{0\} \rightarrow \mathbb{RP}^n$  be the quotient map for the projective  $n$ -space. Note that the unit  $n$ -sphere  $S^n = \{(a_0, \dots, a_n) \in \mathbb{R}^{n+1} : \sum_{j=0}^n a_j^2 = 1\}$  is a compact connected subspace of  $\mathbb{R}^{n+1} \setminus \{0\}$ . Since the restriction map  $q|_{S^n} : S^n \rightarrow \mathbb{RP}^n$  is continuous and surjective,  $\mathbb{RP}^n$  is compact and connected.

**Exercise 2.4.3.** Prove the following.

- (i) Show that the map  $f := q|_{S^n} : S^n \rightarrow \mathbb{RP}^n$  is a quotient map.
- (ii) For each  $\ell \in \mathbb{RP}^n$ , show that  $f^{-1}(\ell) = \{v, -v\}$ , for some  $v \in S^n$ .
- (iii) Show that  $\mathbb{RP}^n$  is Hausdorff.

*Outline of solution.* Note that, the quotient map  $q : \mathbb{R}^{n+1} \setminus \{0\} \rightarrow \mathbb{RP}^n$  is given by sending  $(a_0, \dots, a_n) \in \mathbb{R}^{n+1} \setminus \{0\}$  to the straight line

$$[a_0 : \dots : a_n] := \{\lambda(a_0, \dots, a_n) : \lambda \in \mathbb{R}\} \in \mathbb{RP}^n.$$

Since  $\mathbb{RP}^n$  consists of all straight lines in  $\mathbb{R}^{n+1}$  passing through the origin, given a straight-line  $\ell \in \mathbb{RP}^n$ , choosing any non-zero point  $v := (a_0, \dots, a_n) \in \ell$ , we find an element  $v/\|v\| \in S^n$  with  $f(v/\|v\|) = \ell$ , where  $\|v\| := (\sum_{j=1}^n a_j^2)^{1/2}$ . Thus,  $f$  is surjective.

$$f : S^n \xrightarrow{\iota} \mathbb{R}^{n+1} \setminus \{0\} \xrightarrow{q} \mathbb{RP}^n.$$

Note that given any subset  $V \subseteq \mathbb{RP}^n$ , we have  $f^{-1}(V) = q^{-1}(V) \cap S^n$ . So continuity of  $f$  follows from that of  $q$ . To see that  $f$  is a quotient map, suppose that  $f^{-1}(V)$  is open in  $S^n$ . To show that  $V$  is open in  $\mathbb{RP}^n$ , fix a point  $\ell \in V$ . Its fiber  $f^{-1}(\ell) = \{v, -v\}$  consists of the two antipodal points of  $S^n$  obtained by intersecting the line  $\ell$  with  $S^n$ . Since the points  $v$  and  $-v$  lies on two hemispheres separated by a great circle on  $S^n$ , we can find a small enough (connected) open neighbourhood  $U \subset f^{-1}(V)$  of  $v$  such that  $-U := \{-u : u \in U\} \subset S^n$  is an open neighbourhood of  $-v$  in  $S^n$ , and  $U \cap (-U) = \emptyset$ . Note that,  $-U \subseteq f^{-1}(V)$ . Then  $f|_U$  is a homeomorphism of  $U$  onto the open neighbourhood  $f(U) \subseteq V$  of  $\ell$  in  $\mathbb{RP}^n$ . Thus  $f$  is a quotient map.  $\square$

Next we show that  $\mathbb{RP}^n$  can be covered by  $n+1$  open subsets each homeomorphic to  $\mathbb{R}^n$ . Let  $p_j : \mathbb{R}^{n+1} \rightarrow \mathbb{R}$  be the  $j$ -th projection map defined by

$$p_j(x_0, \dots, x_n) = x_j, \quad \forall (x_0, \dots, x_n) \in \mathbb{R}^{n+1}.$$

For each  $j \in \{0, 1, \dots, n\}$ , consider the *hyperplane*

$$H_j := \{[a_0 : \dots : a_n] \in \mathbb{RP}^n : a_j = 0\} \subset \mathbb{RP}^n.$$

Since  $q$  is a quotient map and

$$\begin{aligned} q^{-1}(H_j) &= \{(a_0, \dots, a_n) \in \mathbb{R}^{n+1} \setminus \{0\} : a_j = 0\} \\ &= p_j^{-1}(0) \cap (\mathbb{R}^{n+1} \setminus \{0\}), \end{aligned}$$

we conclude that  $H_j$  is a closed subset of  $\mathbb{RP}^n$ . Let  $U_j := \mathbb{RP}^n \setminus H_j, \forall j = 0, 1, \dots, n$ . Since any point of  $\mathbb{RP}^n$  is of the form

$$[a_0 : \dots : a_n] := \{\lambda(a_0, \dots, a_n) \in \mathbb{R}^{n+1} \setminus \{0\} : \lambda \in \mathbb{R}\},$$

with  $a_j \neq 0$ , for some  $j$ , we see that  $\{U_0, U_1, \dots, U_n\}$  is an open cover of  $\mathbb{RP}^n$ .

**Proposition 2.4.4.** *The open subset  $U_j \subset \mathbb{RP}^n$  is homeomorphic to  $\mathbb{R}^n$ , for all  $j$ .*

*Proof.* Consider the map  $\phi_j : U_j \rightarrow \mathbb{R}^n$  given by

$$[a_0 : \dots : a_n] \mapsto \left( \frac{a_0}{a_j}, \dots, \frac{a_{j-1}}{a_j}, \frac{a_{j+1}}{a_j}, \dots, \frac{a_n}{a_j} \right).$$

Note that  $\phi_j$  is a well-defined bijective map with its inverse  $\psi_j : \mathbb{R}^n \rightarrow U_j$  given by

$$(b_0, \dots, b_{n-1}) \mapsto [b_0 : \dots : b_{j-1} : 1 : b_j : \dots : b_n].$$

Note that  $V_j = q^{-1}(U_j) = \{(a_0, \dots, a_n) \in \mathbb{R}^{n+1} : a_j \neq 0\}$  is open in  $\mathbb{R}^{n+1} \setminus \{0\}$ , and the map  $f_j : V_j \rightarrow \mathbb{R}^n$  given by  $(a_0, \dots, a_n) \mapsto \left( \frac{a_0}{a_j}, \dots, \frac{a_{j-1}}{a_j}, \frac{a_{j+1}}{a_j}, \dots, \frac{a_n}{a_j} \right)$  is continuous (why?). Since  $q^{-1}(\phi_j^{-1}(V)) = f_j^{-1}(V)$ ,  $\forall V \subseteq \mathbb{R}^n$ , and  $q$  is a quotient map, we conclude that  $\phi_j$  is continuous, for all  $j$  (c.f. Proposition 2.3.20).

$$\begin{array}{ccccc} \mathbb{R}^{n+1} \setminus \{0\} & \xleftarrow{\quad} & V_j & \xrightarrow{f_j} & \mathbb{R}^n \\ q \downarrow & & q_j \downarrow & \nearrow \phi_j & \\ \mathbb{RP}^n & \xleftarrow{\quad} & U_j & \xleftarrow{\psi_j} & \end{array}$$

Since  $f_j$  is a quotient map by Corollary 2.3.16, as before we see that  $\psi_j = \phi_j^{-1}$  is also continuous. This completes the proof.  $\square$

**Corollary 2.4.5.**  $\mathbb{RP}^n$  is a compact connected Hausdorff space.

**Exercise 2.4.6.** Define an equivalence relation  $\sim$  on  $S^n$  by

$$v \sim v' \text{ if } v' = -v.$$

Show that the associated quotient space  $S^n / \sim$  is homeomorphic to  $\mathbb{RP}^n$ . Conclude that  $\mathbb{RP}^n$  is a compact connected Hausdorff space.

The complex projective  $n$ -space  $\mathbb{CP}^n$  is the quotient space of  $\mathbb{C}^{n+1} \setminus \{0\}$  under the equivalence relation  $\sim$  defined by

$$v \sim v' \text{ if } v' = \lambda v, \text{ for some } \lambda \in \mathbb{C}.$$

So the points of  $\mathbb{CP}^n$  are precisely one dimensional  $\mathbb{C}$ -linear subspaces of  $\mathbb{C}^{n+1}$  (i.e., complex lines in  $\mathbb{C}^{n+1}$  passing through the origin  $0 \in \mathbb{C}^{n+1}$ ).

**Exercise 2.4.7.** Show that  $\mathbb{CP}^n$  is a compact connected Hausdorff space.

*Remark on notations:* The real projective  $n$ -space  $\mathbb{RP}^n$  is also denoted by  $\mathbb{P}_{\mathbb{R}}^n$  and  $\mathbb{P}^n(\mathbb{R})$ . Similar notations  $\mathbb{P}_{\mathbb{C}}^n$  and  $\mathbb{P}^n(\mathbb{C})$  are also used for complex projective  $n$ -space  $\mathbb{CP}^n$ .

### 2.4.2 Grassmannian $\text{Gr}(k, \mathbb{R}^n)$

Fix two positive integers  $k$  and  $n$ , with  $k < n$ . Let

$$(\mathbb{R}^n)^k := \underbrace{\mathbb{R}^n \times \cdots \times \mathbb{R}^n}_{k\text{-times}}$$

be  $k$ -fold product of  $\mathbb{R}^n$  together with the product topology. A typical element of  $(\mathbb{R}^n)^k$  is of the form  $(v_1, \dots, v_k)$ , where  $v_j = (a_{j1}, \dots, a_{jn}) \in \mathbb{R}^n$ , for all  $j = 1, \dots, k$ . Note that, we can identify  $(\mathbb{R}^n)^k$  with  $M_{k,n}(\mathbb{R})$  using the bijective map

$$(v_1, \dots, v_k) \mapsto \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{k1} & \cdots & a_{kn} \end{pmatrix}.$$

Consider the subset

$$X := \{(v_1, \dots, v_k) \in (\mathbb{R}^n)^k \mid \{v_1, \dots, v_k\} \text{ is } \mathbb{R}\text{-linearly independent}\}$$

with the subspace topology induced from  $(\mathbb{R}^n)^k$ . Given  $A := (v_1, \dots, v_k)$  and  $A' := (v'_1, \dots, v'_k)$  in  $X$ , we define  $A \sim A'$  if

$$\text{Span}_{\mathbb{R}}\{v_1, \dots, v_k\} = \text{Span}_{\mathbb{R}}\{v'_1, \dots, v'_k\}.$$

Clearly  $\sim$  is an equivalence relation on  $X$ . The associated quotient topological space  $X/\sim$  is known as the *Grassmannian of  $k$ -dimensional  $\mathbb{R}$ -linear subspaces of  $\mathbb{R}^n$* , and is denoted by  $\text{Gr}(k, \mathbb{R}^n)$ . As a set,  $\text{Gr}(k, \mathbb{R}^n)$  consists of all  $\mathbb{R}$ -linear subspaces of  $\mathbb{R}^n$  of dimension  $k$ .

