

MAS331 위상수학

Notes

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CONTENTS

CHAPTER	SET THEORY AND LOGIC	PAGE 2
	1.1 Basic Notation	2
	1.2 Relations	4
	1.3 The Integers and the Real Numbers	6
	1.4 Cartesian Products	6
	1.5 Finite Sets	6
	1.6 Countable and Uncountable Sets	8
	1.7 Infinite Sets and the Axiom of Choice	11
	1.8 Well-Ordered Sets	12
CHAPTER	TOPOLOGICAL SPACES AND CONTINUOUS FUNCTIONS	PAGE 15
	2.1 Topological Spaces	15
	2.2 Basis for a Topology	16
	2.3 The Order Topology	18
	2.4 The Product Topology on $X \times Y$	19
	2.5 The Subspace Topology	21
	2.6 Closed Sets and Limit Points	23
	Closed Sets — 23 • Limit Points — 25 • Hausdorff Spaces — 26	
	2.7 Continuous Functions	27
	Continuity of a Function — 27 • Homeomorphisms — 28 • Constructing Continuous Functions — 29	
	2.8 The Product Topology	31
	2.9 The Metric Topology	35
	2.10 The Metric Topology (continued)	40
	2.11 The Quotient Topology	43

Chapter 1

Set Theory and Logic

1.1 Basic Notation

Note:-

- Sets: $A, B, C, \dots, \mathbb{R}, \mathbb{Q}, \mathbb{Z}$
- Elements: $a, b, c, \dots, 3, 3/4, \pi$
- $a \in A, 3 \in \mathbb{Z}, 3/4 \notin \mathbb{Z}$
- $A \subseteq B, A \subsetneq B, A \not\subseteq B$
- \emptyset : empty set
- $A \times B := \{(a, b) \mid a \in A \text{ and } b \in B\}$ (Cartesian product)

Definition 1.1.1: Function, Restriction, and Composition

A function f from a set A to a set B is an assignment of an element of B to each element of A .

- A : Domain
- B : Range or Codomain
- $\text{Im } f := \{f(a) \mid a \in A\}$: Image; $\text{Im } f \subseteq B$

If $A_0 \subseteq A$ and $f : A \rightarrow B$ is a function, then the *restriction* of f to A_0 is denoted by $f|_{A_0}$ and is defined as

$$f|_{A_0}(a_0) := f(a_0)$$

for each $a_0 \in A_0$. If $f : A \rightarrow B$ and $g : B \rightarrow C$, then the *composite* $g \circ f$ is defined as

$$(g \circ f)(a) := g(f(a))$$

for each $a \in A$.

Definition 1.1.2: Injectivity, Surjectivity and Bijectivity

A function $f : A \rightarrow B$ is

- injective* (or *one-to-one*, 1-1) if $\forall a, a' \in A, f(a) = f(a') \implies a = a'$,
- surjective* (or *onto*) if $\forall b \in B, \exists a \in A, b = f(a)$, and
- bijective* if f is both injective and surjective.

Definition 1.1.3: Inverse Function

If $f : A \rightarrow B$ is bijective, then the inverse of f is denoted by

$$f^{-1} : B \rightarrow A$$

and is defined as

$$f^{-1}(b) = a$$

for each $b \in B$ where $f(a) = b$.

Example 1.1.1

- a) f is bijective $\iff f^{-1}$ is bijective.
- b) The inverse is unique.

Solution: Suppose f is bijective. Then,

$$f^{-1}(b_1) = f^{-1}(b_2) \implies b_1 = (f \circ f^{-1})(b_1) = (f \circ f^{-1})(b_2) = b_2.$$

Therefore, f^{-1} is injective.

Take any $a \in A$. Then, $b := f(a) \in B$ satisfies $f^{-1}(b) = a$. Therefore, f^{-1} is surjective.

Now, suppose f^{-1} is bijective. Then,

$$f(a_1) = f(a_2) \implies a_1 = (f^{-1} \circ f)(a_1) = (f^{-1} \circ f)(a_2) = a_2.$$

Therefore, f is injective.