**Corollary 2.4.8.**  $\text{Gr}(1, \mathbb{R}^n)$  is homeomorphic to  $\mathbb{RP}^{n-1}$ .

**Remark 2.4.9** (Plücker embedding). Given a  $n$ -dimensional  $\mathbb{R}$ -vector space  $V$ , its  $k$ -th exterior power  $\wedge^k V$  is a  $\mathbb{R}$ -vector space of dimension  $\binom{n}{k}$ . Sending  $W \in \text{Gr}(k, \mathbb{R}^n)$  to its  $k$ -th exterior power  $\wedge^k W \subset \wedge^k \mathbb{R}^n$ , we get a continuous map

$$\Phi : \text{Gr}(k, \mathbb{R}^n) \longrightarrow \mathbb{RP}^N,$$

where  $N = \binom{n}{k} - 1$ . It turns out that  $\Phi$  is a closed embedding (homeomorphism onto a closed subspace of  $\mathbb{RP}^N$ ). From this, one can conclude that  $\text{Gr}(k, \mathbb{R}^n)$  is a compact Hausdorff space. We shall not go into detailed proofs of the above statements.

## 2.5 Topological group

**Definition 2.5.1.** A *topological group* is a topological space  $G$  which is also a group  $G$  such that the binary map (group operation)

$$m : G \times G \rightarrow G, \quad (x, y) \mapsto xy,$$



and the inversion map

$$\text{inv} : G \rightarrow G, \quad x \mapsto x^{-1},$$

involved in its group structure, are continuous. Here we consider  $G \times G$  as the product topological space.

We recast the above definition of topological group in more formal language, without using points of  $G$ . This formalism, with appropriate type of spaces and maps between them, defines *Lie group*, *algebraic group*, *group-scheme* and more generally, a *group object* in a category (for curious readers!). Denote by  $*$  the topological space whose underlying set is singleton. This space is unique up to a unique homeomorphism. Given any topological space  $X$ , any map  $*$   $\rightarrow$   $X$  is continuous, and they are in bijection with the underlying set of points of  $X$ . On the other hand, the space  $*$  is the *final object* in the category of topological spaces in the sense that, given any topological space  $X$ , there is a unique continuous map  $X \rightarrow *$ . Clearly the product space  $X \times *$  is homeomorphic to  $X$ , and the set of all such homeomorphisms are in bijection with the set of all *automorphisms* of  $X$  (i.e., homeomorphisms of  $X$  onto itself). Unless explicitly specified, we consider the homeomorphism  $X \times * \rightarrow X$  given by the identity map  $\text{Id}_X : X \rightarrow X$  of  $X$ .

Now the above Definition 2.5.1 essentially says that, a topological group is a pair  $(G, m)$ , where  $G$  is a topological space and  $m : G \times G \rightarrow G$  is a continuous map such that the following axioms holds.

(TG1) *Associativity*: The following diagram is commutative.

$$\begin{array}{ccc} G \times G \times G & \xrightarrow{m \times \text{Id}_G} & G \times G \\ \text{Id}_G \times m \downarrow & & \downarrow m \\ G \times G & \xrightarrow{m} & G \end{array}$$

(TG2) *Existence of neutral element*: There is a continuous map  $e : * \rightarrow G$  such that the following diagram is commutative.

$$\begin{array}{ccccc} * \times G & \xrightarrow{e \times \text{Id}_G} & G \times G & \xleftarrow{\text{Id}_G \times e} & G \times * \\ & \searrow \cong & \downarrow m & \swarrow \cong & \\ & & G & & \end{array}$$

(TG3) *Existence of inverse*: There is a continuous map  $\text{inv} : G \rightarrow G$  such that the following diagram is commutative.

$$\begin{array}{ccccc} G & \xrightarrow{(\text{Id}_G, \text{inv})} & G \times G & \xleftarrow{(\text{inv}, \text{Id}_G)} & G \\ \downarrow & & \downarrow m & & \downarrow \\ * & \xrightarrow{e} & G & \xleftarrow{e} & * \end{array}$$

**Example 2.5.2.** (i) Any abstract group is a topological group with respect to the discrete topology on it.

- (ii)  $(\mathbb{R}, +)$ , the real line with usual addition of real numbers, is a topological group.
- (iii)  $(\mathbb{R}^*, \cdot)$ , the subspace of non-zero real numbers with usual multiplication is a topological group.
- (iv)  $(\mathbb{Z}, +)$  is a topological group, where the topology on  $\mathbb{Z}$  is discrete.
- (v) For any integer  $n \geq 1$ , the Euclidean space  $\mathbb{R}^n$  with the component wise addition, i.e.,

$$(a_1, \dots, a_n) + (b_1, \dots, b_n) := (a_1 + b_1, \dots, a_n + b_n), \quad \forall a_i, b_i \in \mathbb{R},$$

is a topological group.

- (vi) Given integers  $m, n \geq 1$ , the set of all  $(m \times n)$ -matrices with real entries  $M_{m,n}(\mathbb{R})$ , considered as the Euclidean topological space  $\mathbb{R}^{mn}$ , is a topological group with respect to the usual matrix addition.
- (vii)  $GL_n(\mathbb{R})$ , the subspace of all invertible  $(n \times n)$ -matrices with real entries, is a topological group with respect to multiplication of matrices.
- (viii) Circle group: The space  $S^1 = \{z \in \mathbb{C} : |z| = 1\} \subset \mathbb{C}$ , together with the multiplication of complex numbers, is a topological group.
- (ix) Any abstract subgroup of a topological group is a topological group with respect to the subspace topology.
- (x) Product of two topological groups is a topological group.

**Exercise 2.5.3.** Let  $G$  be a topological group. If  $U \subseteq G$  is an open neighbourhood of identity  $e \in G$ , show that there is an open neighbourhood  $V \subset G$  of identity such that  $V^2 := \{ab : a, b \in V\} \subseteq U$ . (Hint: Use continuity of the multiplication map  $m$ .)

**Exercise 2.5.4.** Show that for any  $a \in G$ , the *right translation by a map*

$$R_a : G \rightarrow G, \quad g \mapsto ga,$$

is a homeomorphism. Prove the same statement for the *left translation by a map* given by  $L_a(g) = ga$ , for all  $g \in G$ . (Hint: Note that  $R_a$  is the composite map  $g \mapsto (g, a) \xrightarrow{m} ga$  with inverse  $R_{a^{-1}}$ .)

**Exercise 2.5.5.** Show that a topological group  $G$  is Hausdorff if and only if it is a T1 space. (Hint:  $\Delta_G(G)$  is precisely the inverse image of  $\{e\} \subseteq G$  under the map  $(x, y) \mapsto x^{-1}y$ .)

**Lemma 2.5.6.** Let  $G$  be a topological group. Let  $H$  be the connected component of  $G$  containing the neutral element  $e \in G$ . Then  $H$  is a closed normal subgroup of  $G$ .

*Proof.* Since connected components are closed,  $H$  is closed. Since for any  $a \in H$ , the set  $Ha^{-1} = \{ha^{-1} : h \in H\} = R_{a^{-1}}(H)$  contains  $e$ , and is homeomorphic to  $H$ , we must have  $Ha^{-1} \subseteq H$ . Since this holds for all  $a \in H$ , we see that  $H$  is a subgroup of  $G$ . To see that  $H$  is normal, note that, for any  $g \in G$ , the set  $gHg^{-1} = L_g(R_{g^{-1}}(H))$  is a connected subset of  $G$  containing  $e$ , and hence  $gHg^{-1} \subseteq H$ . This completes the proof.  $\square$

**Definition 2.5.7.** A *right action* of a topological group  $G$  on a topological space  $X$  is a continuous map  $\sigma : X \times G \rightarrow X$  such that  $\sigma(x, e) = x$ , and  $\sigma(\sigma(x, g_1), g_2) = \sigma(x, m(g_1, g_2))$ , for all  $x \in X$  and  $g_1, g_2 \in G$ , where  $m : G \times G \rightarrow G$  is the product operation (multiplication map) on  $G$ . Similarly, one can left action of  $G$  on  $X$ .

Without using points, a right  $G$ -action  $\sigma$  on  $X$  can be defined by commutativity of the following diagrams.

(i)

$$\begin{array}{ccc} X \times * & \xrightarrow{\text{Id}_X \times e} & X \times G \\ & \searrow \cong & \downarrow \sigma \\ & & X \end{array}$$

(ii)

$$\begin{array}{ccc} X \times G \times G & \xrightarrow{\sigma \times \text{Id}_G} & X \times G \\ \text{Id}_X \times m \downarrow & & \downarrow \sigma \\ X \times G & \xrightarrow{\sigma} & X \end{array}$$

A right  $G$ -action  $\sigma$  on  $X$  induces an equivalence relation on  $X$ , which gives a partition of  $X$  as a disjoint union of equivalence classes. A typical equivalence class is of the form

$$\text{orb}_G(x) := \{x' \in X : x' = xg, \text{ for some } g \in G\} = xG,$$

and is called the  $G$ -orbit of  $x \in X$ . The associated quotient space, denoted by  $X/\sigma$  or  $X/G$ , consists of all  $G$ -orbits of elements of  $X$  as its points. For this reason,  $X/G$  is also called *orbit space*. If the  $G$ -action on  $X$  is *transitive* (i.e., given any  $x, x' \in X$ , there exists  $g \in G$  such that  $x' = xg$ ), then  $X$  is called a *homogeneous space*. In this case, the associated quotient space  $X/G$  is singleton.

**Exercise 2.5.8.** Given a subgroup  $H$  of a topological group  $G$ , the  $H$ -action on  $G$  defined by

$$G \times H \mapsto G, (g, h) \mapsto gh$$

gives a partition of  $G$  into all right cosets of  $H$  in  $G$ . Show that the orbit space  $G/H$  is a homogeneous space.

**Exercise 2.5.9.** Let  $I = [0, 1] \subset \mathbb{R}$ . Define the  $\mathbb{Z}_2$ -action on  $I \times I$  which gives identifications  $(0, t) \sim (1, 1 - t)$ , for each  $t \in I$ . Convince yourself that the associated quotient space is homeomorphic to the *Möbius strip* (see Figure 2.9). Note that, Möbius strip has only one side!

**Exercise 2.5.10.** Define a  $\mathbb{Z}_2$ -action on the  $n$ -sphere  $S^n \subset \mathbb{R}^{n+1}$  which identifies  $v \in S^n$  with its *antipodal point*  $-v \in S^n$ . Show that the associated quotient space  $S^n/\mathbb{Z}_2$  is homeomorphic to  $\mathbb{RP}^n$ .

**Exercise 2.5.11.** Show that  $\mathbb{R}/\mathbb{Q}$  is a non-Hausdorff topological group. Hint: Note that  $\mathbb{Q}$  is dense in  $\mathbb{R}$ , and right cosets are just translates of  $\mathbb{Q}$ .



FIGURE 2.9: Möbius strip

**Exercise 2.5.12.** Let  $\sigma : X \times G \rightarrow X$  be a right action of a topological group on a space  $X$ . For each  $g \in G$ , show that the induced map

$$\sigma_g : X \rightarrow X, \quad x \mapsto xg := \sigma(x, g)$$

is a homeomorphism.

**Exercise 2.5.13.** Let  $X$  be a topological space together with an action of a topological group  $G$ . Show that the quotient map  $q : X \rightarrow X/G$  is open. (Hint: For  $V \subseteq X$  open, show that  $q^{-1}(q(V)) = \bigcup_{g \in G} Vg$  is open by Exercise 2.5.12, where  $Vg = \{vg : v \in V\}, \forall g \in G$ .)

**Proposition 2.5.14.** Let  $H$  be a subgroup of a topological group  $G$ . Then the orbit space  $G/H$  is Hausdorff if and only if  $H$  is closed in  $G$ . (Here  $G/H$  is not necessarily a group because  $H$  need not be a normal subgroup of  $G$ .)

*Proof.* If  $G/H$  is Hausdorff, then it is a  $T_1$  space so that  $H = \text{orb}_H(e) \in G/H$  is a closed point. Since  $H$  is the inverse image of this point under the quotient map  $q : G \rightarrow G/H$  (continuous),  $H$  is closed in  $G$ . Conversely, suppose that  $H$  is closed in  $G$ . Since the equivalence relation given by the  $H$ -action on  $G$  is precisely the inverse image of  $H$  under the continuous map

$$G \times G \longrightarrow G, \quad (g_1, g_2) \mapsto g_1^{-1}g_2,$$

and the quotient map  $q : G \rightarrow G/H$  is open by Exercise 2.5.13, the converse part follows from Proposition 2.3.26 because  $H$  is closed in  $G$ .  $\square$

**Corollary 2.5.15.** The topological group  $\mathbb{R}/\mathbb{Q}$  is not Hausdorff.

**Definition 2.5.16.** A *homomorphism* of topological groups is a continuous group homomorphism. An *isomorphism* of topological groups is a bijective bi-continuous homomorphism of topological groups.

**Exercise 2.5.17.** If  $f : G \rightarrow H$  is a homomorphism of topological groups with  $H$  Hausdorff, show that  $\text{Ker}(f) := \{g \in G : f(g) = e_H\}$  is a closed normal subgroup of  $G$ .

**Exercise 2.5.18.** If  $f : G \rightarrow H$  is a homomorphism of topological groups, show that the induced map  $G/\text{Ker}(f) \rightarrow \text{Im}(f)$  is an isomorphism of topological groups.

**Exercise 2.5.19.** Show that  $f : \mathbb{R} \rightarrow S^1$  defined by  $f(t) = e^{2\pi it}$ , for all  $t \in \mathbb{R}$ , is a surjective homomorphism of topological groups. Use Exercise 2.5.18 to show that  $\mathbb{R}/\mathbb{Z} \cong S^1$  as topological groups.

**Exercise 2.5.20.** Let  $f : G \rightarrow H$  be a continuous bijective homomorphism of topological groups. Show that  $f^{-1} : H \rightarrow G$  is continuous (Hint: Use Exercise 2.5.13).

**Corollary 2.5.21.** A bijective homomorphism  $f : G \rightarrow H$  of topological groups is an isomorphism.

**Exercise 2.5.22.** Consider the  $\mathbb{Z}$ -action on  $\mathbb{R}$  given by  $\sigma(t, n) = t + n$ , for all  $t \in \mathbb{R}$  and  $n \in \mathbb{Z}$ . Show that the associated quotient space  $\mathbb{R}/\sigma$  is homeomorphic to  $S^1$ .

**Exercise 2.5.23.** Show that  $\mathrm{GL}_n(\mathbb{R})/\mathrm{SL}_n(\mathbb{R}) \cong \mathbb{R}^*$  as topological groups.

**Exercise 2.5.24.** Show that  $\mathrm{GL}_n(\mathbb{R})$  is disconnected, and has precisely two connected components, whereas  $\mathrm{GL}_n(\mathbb{C})$  is path-connected. (Hint: For the first part, use determinant map. For the second part, given  $A \in \mathrm{GL}_n(\mathbb{C})$  use left and right translation homeomorphisms to move it to an upper triangular matrix, and then use convex combination map for its entries to move it to the identity matrix in  $\mathrm{GL}_n(\mathbb{C})$ .)

**Exercise\*** 2.5.25. Show that the group

$$SO_n = \{A \in \mathrm{GL}_n(\mathbb{R}) : AA^t = A^t A = I_n \text{ and } \det(A) = 1\}$$

is compact and connected.

**Exercise\*** 2.5.26 (Universal property of product). Let  $G_1$  and  $G_2$  be two topological groups. Let  $P$  be a topological group together with homomorphisms of topological groups  $p_1 : P \rightarrow G_1$  and  $p_2 : P \rightarrow G_2$  such that given any topological group  $H$  and homomorphisms of topological groups  $f_1 : H \rightarrow G_1$  and  $f_2 : H \rightarrow G_2$ , there is a unique homomorphism of topological groups  $f : H \rightarrow P$  such that the following diagram commutes.

$$\begin{array}{ccccc} & & H & & \\ & \swarrow f_1 & \downarrow f & \searrow f_2 & \\ G_1 & \xleftarrow{p_1} & P & \xrightarrow{p_2} & G_2. \end{array}$$

Prove that there is a unique isomorphism of topological groups  $\phi : P \rightarrow G_1 \times G_2$ .

## 2.6 Metric topology

Let  $X$  be a topological space.

**Definition 2.6.1.** A topological space  $X$  is said to have a *countable local base* at  $x \in X$  if there is a countable family of open neighbourhoods  $\{U_n : n \in \mathbb{N}\}$  of  $x$  in  $X$  such that given any open neighbourhood  $V$  of  $x$  in  $X$  there exists  $n \in \mathbb{N}$  such that  $U_n \subset V$ .

**Proposition 2.6.2.** Let  $X$  be a topological space, and let  $A \subset X$ . Let  $x \in \overline{A}$ . Then there is a

## 2.7 Connectedness

Let  $X$  be a topological space. A *separation* of  $X$  is a pair of open subsets  $U, V \subseteq X$  such that  $U \neq \emptyset, V \neq \emptyset, U \cap V = \emptyset$  and  $U \cup V = X$ .

**Definition 2.7.1.** A topological space  $X$  is said to be *connected* if there is no separation of  $X$  by non-empty pair of disjoint open subsets of  $X$  that covers  $X$ . If  $X$  is not connected, it is called *disconnected*. A subset  $A \subseteq X$  is said to be *connected* if the topological space  $A$ , with the subspace topology induced from  $X$ , is connected.

**Example 2.7.2.** (i) The empty subset  $\emptyset \subseteq X$  is always connected because there is no separation of it.

(ii) The punctured real line  $\mathbb{R} \setminus \{0\}$  is disconnected in  $\mathbb{R}$  since it has a separation given by the open subsets  $(-\infty, 0)$  and  $(0, \infty)$ .

(iii) The subset  $[0, 1] \setminus \{1/2\} \subset \mathbb{R}$  is disconnected, since it has a separation given by the subsets  $[0, 1/2), (1/2, 1]$  open in  $[0, 1] \setminus \{1/2\}$ .

(iv) Let  $L_{m,c} := \{(x, mx + c) : x \in \mathbb{R}\} \subseteq \mathbb{R}^2$  be a straight-line in the Euclidean plane  $\mathbb{R}^2$ . Then the subset  $\mathbb{R}^2 \setminus L_{m,c}$  is disconnected, since it has a separation given by the subsets  $U = \{(x, y) : y < mx + c\}$  and  $V = \{(x, y) : y > mx + c\}$  open in  $\mathbb{R}^2 \setminus L_{m,c}$ .

**Proposition 2.7.3.** A topological space  $X$  is connected if and only if the only subsets of  $X$  that are both open and closed are the empty subset of  $X$  and  $X$  itself.

*Proof.* Suppose that  $X$  is connected. Suppose on the contrary that there is a non-empty proper subset  $U \subset X$  of  $X$  that is both open and closed in  $X$ . Then  $V := X \setminus U$  is a non-empty proper open subset of  $X$  such that  $U \cap V = \emptyset$  and  $U \cup V = X$ . This is not possible since  $X$  is connected.

Conversely, suppose that the only non-empty subset of  $X$  that is both open and closed in  $X$  is  $X$  itself. Suppose that  $X = U \cup V$  for some open subsets  $U$  and  $V$  of  $X$  with  $U \cap V = \emptyset$ . If  $U \neq \emptyset$ , then  $V = X \setminus U$  is both closed and also open in  $X$ , and hence it must be empty set. Thus  $X$  has no separation in  $X$ , and hence is connected.  $\square$

**Lemma 2.7.4.** Let  $X$  be a topological space. Let  $U, V \subset X$  be two non-empty disjoint open subsets of  $X$  such that  $X = U \cup V$ . If  $A$  is a connected subset of  $X$ , then either  $A \subseteq U$  or  $A \subseteq V$ .

*Proof.* Since  $A \subseteq X = U \cup V$ ,  $A$  intersects at least one of  $U$  and  $V$ . Suppose that  $A \cap U \neq \emptyset$ . Then  $A \cap U$  and  $A \cap V$  are open subsets of  $A$  with  $(A \cap U) \cup (A \cap V) = A$ . Since  $A$  is connected and  $A \cap U \neq \emptyset$ , we must have  $A \cap V = \emptyset$ , and hence  $A \subseteq U$ .  $\square$

**Lemma 2.7.5.** The union of a collection of connected subspaces of  $X$  that have a point in common is connected.

*Proof.* Let  $\{A_\alpha : \alpha \in \Lambda\}$  be a collection of connected subsets of  $X$  having a common point  $x_0 \in \bigcap_{\alpha \in \Lambda} A_\alpha$ . Suppose on the contrary that  $A := \bigcup_{\alpha \in \Lambda} A_\alpha$  is not connected. Then there exists a pair of disjoint non-empty subsets  $U, V \subseteq A$  open in  $A$  such that  $A = U \cup V$ . Since  $A_\alpha$  is

connected,  $A_\alpha$  is entirely contained in exactly one of  $U$  and  $V$ . Suppose that  $A_{\alpha_0} \subseteq U$ . Since  $\bigcap_{\alpha \in \Lambda} A_\alpha \neq \emptyset$ , we see that  $A_\alpha \subseteq U$ ,  $\forall \alpha \in \Lambda$ . Then  $A = \bigcup_{\alpha \in \Lambda} A_\alpha \subseteq U$ . This forces  $V$  to be an empty set, which is a contradiction. Therefore,  $A$  must be connected.  $\square$

**Lemma 2.7.6.** *Let  $f : X \rightarrow Y$  be a continuous map of topological spaces, and let  $A$  be a connected subset of  $X$ . Then  $f(A)$  is a connected subset of  $Y$ .*

*Proof. First proof:* Suppose on the contrary that  $f(A)$  is disconnected. Then there is a pair of non-empty subsets  $U', V' \subseteq f(A)$  open in  $f(A)$  with  $U' \cap V' = \emptyset$  and  $U' \cup V' = f(A)$ . Now  $U' = U \cap f(A)$  and  $V' = V \cap f(A)$ , for some open subsets  $U$  and  $V$  of  $Y$ . Since  $f$  is continuous,  $\tilde{U} := f^{-1}(U) \cap A$  and  $\tilde{V} := f^{-1}(V) \cap A$  are open subsets of  $A$ . Note that  $\tilde{U}$  and  $\tilde{V}$  are non-empty. Indeed,  $U \cap f(A) \neq \emptyset$  implies that  $f(x) \in U$ , for some  $x \in A$ . Then  $x \in f^{-1}(U) \cap A = \tilde{U}$ . Similarly,  $\tilde{V} \neq \emptyset$ . Since  $U \cap V \cap f(A) = U' \cap V' = \emptyset$ , we have

$$\tilde{U} \cap \tilde{V} = (f^{-1}(U) \cap A) \cap (f^{-1}(V) \cap A) = f^{-1}(U \cap V \cap f(A)) = \emptyset.$$

Since  $f(A) = U' \cup V' \subseteq U \cup V$ , we have  $A \subseteq f^{-1}(U) \cup f^{-1}(V)$ , and hence  $A = \tilde{U} \cup \tilde{V}$ . This contradicts our assumption that  $A$  is connected. Therefore,  $f(A)$  must be connected.