Take any $b \in B$. Then, $a := f^{-1}(b) \in A$ satisfies $f(a) = b$. Therefore, f is surjective; a) is now proven.

Let g and h are inverses of f . Take any $b \in B$. Since f is bijective, $\exists! a \in A$, $f(a) = b$. Therefore, $g(b) = a = h(b)$, which implies $g = h$; b) is now proven.

□

Definition 1.1.4: Image and Preimage of a Set

Let $f : A \rightarrow B$ and $A_0 \subseteq A$, $B_0 \subseteq B$.

- $f(A_0) := \{b \mid b = f(a_0) \text{ and } a_0 \in A_0\}$
- $f^{-1}(B_0) := \{a \mid f(a) \in B_0\}$

Example 1.1.2

- a) $A_0 \subseteq f^{-1}(f(A_0))$
- b) f is injective if and only if $\forall A_0 \subseteq A$, $A_0 = f^{-1}(f(A_0))$.
- c) $f(f^{-1}(B_0)) \subseteq B_0$
- d) f is surjective if and only if $\forall B_0 \subseteq B$, $B_0 = f(f^{-1}(B_0))$.

Solution:

- a) For every $a_0 \in A_0$, $f(a_0) \in f(A_0)$, which implies $a_0 \in f^{-1}(f(A_0))$. Therefore, $A_0 \subseteq f^{-1}(f(A_0))$ holds.

b) Suppose f is injective. Take any $A_0 \subseteq A$ and $a_0 \in f^{-1}(f(A_0))$. Then, $f(a_0) \in f(A_0)$. We may take $a_1 \in A_0$ such that $f(a_0) = f(a_1) \in f(A_0)$. Since f is injective, $a_0 = a_1 \in A_0$.

Suppose ' $\forall A_0 \subseteq A, A_0 = f^{-1}(f(A_0))$ ' holds. Suppose $f(a_1) = f(a_2) = b_0$. Let $A_0 := \{a_1\}$. Then, $A_0 = f^{-1}(f(A_0)) = f^{-1}(\{b_0\}) \ni a_2$. This means $a_2 \in \{a_1\}$, which implies $a_1 = a_2$.

c) Take any $b_0 \in f(f^{-1}(B_0))$. Then, there is some $a_0 \in f^{-1}(B_0)$ such that $f(a_0) = b_0$. Such a_0 satisfies $f(a_0) \in B_0$, which implies $b_0 = f(a_0) \in B_0$. Therefore, $f(f^{-1}(B_0)) \subseteq B_0$ holds.

d) Suppose f is surjective. Take any $B_0 \subseteq B$ and $b_0 \in B_0$. Then, there is some $a_0 \in A$ such that $f(a_0) = b_0$, which implies $a_0 \in f^{-1}(B_0)$. Therefore, $b_0 \in f(f^{-1}(B_0))$; $B_0 \subseteq f(f^{-1}(B_0))$.

Suppose ' $\forall B_0 \subseteq B, B_0 = f(f^{-1}(B_0))$ ' holds. Take any $b_0 \in B$ and let $B_0 := \{b_0\}$. Since $b_0 \in f(f^{-1}(B_0))$, There is some $a_0 \in f^{-1}(B_0)$ such that $f(a_0) = b_0$. Therefore, f is surjective.

□

1.2 Relations

Definition 1.2.1: Relation

A relation \sim on a set A is a subset of $A \times A$.

$$x \sim y := (x, y) \in \sim$$

Definition 1.2.2: Equivalence Relation and Equivalence Class

A relation \sim on a set A is an *equivalence relation* if

- (1) $x \sim x$ for each $x \in A$ (reflexive)
- (2) $x \sim y \implies y \sim x$ (symmetric)
- (3) $x \sim y \wedge y \sim z \implies x \sim z$. (transitive)

Moreover, the *equivalence class* of x is defined as

$$\{y \in A \mid y \sim x\}.$$

Example 1.2.1 (Partition)

If there are equivalence classes E and E' , then they are either $E = E'$ or $E \cap E' = \emptyset$. This implies, if we let $\mathcal{E} := \{E \mid E \text{ is an equivalence class of } x \text{ where } x \in A\}$, $A = \bigcup_{E \in \mathcal{E}} E$.