*Second proof:* Suppose on the contrary that  $f(A)$  is disconnected. Then  $f(A) = U \cup V$ , for a pair of non-empty disjoint subsets  $U, V \subset f(A)$  open in  $f(A)$ . Since  $g := f|_A : A \rightarrow f(A)$  is continuous,  $g^{-1}(U)$  and  $g^{-1}(V)$  are open subsets of  $A$ . Since both  $U$  and  $V$  are non-empty and  $g$  is surjective, both  $g^{-1}(U)$  and  $g^{-1}(V)$  are non-empty. Since  $f(A) = U \cup V$ , it follows that  $A = f^{-1}(U) \cup f^{-1}(V)$ . But this is not possible since  $A$  is connected. Therefore,  $f(A)$  must be connected.  $\square$

**Corollary 2.7.7.** *Let  $X$  and  $Y$  be homeomorphic topological spaces. Then  $X$  is connected if and only if  $Y$  is connected.*

**Theorem 2.7.8** (Intermediate value theorem). *Let  $f : X \rightarrow Y$  be a continuous map, where  $X$  is a connected space and  $Y$  is a totally ordered set together with the order topology. Let  $a, b \in X$  and  $y \in Y$  be such that  $f(a) < y < f(b)$  in  $Y$ . Then there exists  $c \in X$  such that  $f(c) = y$ .*

*Proof.* Note that  $U := f(X) \cap (-\infty, y)$  and  $V := f(X) \cap (y, \infty)$  are disjoint open subsets of  $f(X)$  containing  $f(a)$  and  $f(b)$ , respectively. If  $f^{-1}(y) = \emptyset$ , then  $f(X) = U \cup V$ . Which is not possible since  $f(X)$  is connected by Lemma 2.7.6. Therefore,  $f^{-1}(y) \neq \emptyset$ .  $\square$

**Theorem 2.7.9.** *If  $X$  and  $Y$  are connected topological spaces, so is their product space  $X \times Y$ .*

*Proof.* Let  $X$  and  $Y$  be connected topological spaces, and let  $X \times Y$  be their product space. Fix a point  $b \in Y$ . Since  $X \times \{b\}$  is homeomorphic to  $X$ , it follows from Lemma 2.7.6 that  $X \times \{b\}$  is connected. Similarly, since  $Y$  is connected,  $\{x\} \times Y$  is connected, for all  $x \in X$ . Since  $(X \times \{b\}) \cap (\{x\} \times Y) = \{(x, b)\} \neq \emptyset$ , it follows from Lemma 2.7.5 that

$$T_{x,b} := (X \times \{b\}) \cup (\{x\} \times Y)$$

is connected. Since  $\bigcup_{x \in X} T_{x,b} = X \times Y$  and  $\bigcap_{x \in X} T_{x,b} = X \times \{b\} \neq \emptyset$ , it follows from Lemma 2.7.5 that  $X \times Y$  is connected.  $\square$

**Corollary 2.7.10.** *Let  $X$  and  $Y$  be two topological spaces. Then  $X \times Y$  is connected if and only if both  $X$  and  $Y$  are connected.*

*Proof.* One direction is already proved in Theorem 2.7.9. Since both of the projection maps  $\pi_1 : X \times Y \rightarrow X$  and  $\pi_2 : X \times Y \rightarrow Y$  are continuous and surjective, the converse part follows from Lemma 2.7.6.  $\square$

**Corollary 2.7.11.** *A finite Cartesian product of connected spaces is connected.*

*Proof.* Let  $X_1, \dots, X_n$  be connected topological spaces. For  $n = 1$ , the result holds trivially. Assume that  $n > 1$ , and the result holds for any  $n - 1$  number of connected topological spaces. Then  $Y := X_1 \times \dots \times X_{n-1}$  is connected by induction hypothesis. Since  $X_1 \times \dots \times X_n$  is homeomorphic to  $Y \times X_n$ , and that  $Y \times X_n$  is connected by Corollary 2.7.9, it follows from Lemma 2.7.6 that  $X_1 \times \dots \times X_n$  is connected.  $\square$

**Lemma 2.7.12.** *Let  $X$  be a topological space. Let  $A$  be a connected subset of  $X$ . If  $B \subseteq X$  with  $A \subseteq B \subseteq \overline{A}$ , then  $B$  is connected in  $X$ .*

*Proof.* If possible suppose that  $B$  is not connected in  $X$ . Then there exists a pair of non-empty subsets  $V_1, V_2 \subseteq B$  open in  $B$  such that  $V_1 \cup V_2 = B$  and  $V_1 \cap V_2 = \emptyset$ . Now  $V_1 = U_1 \cap B$  and  $V_2 = U_2 \cap B$ , for some open subsets  $U_1, U_2$  of  $X$ . Since  $A \subseteq B$ ,  $W_1 := U_1 \cap A = V_1 \cap A$  and  $W_2 := U_2 \cap A = V_2 \cap A$  are open subsets of  $A$  with  $W_1 \cup W_2 = V_1 \cap V_2 \cap A = \emptyset$  and  $W_1 \cup W_2 = (V_1 \cap A) \cup (V_2 \cap A) = (V_1 \cup V_2) \cap A = B \cap A = A$ . We claim that both  $W_1$  and  $W_2$  are non-empty. Indeed, since  $U_1 \cap B = V_1 \neq \emptyset$ , there exists a point  $b \in B \subseteq \overline{A}$  such that  $b \in U_1$ . Since  $b \in \overline{A}$ , we must have  $W_1 = U_1 \cap A \neq \emptyset$ . Similarly, we have  $W_2 \neq \emptyset$ . Thus we get a separation of  $A$ , which contradicts our assumption that  $A$  is connected in  $X$ . Therefore,  $B$  must be connected.  $\square$

**Definition 2.7.13.** A subset  $I \subseteq \mathbb{R}$  is said to be an *interval* in  $\mathbb{R}$  if given any two points  $a, b \in I$  with  $a < b$ , we have  $(a, b) := \{x \in \mathbb{R} : a < x < b\} \subseteq I$ .

**Proposition 2.7.14.** *A connected subset of  $\mathbb{R}$  is an interval.*

*Proof.* Let  $I \subseteq \mathbb{R}$  be a connected subset of  $\mathbb{R}$ . If  $I$  is an empty set or a singleton subset of  $\mathbb{R}$ , the result holds trivially. Assume that  $I$  contains at least two distinct points. Let  $a, b \in I$  be arbitrary. Let  $x \in \mathbb{R}$  be such that  $a < x < b$ . Let  $U_x = (-\infty, x) \cap I$  and  $V_x = (x, \infty) \cap I$ . Note that  $a \in U_x$  and  $b \in V_x$ . Then  $U_x$  and  $V_x$  are non-empty open subsets of  $I$ . If  $x \notin I$ , then  $I = U_x \cup V_x$ . This is not possible since  $I$  is connected. Therefore,  $I$  must be an interval in  $\mathbb{R}$ .  $\square$

**Theorem 2.7.15.** *Any non-empty interval in  $\mathbb{R}$  is connected.*

*Proof.* In view of Lemma 2.7.12, it suffices to show that any open interval in  $\mathbb{R}$  is connected. Let  $I$  be an open interval in  $\mathbb{R}$ . If possible suppose that  $I$  is not connected. Then there exists a pair



of non-empty subsets  $U, V \subseteq I$  open in  $I$  (and hence in  $\mathbb{R}$ ) such that  $U \cup V = I$  and  $U \cap V = \emptyset$ . Fix two points  $a \in U$  and  $b \in V$ . Without loss of generality, we may assume that  $a < b$ . Let

$$A := \{x \in \mathbb{R} : [a, x] \subseteq U\}.$$

Since  $b \in V$  and  $V \subseteq I$  is open, there exists a  $\delta > 0$  such that  $(b - \delta, b + \delta) \subseteq V$ . Since  $[a, b) \cap (b - \delta, b + \delta) \neq \emptyset$  and  $U \cap V = \emptyset$ , we must have  $b \notin A$ . Then  $x < b, \forall x \in A$ . Therefore,  $A$  is a bounded above subset of  $I \subseteq \mathbb{R}$ , and so it has a least upper bound, say  $\ell := \sup(A) \in \mathbb{R}$ . Clearly  $a \leq \ell \leq b$ . Since  $I$  is an interval,  $\ell \in I$ . Since  $I = U \cup V$ , either  $\ell \in U$  or  $\ell \in V$ .

*Case 1:* Suppose that  $\ell \in U$ . Then  $U$  being an open set,  $(\ell - \epsilon, \ell + \epsilon) \subseteq U$ , for some  $\epsilon > 0$ . On the other hand, since  $\ell = \sup(A)$  and  $\epsilon/2 > 0$ , there exists  $x_0 \in A$  such that  $\ell - \frac{\epsilon}{2} < x_0$ . Then  $[a, \ell + \epsilon) = [a, x_0) \cup (\ell - \epsilon, \ell + \epsilon) \subseteq U$ , and so  $\ell + \epsilon \in A$ , which is not possible since  $\ell = \sup(A)$ .

*Case 2:* Suppose that  $\ell \in V$ . Since  $V$  is open, there exists  $\epsilon' > 0$  such that  $(\ell - \epsilon', \ell + \epsilon') \subseteq V$ . Since  $\ell = \sup(A)$ , there exists  $x_1 \in A$  such that  $\ell - \frac{\epsilon'}{2} < x_1$ . Then  $\ell - \frac{\epsilon'}{2} \in [a, x_1) \cap (\ell - \epsilon', \ell + \epsilon') \subseteq U \cap V$ , which is not possible since  $U \cap V = \emptyset$ .

Since we are getting contradictions in both cases,  $I$  must be connected.  $\square$

**Corollary 2.7.16.** *The Euclidean space  $\mathbb{R}^n$  is connected, for all  $n \geq 1$ .*

*Proof.* For  $n = 1$ , since  $\mathbb{R}$  is an interval in itself, it is connected by Theorem 2.7.15. Suppose that  $n > 1$ . Since  $\mathbb{R}^n$  is homeomorphic to the product topological space  $X_1 \times \cdots \times X_n$ , where  $X_j = \mathbb{R}, \forall j = 1, \dots, n$ , the result follows from Corollary 2.7.11.  $\square$

**Theorem 2.7.17.** *Let  $\{X_\alpha : \alpha \in \Lambda\}$  be an indexed family of connected topological spaces. Then the product space  $\prod_{\alpha \in \Lambda} X_\alpha$  is connected.*

*Proof.* Let  $X := \prod_{\alpha \in \Lambda} X_\alpha$  be equipped with the product topology. Fix a point  $\mathbf{a} = (a_\alpha)_{\alpha \in \Lambda} \in X$ . Let  $\mathcal{F}(\Lambda)$  be the collection of all finite subsets of  $\Lambda$ . Given a finite subset  $K \in \mathcal{F}(\Lambda)$  of  $\Lambda$ , let

$$X_K := \{\mathbf{x} = (x_\alpha)_{\alpha \in \Lambda} \in X : x_\alpha = a_\alpha, \forall \alpha \in \Lambda \setminus K\}.$$

Then the subset  $X_K \subseteq X$ , with the subspace topology induced from  $X$ , is homeomorphic to  $X_{\alpha_1} \times \cdots \times X_{\alpha_n}$ , where  $K = \{\alpha_1, \dots, \alpha_n\} \subseteq \Lambda$ . Since  $X_\alpha$  is connected, for each  $\alpha \in \Lambda$ , it follows from Corollary 2.7.11 that  $X_K$  is connected. Let  $Y = \bigcup_{F \in \mathcal{F}(\Lambda)} X_F$ . Since  $X_F$  is connected, for all  $F \in \mathcal{F}(\Lambda)$ , and since  $\mathbf{a} \in \bigcap_{F \in \mathcal{F}(\Lambda)} X_F$ , it follows from Lemma 2.7.5 that  $Y$  is connected.

We now show that the closure of  $Y$  in  $X$  is  $X$  itself. Let  $\mathbf{b} = (b_\alpha)_{\alpha \in \Lambda} \in X$  be arbitrary. Let  $U = \prod_{\alpha \in \Lambda} U_\alpha$  be a non-empty basic open subset of  $X$  containing  $\mathbf{b}$ . Then  $U_\alpha \subseteq X_\alpha$  is an open neighbourhood of  $b_\alpha$  in  $X_\alpha, \forall \alpha \in \Lambda$ , and there is a finite subset  $G \in \mathcal{F}(\Lambda)$  such that

$U_\alpha = X_\alpha$ ,  $\forall \alpha \in \Lambda \setminus G$ . Consider the point  $\mathbf{c} = (c_\alpha)_{\alpha \in \Lambda} \in X$  defined by

$$c_\alpha = \begin{cases} b_\alpha, & \text{if } \alpha \in G, \\ a_\alpha, & \text{if } \alpha \in \Lambda \setminus G. \end{cases}$$

Then  $\mathbf{c} \in U \cap X_G \subseteq U \cap Y$ . Therefore,  $\mathbf{c} \in \bar{Y}$ , and hence  $\bar{Y} = X$ . Since closure of a connected set is connected (see Lemma 2.7.6), the result follows.  $\square$

However, the following example shows that the conclusion of the Theorem 2.7.17 fails if we equip  $X = \prod_{\alpha \in \Lambda} X_\alpha$  with the box topology instead of the product topology.

**Example 2.7.18.** For each  $n \in \mathbb{N}$ , let  $X_n$  be the Euclidean space  $\mathbb{R}$ . Let  $\mathbb{R}_{\text{box}}^{\mathbb{N}}$  be the set  $\prod_{n \in \mathbb{N}} X_n$  of all sequences of real numbers. Equip the set  $\prod_{n \in \mathbb{N}} X_n$  with the box topology. Consider the subsets

$$U = \{(a_n)_{n \in \mathbb{N}} : (a_n)_{n \in \mathbb{N}} \text{ is a bounded sequence}\},$$

$$\text{and } V = \{(a_n)_{n \in \mathbb{N}} : (a_n)_{n \in \mathbb{N}} \text{ is an unbounded sequence}\}.$$

of  $\mathbb{R}_{\text{box}}^{\mathbb{N}}$ . Clearly both  $U$  and  $V$  are non-empty subsets of  $\mathbb{R}_{\text{box}}^{\mathbb{N}}$  with  $U \cap V = \emptyset$ . Given a point  $\mathbf{a} = (a_n)_{n \in \mathbb{N}} \in \mathbb{R}_{\text{box}}^{\mathbb{N}}$ , the subset  $W := \prod_{n \in \mathbb{N}} U_n$ , where  $U_n = (a_n - 1, a_n + 1) \subset \mathbb{R}$ ,  $\forall n \in \mathbb{N}$ , is an open neighbourhood of  $\mathbf{a}$  in the box topological space  $\mathbb{R}_{\text{box}}^{\mathbb{N}}$ . Note that all sequences in  $W$  are bounded (resp., unbounded) if  $\mathbf{a}$  is bounded (resp., unbounded). Therefore, both  $U$  and  $V$  are open in  $\mathbb{R}_{\text{box}}^{\mathbb{N}}$ . Thus we get a separation of  $\mathbb{R}_{\text{box}}^{\mathbb{N}}$ , and hence the space  $\mathbb{R}_{\text{box}}^{\mathbb{N}}$  is disconnected.

Let  $X$  be a topological space. Let

$$\rho := \{(a, b) \in X \times X : \text{there is a connected subspace of } X \text{ containing } a \text{ and } b\} \subseteq X \times X.$$

Clearly  $\rho$  is reflexive and symmetric. If  $(a, b), (b, c) \in \rho$ , then there are connected subspaces  $A$  and  $B$  of  $X$  with  $a, b \in A$  and  $b, c \in B$ . Then  $A \cap B \neq \emptyset$ , and hence  $A \cup B$  is connected by Lemma 2.7.5. Therefore,  $(a, c) \in \rho$ . Thus,  $\rho$  is an equivalence relation on  $X$ . The  $\rho$ -equivalence classes in  $X$  are called the *connected components* of  $X$ . Clearly, connected components of  $X$  are precisely maximal connected subsets of  $X$ , and gives a partition of  $X$ . Moreover, any non-empty connected subspace of  $X$  is contained in exactly one of the connected components of  $X$ . Since closure of a connected subspace is connected, it follows that connected components of  $X$  are closed in  $X$ . Therefore, if  $X$  has only finitely many connected components, then the connected components of  $X$  are both open and closed in  $X$ .

**Example 2.7.19.** All connected components of  $\mathbb{Q}$  are one-point space. Indeed, if  $A$  is a subspace of  $\mathbb{Q}$  containing at least two points, say  $a, b \in A$ , then choosing an irrational number  $\alpha \in \mathbb{R}$  with  $a < \alpha < b$  we get a separation of  $A$  by two non-empty disjoint open subsets  $(-\infty, \alpha) \cap A$  and  $(\alpha, \infty) \cap A$  of  $A$ . Moreover, any one-point subspace of  $\mathbb{Q}$  does not admit any separation, and hence is connected. Therefore, the only connected subspaces of  $\mathbb{Q}$  are one-point subspaces.

**Definition 2.7.20.** A topological space  $X$  is said to be *locally connected at*  $x \in X$  if each open neighbourhood of  $x$  in  $X$  contains a connected open neighbourhood of  $x$ . A topological space  $X$  is said to be *locally connected* if it is locally connected at each  $x \in X$ .

### 2.7.1 Path-connectedness

**Definition 2.7.21.** A *path* in  $X$  from  $x_0 \in X$  to  $x_1 \in X$  is a continuous map  $\gamma : [0, 1] \rightarrow X$  such that  $\gamma(0) = x_0$  and  $\gamma(1) = x_1$ . A topological space  $X$  is said to be *path-connected* if given any two points  $x_0$  and  $x_1$  of  $X$ , there is a path in  $X$  from  $x_0$  to  $x_1$ .

**Remark 2.7.22.** A path in  $X$  joining  $x_0 \in X$  to  $x_1 \in X$  can equivalently be defined to be a continuous map  $\gamma : [a, b] \rightarrow X$  with  $\gamma(a) = x_0$  and  $\gamma(b) = x_1$ , where  $a, b \in \mathbb{R}$  with  $a < b$ . To see this, note that given  $a, b \in \mathbb{R}$  with  $a < b$ , we have continuous maps

$$\sigma : [0, 1] \rightarrow [a, b] \text{ and } \sigma' : [a, b] \rightarrow [0, 1]$$

defined by

$$\begin{aligned} \sigma(t) &= (1-t)a + tb, \quad \forall t \in [0, 1], \\ \text{and } \sigma'(s) &= \frac{s-a}{b-a}, \quad \forall s \in [a, b]. \end{aligned}$$

Note that both  $\sigma$  and  $\sigma'$  are continuous with  $\sigma \circ \sigma' = \text{Id}_{[a, b]}$  and  $\sigma' \circ \sigma = \text{Id}_{[0, 1]}$ .

Then given a continuous map  $\gamma : [0, 1] \rightarrow X$  with  $\gamma(0) = x_0$  and  $\gamma(1) = x_1$ , the composite map  $\sigma' \circ \gamma : [a, b] \rightarrow X$  is continuous and  $(\sigma' \circ \gamma)(a) = x_0$  and  $(\sigma' \circ \gamma)(b) = x_1$ . Conversely, given a continuous map  $\delta : [a, b] \rightarrow X$  with  $\delta(a) = x_0$  and  $\delta(b) = x_1$ , the composite map  $\delta \circ \sigma$  is continuous and satisfies  $(\delta \circ \sigma)(0) = x_0$  and  $(\delta \circ \sigma)(1) = x_1$ .

**Example 2.7.23.** (i) Any interval  $I$  in  $\mathbb{R}$  is path-connected. Indeed, given any two points  $a, b \in I$ , the map  $\gamma : [0, 1] \rightarrow \mathbb{R}$  defined by

$$\gamma(t) = (1-t)a + tb, \quad \forall t \in [0, 1],$$

is continuous with  $\gamma(0) = a$  and  $\gamma(1) = b$ . Note that,  $\gamma(t) = a + t(b-a) \in I$ ,  $\forall t \in [0, 1]$ . Therefore,  $\gamma$  is a path in  $I$  from  $a$  to  $b$ .

- (ii) Consider the subspace  $X_n = \mathbb{R}^n \setminus \{0\}$  of the Euclidean space  $\mathbb{R}^n$ . For  $n = 1$ , it follows from the intermediate value theorem that there is no path in  $\mathbb{R} \setminus \{0\}$  joining a negative real number to a positive real number. Therefore,  $\mathbb{R} \setminus \{0\}$  is not path-connected. In fact, it is not connected. Assume that  $n \geq 2$ . Let  $a, b \in \mathbb{R}^n \setminus \{0\}$  be arbitrary. Consider the convex combination of  $a$  and  $b$ , namely

$$\gamma(t) := (1-t)a + tb, \quad t \in [0, 1].$$

If  $\gamma(t) \neq 0$ ,  $\forall t \in [0, 1]$ , then  $t \mapsto \gamma(t)$  gives a path in  $\mathbb{R}^n \setminus \{0\}$  from  $a$  to  $b$ , and we are done. If  $\gamma(t) = 0$ , for some  $t \in [0, 1]$ , then choose a point  $c \in \mathbb{R}^n \setminus \{0\}$  that does not lie on

the straight-line passing through  $a$  and  $b$  in  $\mathbb{R}^n$ . Then the straight-lines in  $\mathbb{R}^n$  joining  $a$  to  $c$  and  $c$  to  $b$  do not pass through the origin, and thus we get a path in  $\mathbb{R}^n \setminus \{0\}$  from  $a$  to  $b$ .