Solution: Since if $E \cap E' = \emptyset$ it is done, suppose $E \cap E' \neq \emptyset$. There are a and a' such that E and E' are equivalence classes of a and a' respectively. We may take $a_0 \in E \cap E'$. By definition and transitivity, $a \sim a_0 \sim a'$. Therefore, for all $x \in E$, $x \in E'$ since $x \sim a \sim a'$, which implies $E \subseteq E'$. In the same way, $E' \subseteq E$.

□

Definition 1.2.3: Order Relation

A relation $<$ on a set A is an *order relation* if

- (1) $x < y$ or $y < x$ for each $x \neq y \in A$
- (2) $x \not< x$ for each $x \in A$
- (3) $x < y \wedge y < z \implies x < z$.

Also, we define

$$(a, b) := \{x \in X \mid a < x < b\}.$$

Definition 1.2.4: Order Type

Let A and B be sets with order relations $<_A$ and $<_B$, respectively. Then, A and B have the same *order type* if there is a bijection $f : A \rightarrow B$ such that $a_1 <_A a_2 \iff f(a_1) <_B f(a_2)$.

Definition 1.2.5: Dictionary Order Relation

Let A, B be sets with order relations $<_A, <_B$ respectively. Then, there is an order relation $<_{A \times B}$ on $A \times B$ defined as $(a_1, b_1) <_{A \times B} (a_2, b_2)$ if

$$a_1 <_A a_2 \text{ or } a_1 = a_2 \text{ and } b_1 <_B b_2.$$

This is often called *dictionary order relation* on $A \times B$.

Definition 1.2.6: Boundedness

Let $A_0 \subseteq A$ with an order relation $<_A$.

- The *largest element* of A_0 is $b \in A_0$ if $x \in A_0 \implies x \leq b$.
- The *smallest element* of A_0 is $b \in A_0$ if $x \in A_0 \implies x \geq b$.
- A_0 is *bounded above* by $b \in A$ if $x \in A_0 \implies x \leq b$.
 - The smallest such b is called the *least upper bound* or the *supremum* of A_0 .
- A_0 is *bounded below* by $b \in A$ if $x \in A_0 \implies x \geq b$.
 - The largest such b is called the *greatest lower bound* or the *infimum* of A_0 .
- A has *least upper bound property* if every bounded above nonempty set $A_0 \subseteq A$ has a least upper bound.
- A has *greatest lower bound property* if every bounded below nonempty set $A_0 \subseteq A$ has a greatest lower bound.

Theorem 1.2.1

A set A with an order relation $<_A$ has l.u.b. property if and only if A has g.l.b. property.

Proof. Suppose A has l.u.b. property. Let A_0 be any bounded below nonempty subset of A . Let $L := \{a \in A \mid a \text{ is a lower bound of } A_0\}$. Take a $a_0 \in A_0$. Then, since $\ell \leq_A a_0$ for all $\ell \in L$, L is bounded above by a_0 . By l.u.b. property of A , there is $\ell_0 := \sup L \in A$.

Take any a_0 in A_0 . Since a_0 is an upper bound of L and ℓ_0 is the least upper bound, $\ell_0 \leq_A a_0$. Therefore, ℓ_0 is a lower bound of A_0 .

Suppose $\ell_0 <_A \ell_1$ and ℓ_1 is a lower bound of A_0 . This implies $\ell_1 \in L$, which contradicts

to $\ell_1 \leq_A \sup L = \ell_0$. Therefore, ℓ_0 is the greatest lower bound, and A has g.l.b. property. The inverse can be proven by the similar reasoning. \square

Theorem 1.2.2 Completeness of \mathbb{R}

The set of real numbers \mathbb{R} has least upper bound property.

1.3 The Integers and the Real Numbers

Theorem 1.3.1 Well-Ordering Property

Every nonempty subset of \mathbb{Z}_+ has a smallest element.