- (iii) Given a point  $x = (x_1, \dots, x_n) \in \mathbb{R}^n$ , let  $\|x\| = \sqrt{x_1^2 + \dots + x_n^2}$  be the Euclidean norm of  $x$  in  $\mathbb{R}^n$ . The subspace  $B(0, r) = \{x \in \mathbb{R}^n : \|x\| < r\}$  of  $\mathbb{R}^n$  is path-connected. Indeed, let  $a, b \in B(0, r)$  be arbitrary. Consider the convex combination

$$\gamma_{a,b}(t) := (1-t)a + tb, \quad \forall t \in [0, 1].$$

Since  $\|\gamma_{a,b}(t)\| \leq (1-t)\|a\| + t\|b\| < (1-t)r + tr = r$ , the map  $t \mapsto \gamma_{a,b}(t)$  gives a path in  $B(0, r)$  joining  $a$  to  $b$ . Therefore,  $B(0, r)$  is path-connected.

**Proposition 2.7.24.** *Continuous image of a path-connected space is path-connected.*

*Proof.* Let  $f : X \rightarrow Y$  be a surjective continuous map of topological spaces. Assume that  $X$  is path-connected. Let  $y_0, y_1 \in Y$  be given. Since  $f$  is surjective, there exists  $x_0, x_1 \in X$  such that  $f(x_0) = y_0$  and  $f(x_1) = y_1$ . Since  $X$  is path-connected, there is a continuous map  $\gamma : [0, 1] \rightarrow X$  with  $\gamma(0) = x_0$  and  $\gamma(1) = x_1$ . Then  $f \circ \gamma : [0, 1] \rightarrow Y$  is a continuous map with  $(f \circ \gamma)(0) = y_0$  and  $(f \circ \gamma)(1) = y_1$ . Thus,  $Y$  is path-connected.  $\square$

**Example 2.7.25.** For each integer  $n \geq 2$ , the subspace  $S^{n-1} := \{x \in \mathbb{R}^n : \|x\| = 1\}$  of the Euclidean space  $\mathbb{R}^n$  is path-connected. To see this, note that  $\mathbb{R}^n \setminus \{0\}$  is path-connected and the map  $f : \mathbb{R}^n \setminus \{0\} \rightarrow S^{n-1}$  defined by

$$f(x) = \frac{x}{\|x\|}, \quad \forall x \in \mathbb{R}^n \setminus \{0\},$$

is continuous and surjective. Therefore, it follows from Proposition 2.7.24 that  $S^{n-1}$  is path-connected, for all  $n \geq 2$ .

**Proposition 2.7.26.** *A path-connected space  $X$  is connected.*

*Proof. First proof:* Suppose on the contrary that  $X = U \cup V$ , where  $U$  and  $V$  are non-empty open subsets of  $X$  with  $U \cap V = \emptyset$ . Choose points  $x_0 \in U$  and  $x_1 \in V$ . Since  $X$  is path-connected, there is a continuous map  $\gamma : [0, 1] \rightarrow X$  such that  $\gamma(0) = x_0$  and  $\gamma(1) = x_1$ . Since  $\gamma$  is continuous and  $[0, 1] \subset \mathbb{R}$  is connected, the subset  $\gamma([0, 1])$  is connected in  $X$ , and hence  $\gamma([0, 1])$  lies entirely either in  $U$  or in  $V$  by Lemma 2.7.4. This gives a contradiction because  $x_0 = \gamma(0) \in U$ ,  $x_1 = \gamma(1) \in V$ , and  $U \cap V = \emptyset$  by assumption. Thus  $X$  must be connected.

*Second proof:* Fix a point  $a \in X$ . Since  $X$  is path-connected, given any  $x \in X$ , there is a continuous map  $\gamma_x : [0, 1] \rightarrow X$  with  $\gamma_x(0) = a$  and  $\gamma_x(1) = x$ . For each  $x \in X$ , the subset  $\gamma_x([0, 1]) \subseteq X$  is connected by Lemma 2.7.6, and  $a \in \bigcap_{x \in X} \gamma_x([0, 1])$ . Then  $X = \bigcup_{x \in X} \gamma_x([0, 1])$  is connected by Lemma 2.7.5.  $\square$

However, the following example shows that a connected space need not be path-connected.

**Example 2.7.27 (Topologist's sine curve).** Consider the subspace  $S = \{(x, \sin \frac{1}{x}) : x \in (0, \infty)\}$  of the Euclidean space  $\mathbb{R}^2$ . Since  $(0, \infty) \subset \mathbb{R}$  is path-connected and the map

$$f : (0, \infty) \rightarrow S$$

defined by

$$f(x) = \left(x, \sin \frac{1}{x}\right), \quad \forall x \in (0, \infty),$$

is continuous and surjective, it follows from Proposition 2.7.24 that  $S$  is path-connected, and hence  $S$  is connected. It follows from Lemma 2.7.12 that the subspace  $\bar{S}$  is connected. The subspace  $\bar{S}$  is called *topologist's sine curve*. Note that,  $\bar{S} = S \cup A$ , where  $A = \{0\} \times [-1, 1] \subset \mathbb{R}^2$ . To see this, fix a point  $(0, t) \in A$  and a real number  $r > 0$ . Consider the open neighbourhood  $U = (-r, r) \times (t - r, t + r) \subset \mathbb{R}^2$  of  $(0, t)$ . By Archimedean property of  $\mathbb{R}$ , there exists  $n \in \mathbb{N}$  such that  $0 < \frac{1}{4n\pi} < \frac{1}{2n\pi} < r$ . Then it follows from the intermediate value theorem (Theorem 2.7.8) that, there exists a real number  $x \in (\frac{1}{4n\pi}, \frac{1}{2n\pi}) \subseteq (0, r)$  such that  $\sin \frac{1}{x} = t$ . Therefore,  $(0, t) \in \bar{S}$ , and hence  $\bar{S} = S \cup A$ . We claim that there is no path in  $\bar{S}$  joining  $(0, 0)$  to  $(x, \sin \frac{1}{x}) \in S$ , where  $x > 0$ , and hence  $\bar{S}$  is not path-connected. Suppose on the contrary that there is a path  $\gamma : [0, 1] \rightarrow \bar{S}$  in  $\bar{S}$  joining the origin  $(0, 0)$  to  $(x, \sin \frac{1}{x}) \in S$ , for some  $x > 0$ . By Archimedean property of  $\mathbb{R}$ , there exists  $m \in \mathbb{N}$  such that  $\frac{1}{2m\pi} < x$ . For each  $n \in \mathbb{N}$ , let  $t_n := \frac{1}{(2mn+1)\pi}$ . Note that,  $(t_n)_{n \in \mathbb{N}}$  is a sequence of points of  $[0, 1]$  converging to 0. Since  $\gamma$  is continuous, the sequence  $(\gamma(t_n))_{n \in \mathbb{N}}$  should converge to  $\gamma(0) = (0, 0)$ . But

$$\gamma(t_n) = \left(t_n, \sin \frac{1}{t_n}\right) = \left(\frac{1}{(2mn+1)\pi}, 1\right) \quad \forall n \in \mathbb{N}.$$

So  $(\gamma(t_n))_{n \in \mathbb{N}}$  does not converge to  $(0, 0)$ , contradicting continuity of  $\gamma$ . Therefore, there is no path in  $\bar{S}$  joining  $(0, 0)$  to a point of  $S$ .

**Proposition 2.7.28.** Let  $X$  be a topological space. The relation “being path-connected” is an equivalence relation on  $X$ .

*Proof.* Let

$$\rho := \{(x, y) \in X \times X : \text{there is a path in } X \text{ from } x \text{ to } y\}.$$

For each  $x \in X$ , the constant map  $c_x : [0, 1] \rightarrow X$  sending all points of  $[0, 1]$  to  $x$  is a path from  $x$  to itself in  $X$ . Therefore,  $(x, x) \in \rho$ , for all  $x \in X$ . Thus  $\rho$  is reflexive. Let  $(x, y) \in \rho$ . Then there is a continuous map  $\gamma : [0, 1] \rightarrow X$  with  $\gamma(0) = x$  and  $\gamma(1) = y$ . Then the map  $\bar{\gamma} : [0, 1] \rightarrow X$  defined by  $\bar{\gamma}(t) = \gamma(1 - t)$ ,  $\forall t \in [0, 1]$ , is a path in  $X$  from  $y$  to  $x$ , and hence  $(y, x) \in \rho$ . Thus  $\rho$  is symmetric. Let  $(a, b), (b, c) \in \rho$ . Let  $\gamma, \delta : [0, 1] \rightarrow X$  be two continuous maps with  $\gamma(0) = a$ ,  $\gamma(1) = b = \delta(0)$  and  $\delta(1) = c$ . Then the map  $\gamma \star \delta : [0, 1] \rightarrow X$  defined by

$$(\gamma \star \delta)(t) := \begin{cases} \gamma(2t), & \text{if } 0 \leq t \leq 1/2, \\ \delta(2t - 1), & \text{if } 1/2 \leq t \leq 1, \end{cases}$$

is continuous, and hence is a path in  $X$  joining  $a$  to  $c$ . Thus  $(a, c) \in \rho$ , and hence  $\rho$  is transitive. Therefore,  $\rho$  is an equivalence relation on  $X$ . The  $\rho$ -equivalence classes in  $X$  are called *path-components* of  $X$ , and  $X$  can be written as a disjoint union of its path-components.  $\square$

**Proposition 2.7.29.** Let  $\{A_\alpha : \alpha \in \Lambda\}$  be a family of path-connected subspaces of a topological space  $X$ . If  $\bigcap_{\alpha \in \Lambda} A_\alpha \neq \emptyset$ , then  $\bigcup_{\alpha \in \Lambda} A_\alpha$  is path-connected.