Proof. We first prove that, for each $n \in \mathbb{Z}_+$, every nonempty subset of $[n] := \{1, 2, \dots, n\}$ has a smallest element, using induction. For the base case, it is known the the only nonempty subset of $[1]$, $\{1\}$, has 1 as its smallest element.

Suppose the statement holds for $n = k$. Now take any nonempty subset S of $[k + 1]$. If $S = \{k + 1\}$, $k + 1$, the only element of S , is a smallest element of S . Otherwise, $S \setminus \{k + 1\}$ is nonempty and is a subset of $[k]$; we may let $\mu := \min S$ by the induction hypothesis. Then, μ is also a smallest element of S , regardless of whether it is $k + 1 \in S$ or $k + 1 \notin S$.

Now, take any $\emptyset \neq T \subseteq \mathbb{Z}_+$ and $m \in T$. Then, by our previous result, since $T \cap [m]$ is a nonempty subset of $[m]$, it has a smallest element, which is also a smallest element of T . \square

1.4 Cartesian Products

Definition 1.4.1: Indexing Function and Indexed Family of Sets

Let \mathcal{A} be a nonempty collection of sets. An *indexing function* for \mathcal{A} is a surjective function $f : J \rightarrow \mathcal{A}$ where $A_\alpha := f(\alpha)$. An *indexed family* of sets is defined as $\{A_\alpha\}_{\alpha \in J}$. Now, we define

$$\begin{aligned}\bigcup_{\alpha \in J} A_\alpha &:= \{x \mid \exists \alpha \in J, x \in A_\alpha\} \\ \bigcap_{\alpha \in J} A_\alpha &:= \{x \mid \forall \alpha \in J, x \in A_\alpha\} \\ \prod_{\alpha \in J} A_\alpha &:= \{f : J \rightarrow \bigcup_{\alpha \in J} A_\alpha \mid \forall \alpha \in J, f(\alpha) \in A_\alpha\}.\end{aligned}$$

1.5 Finite Sets

Definition 1.5.1: Finite Set and Cardinality

A set A is *finite* if there is a bijective $f : A \rightarrow [n]$ for some $n \in \mathbb{Z}_+$ or $A = \emptyset$.

- In the former case, we say *cardinality* n or $|A| = n$.
- In the latter case, we say *cardinality* 0 or $|A| = 0$.

Note:-

Let A and B be finite sets. Then, $|A| = |B| = n$ if and only if \exists bijective $f : A \rightarrow B$.

Lemma 1.5.1

Let $a_0 \in A$. Then,

$$|A| = n \iff |A \setminus \{a_0\}| = n - 1.$$

Proof. For $n = 1$, it is trivial. So suppose $n \geq 2$.

(\Rightarrow) There is a bijection $f : A \rightarrow [n]$. If $f(a_0) = n$, then $f|_{A \setminus \{a_0\}}$ is a bijection from $A \setminus \{a_0\}$ to $[n - 1]$, and it's done. Otherwise, let $a_1 := f^{-1}(n)$. Define $g : A \rightarrow A$ by

$$g(a) := \begin{cases} a_0 & \text{if } a = a_1 \\ a_1 & \text{if } a = a_0 \\ a & \text{otherwise.} \end{cases}$$

g is bijective. Then, $f \circ g$ is a bijection from A to $[n]$ such that $(f \circ g)(a_0) = n$.

(\Leftarrow) Trivial. □

Theorem 1.5.1

Let A be a set with $|A| = n$ and $B \subsetneq A$. Then, there is no bijection between B and $[n]$, but (provided $B \neq \emptyset$) there is a bijection between B and $[m]$ for some $m < n$.

Proof by Induction. (Base case) It is trivial for $n = 1$.

(Induction) Suppose it is true for $n \geq 1$. WTS for the case $|A| = n + 1$. Suppose $B \neq \emptyset$ because we have nothing to talk about then. Let $a_0 \in B$. By Lemma 1.5.1, there is a bijection $g : A \setminus \{a_0\} \rightarrow [n]$. Since $B \setminus \{a_0\} \subsetneq A \setminus \{a_0\}$, by induction hypothesis, we have two things.

- There is no bijection between $B \setminus \{a_0\}$ and $[n]$.
- As long as $B \neq \{a_0\}$, there is a bijection from $B \setminus \{a_0\}$ to $[m]$ for some $m < n$.

We conclude that there is no bijection from B and $[n + 1]$ since, if there were, there would be a trivial bijection from $B \setminus \{a_0\}$ to $[n]$. Moreover, we can construct a bijection between B and $[m + 1]$, and $m + 1 < n + 1$. □

Corollary 1.5.1 Uniqueness of Cardinality

The cardinality of a finite set is uniquely determined.

Proof. Let $m < n$ and suppose m and n are cardinalities of a finite set A . Then there are bijections $f : A \rightarrow [m]$ and $g : A \rightarrow [n]$. Then, $f \circ g^{-1}$ is a bijection from $[m]$ to $[n]$ but it is impossible since $[m] \subsetneq [n]$ and because of Theorem 1.5.1. □

Corollary 1.5.2

\mathbb{Z}_+ is not finite.

Proof by Contradiction. Suppose \mathbb{Z}_+ is finite and $|\mathbb{Z}_+| = n$. $f : \mathbb{Z}_+ \rightarrow \mathbb{Z}_+ \setminus \{1\}$ with $x \mapsto x + 1$ is bijective. Then, by Lemma 1.5.1, $n - 1 = |\mathbb{Z}_+ \setminus \{1\}| = |\mathbb{Z}_+| = n$, $\#$. □

Theorem 1.5.2

Let A be a set. TFAE

- (i) $|A| = n$
- (ii) \exists surjective $[m] \rightarrow A$ for some $m \in \mathbb{Z}_+$.
- (iii) \exists injective $A \hookrightarrow [m]$ for some $m \in \mathbb{Z}_+$.

Proof. ((i) \rightarrow (ii)) There is a bijective function from A to $[n]$, and it is also surjective.

((ii) \rightarrow (iii)) Let f be a surjective function from $[m]$ to A . Since f is surjective, $f^{-1}(\{a\}) \neq \emptyset$ for every $a \in A$. Let $M := \max\{\min f^{-1}(\{a\}) \mid a \in A\}$. M is well defined thanks to Theorem 1.3.1 and the fact that $\emptyset \neq f^{-1}(\{a\}) \subseteq [m]$. Then the function $g: A \rightarrow [M]$ defined by $a \mapsto \min f^{-1}(\{a\})$ is injective.

((iii) \rightarrow (i)) Let f be an injective function from A to $[m]$. Then, $g: A \rightarrow \text{Im } f$ defined by $a \mapsto f(a)$ is bijective. A is finite because $\text{Im } f$ is finite by Theorem 1.5.1. \square

Exercise 1.5.1

- (i) Finite unions of finite sets are finite.
- (ii) Finite Cartesian products of finite sets are finite.

Solution: (i) Suppose there are n finite sets A_1, A_2, \dots, A_n to union. WLOG, $A_i \neq \emptyset$ for each $i \in [n]$. Let $M := \max_{i \in [n]} |A_i|$ and $g_i: [|A_i|] \rightarrow A_i$ be a bijective function for each $i \in [n]$. Extend each g_i to $g'_i: [M] \rightarrow A_i$ by

$$g'_i(k) = \begin{cases} g_i(k) & \text{if } k \leq |A_i| \\ g_i(1) & \text{otherwise.} \end{cases}$$

for $k \in [M]$. Now, we define $f: [nM] \rightarrow \bigcup_{i \in [n]} A_i$ by

$$f(n(i-1) + k) := g'_i(k)$$

for each $i \in [n]$ and $k \in [M]$. Then, f is surjective. Therefore, $\bigcup_{i \in [n]} A_i$ is finite by Theorem 1.5.2.