*Proof.* Choose a point  $p \in \bigcap_{\alpha \in \Lambda} A_\alpha$ . Let  $a, b \in \bigcup_{\alpha \in \Lambda} A_\alpha$  be arbitrary. Then  $a \in A_\alpha$  and  $b \in A_\beta$ , for some  $\alpha, \beta \in \Lambda$ . Since  $A_\alpha$  and  $A_\beta$  are path-connected, there exist continuous maps (paths)

$$\gamma_{a,p} : [0, 1] \rightarrow A_\alpha \quad \text{and} \quad \gamma_{p,b} : [0, 1] \rightarrow A_\beta$$

joining  $a$  to  $p$  in  $A_\alpha$  and  $p$  to  $b$  in  $A_\beta$ , respectively. Then the map

$$\gamma_{a,p} * \gamma_{p,b} : [0, 1] \rightarrow A_\alpha \cup A_\beta \subseteq \bigcup_{\alpha \in \Lambda} A_\alpha$$

defined by

$$(\gamma_{a,p} * \gamma_{p,b})(t) := \begin{cases} \gamma_{a,p}(2t), & \text{if } 0 \leq t \leq 1/2, \\ \gamma_{p,b}(2t - 1), & \text{if } 1/2 \leq t \leq 1, \end{cases}$$

is a path in  $\bigcup_{\alpha \in \Lambda} A_\alpha$  joining  $a$  to  $b$ . This completes the proof.  $\square$

**Exercise 2.7.30.** A *hyperplane* in the Euclidean space  $\mathbb{R}^n$  is the zero locus of a non-constant linear polynomial  $f \in \mathbb{R}[x_1, \dots, x_n]$ . In other words, a hyperplane in  $\mathbb{R}^n$  is a subspace of the form

$$H = \{(a_1, \dots, a_n) : f(a_1, \dots, a_n) = 0\},$$

where  $f$  is a non-constant linear polynomial over  $\mathbb{R}$ , i.e.,  $f$  is of the form  $f = c_0 + c_1x_1 + \dots + c_nx_n$  with coefficients  $c_0, c_1, \dots, c_n \in \mathbb{R}$  such that not all of  $c_1, \dots, c_n$  are simultaneously zero. Show that a hyperplane in  $\mathbb{R}^n$  is path-connected.

**Proposition 2.7.31.** Assume that  $n \geq 2$ . For any countable subset  $A$  of  $\mathbb{R}^n$ , the subspace  $\mathbb{R}^n \setminus A$  of  $\mathbb{R}^n$  is path-connected.

*Proof.* Given a point  $p \in \mathbb{R}^n$ , let  $\mathcal{L}_p$  be the set of all straight-lines in  $\mathbb{R}^n$  passing through  $p$ . Since for each  $q \in \mathbb{R}^n \setminus \{p\}$  there is a unique straight-line in  $\mathbb{R}^n$  passing through  $p$  and  $q$ , the set  $\mathcal{L}_p$  is uncountable. To show  $\mathbb{R}^n \setminus A$  is path-connected, we fix any two points  $a, b \in \mathbb{R}^n$ , and join them by a path in  $\mathbb{R}^n \setminus A$ .

Let  $a, b \in \mathbb{R}^n \setminus A$  be arbitrary. Since  $A$  is countable, there exists a straight-line  $L \in \mathcal{L}_a$  passing through  $a$  that does not intersect  $A$ . For each point  $p \in L$ , we have a unique straight-line  $L_{p,b}$  in  $\mathbb{R}^n$  passing through  $p$  and  $b$ . Since there are uncountably many points on  $L$  and  $A$  is a countable set, we can choose a straight-line  $L_{p,b}$  in  $\mathbb{R}^n$  that passes through  $b$  and  $p \in L$  and does not intersect  $A$ . Since  $L$  and  $L_{p,b}$  are path-connected (as being continuous image of the Euclidean line  $\mathbb{R}$ ) and  $L \cap L_{p,b} \neq \emptyset$ , it follows from Proposition 2.7.29 that  $L \cup L_{p,b}$  is path-connected. Since  $a, b \in Y_{a,b} := L \cup L_{p,b}$ , we have a path in  $Y_{a,b} \subseteq \mathbb{R}^n \setminus A$  joining  $a$  to  $b$ . This completes the proof.  $\square$

**Proposition 2.7.32.** A connected open subspace of  $\mathbb{R}^n$  is path-connected.

*Proof.* Note that, given  $a \in \mathbb{R}^n$  and any real number  $r > 0$ , the Euclidean open ball

$$B(a, r) := \{x \in \mathbb{R}^n : \|a - x\| < r\}$$

in  $\mathbb{R}^n$  is path-connected. This follows by observing that given any point  $x \in B(a, r)$  there is a path

$$t \mapsto \gamma_x(t) := (1 - t)a + tx, \quad \forall t \in [0, 1],$$

in  $B(a, r)$  joining  $a$  to  $x$ .

Let  $A$  be a non-empty connected open subset of  $\mathbb{R}^n$ . Fix a point  $a \in A$ , and let

$$U_a = \{x \in A : \text{there is a path in } A \text{ joining } a \text{ to } x\}.$$

Note that  $U_a \neq \emptyset$ , since  $a \in U_a$ . Let  $x \in U_a$  be arbitrary. Let  $\gamma_{a,x} : [0, 1] \rightarrow A$  be a path in  $A$  joining  $a$  to  $x$ . Since  $x \in A$  and  $A$  is open in  $\mathbb{R}^n$ , there exists a real number  $r > 0$  such that

$$B(x, r) := \{y \in \mathbb{R}^n : d(x, y) < r\} \subseteq A,$$

where  $d(x, y)$  is the Euclidean distance between  $x$  and  $y$  in  $\mathbb{R}^n$ . Since  $B(x, r)$  is path-connected, for each  $y \in B(x, r)$  there is a path, say

$$\gamma_{x,y} : [0, 1] \rightarrow B(x, r)$$

in  $B(x, r)$  joining  $x$  to  $y$ . Then the map

$$\gamma_{a,x} * \gamma_{x,y} : [0, 1] \rightarrow A$$

defined by

$$(\gamma_{a,x} * \gamma_{x,y})(t) := \begin{cases} \gamma_{a,x}(2t), & \text{if } 0 \leq t \leq 1/2, \\ \gamma_{x,y}(2t - 1), & \text{if } 1/2 \leq t \leq 1, \end{cases}$$

is a path in  $A$  joining  $a$  to  $y$ . Therefore,  $B(x, r) \subseteq U_a$ , and hence  $U_a$  is open in  $A$ .

If  $A \setminus U_a \neq \emptyset$ , choose a point  $y \in A \setminus U_a$ . Then there is no path in  $A$  joining  $a$  to  $y$ . Since  $A$  is open in  $\mathbb{R}^n$ , there is a real number  $r_0 > 0$  such that  $B(y, r_0) \subseteq A$ . We show that  $B(y, r_0) \cap U_a = \emptyset$ . For otherwise, if  $x \in B(y, r_0) \cap U_a$ , then there is a path, say  $\gamma_x : [0, 1] \rightarrow A$ , in  $A$  joining  $a$  to  $x$ . Since  $B(y, r_0)$  is also path-connected, there is a path, say  $\gamma_{x,y} : [0, 1] \rightarrow B(y, r_0) \subseteq A$  in  $B(y, r_0)$  joining  $x$  to  $y$ . Then  $(\gamma_{a,x} * \gamma_{x,y}) : [0, 1] \rightarrow A$  is a path in  $A$  joining  $a$  to  $y$ . This contradicts the fact that  $y \in A \setminus U_a$ . Therefore,  $A \setminus U_a$  is also open in  $A$ . Thus,  $U_a$  is both open and closed in  $A$ , and hence is equal to  $A$  because  $A$  is connected.  $\square$

**Definition 2.7.33.** A topological space  $X$  is said to be *locally connected at*  $x \in X$  if each open neighbourhood of  $x$  contains a connected open neighbourhood of  $x$ . If  $X$  is locally connected at each point of it, then  $X$  is said to be *locally connected*. Similarly,  $X$  is said to be *locally path-connected at*  $x \in X$  if each open neighbourhood of  $x$  contains a path-connected open neighbourhood of  $x$ ; and  $X$  is said to be *locally path-connected* if it is locally path-connected at each of its points.

**Example 2.7.34.** The Euclidean line  $\mathbb{R}$  is both locally connected and locally path-connected. The subspace  $[0, 1) \cup (1, 2] \subset \mathbb{R}$  is locally connected and locally path-connected, but neither connected nor path-connected. The topologist's sine curve is connected but not locally connected.

**Proposition 2.7.35.** Let  $X$  be a topological space. Then  $X$  is locally connected if and only if for each open subset  $U$  of  $X$ , any connected component of  $U$  is open in  $X$ .

*Proof.* Suppose that  $X$  is locally connected. □

## 2.8 Compactness

Let  $X$  be a topological space. Let  $A \subseteq X$ . A collection  $\mathcal{F} = \{V_\alpha : \alpha \in \Lambda\}$  of subsets of  $X$  is said to be a *cover* of  $A$  if  $A \subseteq \bigcup_{\alpha \in \Lambda} V_\alpha$ . If all members  $V_\alpha$  of  $\mathcal{F}$  are open subsets of  $X$ , then  $\mathcal{F}$  is called an *open cover* of  $A$  in  $X$ . A *subcover* of  $\mathcal{F}$  is a subcollection of  $\mathcal{F}$  such that union of all its members cover  $A$ .

**Definition 2.8.1.** A topological space  $X$  is said to be *compact* if every open cover of  $X$  has a finite subcover. In other words, given a family of open subsets  $\mathcal{F} = \{U_\alpha : \alpha \in \Lambda\}$  such that  $X = \bigcup_{\alpha \in \Lambda} U_\alpha$ , there exists a finite subcollection  $\{U_{\alpha_1}, \dots, U_{\alpha_n}\}$  of  $\mathcal{F}$  such that  $X = \bigcup_{j=1}^n U_{\alpha_j}$ . A subset  $K$  of a topological space  $X$  is said to be *compact* if it is compact with respect to the subspace topology on  $K$  induced from  $X$ .

**Example 2.8.2.** The Euclidean space  $\mathbb{R}$  is not compact, as it has an open cover  $\{(n, n+2) : n \in \mathbb{N}\}$  which has no finite subcover.

**Example 2.8.3.** The subspace  $K := \{\frac{1}{n} : n \in \mathbb{N}\} \subset \mathbb{R}$  is not compact. To see this, for each  $n \in \mathbb{N}$  we consider the open interval  $U_n := (\frac{1}{n} - r_n, \frac{1}{n} + r_n)$ , where  $r_n := \frac{1}{3} \left( \frac{1}{n} - \frac{1}{n+1} \right)$ . Then  $U_n$  is an open neighbourhood of  $\frac{1}{n}$  and that  $U_n \cap U_m = \emptyset$ , for all  $n \neq m$  in  $\mathbb{N}$ . Then  $\{U_n : n \in \mathbb{N}\}$  is an open cover of  $K$ , which has no finite subcover. However,  $K \cup \{0\}$  is compact. To see this, consider an open cover  $\mathcal{F} = \{U_\alpha : \alpha \in \Lambda\}$  of  $K \cup \{0\}$ . Then  $0 \in U_{\alpha_0}$ , for some  $\alpha_0 \in \Lambda$ . Since  $U_{\alpha_0}$  is an open subset of  $\mathbb{R}$ , there exists a real number  $r > 0$  such that  $(-r, r) \subseteq U_{\alpha_0}$ . Then by Archimedean property of  $\mathbb{R}$ , there is  $n_0 \in \mathbb{N}$  such that  $\frac{1}{n} < r$ ,  $\forall n \geq n_0$ . For each  $j \in \{1, \dots, n_0\}$ , we can choose an open subset  $U_{\alpha_j} \in \mathcal{F}$  such that  $\frac{1}{j} \in U_{\alpha_j}$ ,  $\forall j = 1, \dots, n_0$ . Then  $K \cup \{0\} \subseteq U_{\alpha_0} \cup \left( \bigcup_{j=1}^{n_0} U_{\alpha_j} \right)$ . Therefore,  $K \cup \{0\}$  is compact.