(ii) Suppose there are n finite sets A_1, A_2, \dots, A_n to construct a Cartesian product with. WLOG, $A_i \neq \emptyset$ for each $i \in [n]$. Let $M := \max_{i \in [n]} |A_i|$ and $h_i: A_i \rightarrow [|A_i|]$ be a bijective function for each $i \in [n]$. Let p_i be the i^{th} prime. (i.e., $p_1 = 2, p_2 = 3, p_3 = 5$.) Define a function $f: \prod_{i \in [n]} A_i \rightarrow \left[\left(\prod_{i=1}^n p_i \right)^M \right]$ by

$$f(a_1, a_2, \dots, a_n) := \prod_{i=1}^n p_i^{h_i(a_i)}.$$

f is injective since prime factorization of a natural number is unique. Therefore, $\prod_{i \in [n]} A_i$ is finite by Theorem 1.5.2. \square

1.6 Countable and Uncountable Sets

Definition 1.6.1: Infinite and Countably Infinite

A set A is said to be *infinite* if it is not finite. It is said to be *countably infinite* if there is a bijective correspondence

$$f: A \rightarrow \mathbb{Z}_+.$$

Example 1.6.1

\mathbb{Z}_+, \mathbb{Z} , and $\mathbb{Z}_+ \times \mathbb{Z}_+$ are countably infinite.

Definition 1.6.2: Countability

A set is said to be *countable* if it is either finite or countably infinite. A set that is not countable is said to be *uncountable*.

Lemma 1.6.1

Any subset of \mathbb{Z}_+ is countable.

Proof. Let $C \subseteq \mathbb{Z}_+$. If C is finite, then it's done; we now assume C is infinite. Now we want to show that C is countably infinite.

Define $h: \mathbb{Z}_+ \rightarrow C$ by the following.

(a) $h(1) := \min C$

(b) $h(n+1) := \min(C \setminus h([n]))$ for each $n \in \mathbb{Z}_+$

h is well defined because $C \setminus h([n])$ is always nonempty. Moreover, h is injective since it is $h(m) < h(n)$ whenever $m < n$.

Now, we are going to show h is surjective. To do this, first take any $c \in C$. Since C is infinite and h is injective, $\text{Im } h \not\subseteq [c]$, which means $\exists n \in \mathbb{Z}_+, h(n) > c$. From this, we get $m := \min\{n \in \mathbb{Z}_+ \mid h(n) \geq c\}$ is well-defined. From the definition of m , we also get, for any $1 \leq i < m$, we have $h(i) < c \leq h(m)$. Therefore, $c \notin h([m-1])$. Together with $h(m) = \min(C \setminus h([m-1]))$, we get $h(m) \leq c \leq h(m)$, which implies $c = h(m)$. \square

Theorem 1.6.1

Let $A \neq \emptyset$. TFAE

- (i) A is countable.
- (ii) \exists surjective $\mathbb{Z}_+ \twoheadrightarrow A$.
- (iii) \exists injective $A \hookrightarrow \mathbb{Z}_+$.

Proof. ((i) \rightarrow (ii)) Trivial.

((ii) \rightarrow (iii)) Let $f: \mathbb{Z}_+ \twoheadrightarrow A$. Define $g: A \rightarrow \mathbb{Z}_+$ by $a \mapsto \min f^{-1}(\{a\})$. g is well-defined because $f^{-1}(\{a\}) \neq \emptyset$ for every $a \in A$ and Theorem 1.3.1 holds. g is also injective since $f^{-1}(\{a_1\}) \cap f^{-1}(\{a_2\}) = \emptyset$ if $a_1 \neq a_2 \in A$.

((iii) \rightarrow (i)) Let f be an injection from A to \mathbb{Z}_+ . If we define $g: A \rightarrow \text{Im } f$ by $a \mapsto f(a)$, g is a bijection. Since $\text{Im } f \subseteq \mathbb{Z}_+$, A is countable by Lemma 1.6.1. \square

Corollary 1.6.1

If $A \subseteq B$ and B is countable, then A is countable.