**Lemma 2.8.4.** Let  $X$  be a topological space. A subspace  $K \subseteq X$  is compact if and only if every open cover of  $K$  in  $X$  has a finite subcover.

*Proof.* Let  $K \subseteq X$ . Assume that  $K$  is compact. Let  $\mathcal{F} = \{U_\alpha : \alpha \in \Lambda\}$  be a collection of open subsets  $U_\alpha$  of  $X$  such that  $K \subseteq \bigcup_{\alpha \in \Lambda} U_\alpha$ . Then  $\mathcal{F}_K := \{U_\alpha \cap K : \alpha \in \Lambda\}$  is a collection of open subsets of  $K$  such that  $K = \bigcup_{\alpha \in \Lambda} (U_\alpha \cap K)$ . Since  $K$  is compact, there exists  $\alpha_1, \dots, \alpha_n \in \Lambda$  such that  $K = \bigcup_{j=1}^n (U_{\alpha_j} \cap K)$ . Then  $\{U_{\alpha_1}, \dots, U_{\alpha_n}\}$  is a required finite subcover for  $K$ .



Conversely, suppose that every open cover of  $K$  has a finite subcover. Let  $\{V_\alpha : \alpha \in \Lambda\}$  be a collection of open subsets of  $K$  such that  $K = \bigcup_{\alpha \in \Lambda} V_\alpha$ . Note that, for each  $\alpha \in \Lambda$ , we have  $V_\alpha = U_\alpha \cap K$ , for some open subset  $U_\alpha$  of  $X$ . Since  $K \subseteq \bigcup_{\alpha \in \Lambda} U_\alpha$ , the collection  $\mathcal{F} = \{U_\alpha : \alpha \in \Lambda\}$  is an open cover of  $K$  in  $X$ . Then there exists  $\alpha_1, \dots, \alpha_n \in \Lambda$  such that  $K \subseteq \bigcup_{j=1}^n U_{\alpha_j}$ . Then  $K = \bigcup_{j=1}^n V_{\alpha_j}$ . This completes the proof.  $\square$

**Proposition 2.8.5.** *A closed subspace of a compact space is compact.*

*Proof.* Let  $K$  be a closed subspace of a compact space  $X$ . Let  $\mathcal{F} = \{U_\alpha : \alpha \in \Lambda\}$  be an open cover of  $K$  in  $X$ . Then  $\mathcal{F} \cup \{X \setminus K\}$  is an open cover of  $X$ . Since  $X$  is compact, there exists  $\alpha_1, \dots, \alpha_n \in \Lambda$  such that  $X = (X \setminus K) \cup (\bigcup_{j=1}^n U_{\alpha_j})$ . Since  $K$  does not intersect  $X \setminus K$ , we have  $K \subseteq \bigcup_{j=1}^n U_{\alpha_j}$ . Thus,  $K$  is compact.  $\square$

**Proposition 2.8.6.** *Let  $K$  be a compact subspace of a Hausdorff space  $X$ . Assume that  $X \setminus K \neq \emptyset$ . Then given  $x \in X \setminus K$ , there exists a pair of open subsets  $U$  and  $V$  of  $X$  such that  $x \in U$ ,  $K \subseteq V$  and  $U \cap V = \emptyset$ .*

*Proof.* Since  $X$  is Hausdorff, for each  $y \in K$  there exists a pair of open subsets  $U_y$  and  $V_y$  of  $X$  containing  $x$  and  $y$ , respectively, such that  $U_y \cap V_y = \emptyset$ . Then  $\{V_y : y \in K\}$  is an open cover of  $K$ . Since  $K$  is compact, there exists finite number of points  $y_1, \dots, y_n \in K$  such that  $K \subseteq \bigcup_{j=1}^n V_{y_j}$ . Let  $U := \bigcap_{j=1}^n U_{y_j}$  and  $V := \bigcup_{j=1}^n V_{y_j}$ . Then  $U$  and  $V$  are open subsets of  $X$  containing  $x$  and  $K$ , respectively. Since  $U_{y_j} \cap V_{y_j} = \emptyset$ , for all  $j = 1, \dots, n$ , it follows that  $U \cap V = \emptyset$ .  $\square$

**Corollary 2.8.7.** *A compact subspace of a Hausdorff space is closed.*

*Proof.* Let  $K$  be a compact subspace of a Hausdorff space  $X$ . It follows from Proposition 2.8.6 that a point of  $X \setminus K$  cannot be a limit point of  $K$ . Therefore,  $K$  is closed in  $X$ .  $\square$

**Proposition 2.8.8.** *Continuous image of a compact space is compact.*

*Proof.* Let  $f : X \rightarrow Y$  be a continuous map of topological spaces with  $X$  compact. We show that  $f(X)$  is a compact subspace of  $Y$ . Let  $\mathcal{F} = \{V_\alpha : \alpha \in \Lambda\}$  be a collection of open subsets of  $Y$  such that  $f(X) \subseteq \bigcup_{\alpha \in \Lambda} V_\alpha$ . Since  $f$  is continuous,  $\{f^{-1}(V_\alpha) : \alpha \in \Lambda\}$  is an open cover of  $X$ . Since  $X$  is compact, there exists  $\alpha_1, \dots, \alpha_n \in \Lambda$  such that  $X = \bigcup_{j=1}^n f^{-1}(V_{\alpha_j})$ . Then  $f(X) \subseteq \bigcup_{j=1}^n V_{\alpha_j}$ . Therefore,  $f(X)$  is compact.  $\square$

**Corollary 2.8.9.** *Let  $f : X \rightarrow Y$  be a continuous bijective map. If  $X$  is compact and  $Y$  is Hausdorff,  $f$  is a homeomorphism.*

*Proof.* To show  $f$  is a homeomorphism, we show that  $f^{-1} : Y \rightarrow X$  is continuous. Let  $g = f^{-1}$ . Let  $Z \subseteq X$  be a closed subset of  $X$ . Since  $X$  is compact,  $Z$  is compact by Proposition 2.8.5. Then  $g^{-1}(Z) = f(Z)$  is compact by Proposition 2.8.8. Since  $Y$  is Hausdorff,  $g^{-1}(Z) = f(Z)$  is closed by Proposition 2.8.5. Therefore,  $f^{-1}$  is continuous, and hence  $f$  is a homeomorphism.  $\square$

**Theorem 2.8.10.** *Finite product of compact spaces is compact.*

*Proof.* By induction, it suffices to show that  $X \times Y$  is compact when both  $X$  and  $Y$  are compact spaces.  $\square$

## 2.9 Separation axioms

**Definition 2.9.1.** Let  $X$  be a topological space. Then  $X$  is said to be

- (i) a *T0 space* if given any two distinct points  $x_1, x_2 \in X$ , either there is an open neighbourhood  $U_1 \subset X$  of  $x_1$  with  $x_2 \notin U_1$  or there is an open neighbourhood  $U_2 \subset X$  of  $x_2$  with  $x_1 \notin U_2$ .
- (ii) a *T1 space* if given any two distinct points  $x_1, x_2 \in X$ , there exist a pair of open neighbourhoods  $U_1, U_2 \subset X$  (not necessarily disjoint) of  $x_1$  and  $x_2$ , respectively, such that  $x_2 \notin U_1$  and  $x_1 \notin U_2$ .
- (iii) a *T2 space* or a *Hausdorff space* if given any two distinct points  $x_1, x_2 \in X$ , there exist a pair of open neighbourhoods  $U_1, U_2 \subset X$  of  $x_1$  and  $x_2$ , respectively, such that  $U_1 \cap U_2 = \emptyset$ .
- (iv) a *T3 space* if  $X$  is a T1 space and given any closed subset  $Z \subset X$  and a point  $x \in X \setminus Z$ , there exist a pair of open subsets  $U, V \subset X$  such that  $x \in U$ ,  $Z \subseteq V$  and  $U \cap V = \emptyset$ .
- (v) a *completely regular space* if given any closed subset  $Z \subset X$  and a point  $x \in X \setminus Z$ , there exist a continuous function  $f : X \rightarrow \mathbb{R}$  such that  $f(x) = 0$  and  $f(z) = 1$ ,  $\forall z \in Z$ .
- (vi) a  $T3\frac{1}{2}$  space or a *Tychonoff space* if  $X$  is completely regular and Hausdorff.
- (vii) a *T4 space* or a *normal space* if  $X$  is a T1 space and given any two closed subsets  $A, B \subset X$  with  $A \cap B = \emptyset$ , there exist a pair of open subsets  $U, V \subset X$  with  $A \subset U$ ,  $B \subset V$  and  $U \cap V = \emptyset$ .

## 2.10 Metrization theorem

**Theorem 2.10.1** (Nagata-Smirnov).

## **2.11 Paracompactness**

### **2.11.1 Partition of unity**

## **2.12 Compactification**



## Chapter 3

# Appendix

### 3.1 Category Theory

**Definition 3.1.1.** A category  $\mathcal{C}$  consists of the following data:

- (i) a collection of objects  $\text{ob}(\mathcal{C})$ ,
- (ii) for each ordered pair of objects  $(X, Y)$  of  $\text{ob}(\mathcal{C})$ , there is a collection  $\text{Mor}_{\mathcal{C}}(X, Y)$ , whose members are called *arrows* or *morphisms from  $X$  to  $Y$  in  $\mathcal{C}$* ; an object  $\varphi \in \text{Mor}_{\mathcal{C}}(X, Y)$  is usually denoted by an arrow  $\varphi : X \rightarrow Y$ .
- (iii) for each ordered triple  $(X, Y, Z)$  of objects of  $\mathcal{C}$ , there is a map (called *composition map*)

$$\circ : \text{Mor}_{\mathcal{C}}(X, Y) \times \text{Mor}_{\mathcal{C}}(Y, Z) \rightarrow \text{Mor}_{\mathcal{C}}(X, Z), \quad (f, g) \mapsto g \circ f,$$

such that the following conditions hold.

- (a) *Associativity:* Given  $X, Y, Z, W \in \text{ob}(\mathcal{C})$ , and  $f \in \text{Mor}_{\mathcal{C}}(X, Y)$ ,  $g \in \text{Mor}_{\mathcal{C}}(Y, Z)$  and  $h \in \text{Mor}_{\mathcal{C}}(Z, W)$ , we have  $h \circ (g \circ f) = (h \circ g) \circ f$ .
- (b) *Existence of identity:* For each  $X \in \text{ob}(\mathcal{C})$ , there exists a morphism  $\text{Id}_X \in \text{Mor}_{\mathcal{C}}(X, X)$  such that given any objects  $Y, Z \in \text{ob}(\mathcal{C})$  and morphism  $f : Y \rightarrow Z$  we have  $f \circ \text{Id}_Y = f$  and  $\text{Id}_Z \circ f = f$ .