Proof. $A \xrightarrow{\text{trivial injection}} B \xrightarrow{\text{injection}} \mathbb{Z}_+$ and Theorem 1.6.1. \square

Corollary 1.6.2

$\mathbb{Z}_+ \times \mathbb{Z}_+$ is countably infinite.

Proof. $f: \mathbb{Z}_+ \times \mathbb{Z}_+ \rightarrow \mathbb{Z}_+$ with $(x, y) \mapsto 2^x 3^y$ is an injection.

Or, $g: \mathbb{Z}_+ \times \mathbb{Z}_+ \rightarrow \mathbb{Z}_+$ with $(x, y) \mapsto \frac{(x+y-1)(x+y-2)}{2} + y$ is a bijection. \square

Corollary 1.6.3

\mathbb{Q} is countably infinite.

Proof. $f : \mathbb{Z} \times \mathbb{Z}_+ \rightarrow \mathbb{Q}$ with $(x, y) \mapsto x/y$ is surjective. \square

Exercise 1.6.1

The union of a countable number of countable sets is countable.

Solution: Let $\{A_i\}_{i \in J}$ be an indexed family of sets where J and A_i 's are countable. WLOG, $A_i \neq \emptyset$ for each $i \in J$. For each $i \in J$, since A_i is countable, by Theorem 1.6.1, there is a surjection $g_i : \mathbb{Z}_+ \twoheadrightarrow A_i$. Similarly, since J is countable, there is a surjection $h : \mathbb{Z}_+ \twoheadrightarrow J$.

Now, construct a function $f : \mathbb{Z}_+ \times \mathbb{Z}_+ \rightarrow \bigcup_{i \in J} A_i$ by

$$f(i, j) := g_{h(i)}(j).$$

f is naturally surjective by the construction. Therefore, $\bigcup_{i \in J} A_i$ is countable. \square

Exercise 1.6.2

The Cartesian product of a finite number of countable sets is countable.

Solution: Suppose there are $n \in \mathbb{Z}_+$ sets A_1, A_2, \dots, A_n to make Cartesian product with and each A_i is countable. WLOG, $A_i \neq \emptyset$ for each $i \in [n]$. For each $i \in [n]$, there is an injection $g_i : A_i \rightarrow \mathbb{Z}_+$ by Theorem 1.6.1.

Now, construct a function $f : \prod_{i=1}^n A_i \rightarrow \mathbb{Z}_+$ by

$$f(a_1, a_2, \dots, a_n) := \prod_{i=1}^n p_i^{g_i(a_i)},$$

where p_i is the i^{th} prime. Since prime factorization of a natural number is unique, f is injective; therefore $\prod_{i=1}^n A_i$ is countable. \square

Theorem 1.6.2

Let $X_i := \{0, 1\}$ for each $i \in \mathbb{Z}_+$. Then, $\prod_{i \in \mathbb{Z}_+} X_i$ is uncountable.

Proof. Let $f : \mathbb{Z}_+ \rightarrow \prod_{i \in \mathbb{Z}_+} X_i$ be any function. Denote $f(n) = (x_{n,1}, x_{n,2}, \dots) \in \prod_{i \in \mathbb{Z}_+} X_i$ and construct $y = (y_1, y_2, \dots) \in \prod_{i \in \mathbb{Z}_+} X_i$ by

$$y_i := 1 - x_{i,i}$$

for each $i \in \mathbb{Z}_+$. Then, $y \notin \text{Im } f$; therefore, one cannot construct a surjection from \mathbb{Z}_+ to $\prod_{i \in \mathbb{Z}_+} X_i$. \square

Corollary 1.6.4

$\mathcal{P}(\mathbb{Z}_+)$ is uncountable.

Proof. $f : \mathcal{P}(\mathbb{Z}_+) \rightarrow \prod_{i \in \mathbb{Z}_+} X_i$ defined by

$$S \mapsto (y_1, y_2, \dots) \text{ where } y_i := \begin{cases} 0 & \text{if } i \in S \\ 1 & \text{if } i \notin S \end{cases}$$

is a bijection, and $\prod_{i \in \mathbb{Z}_+} X_i$ is uncountable by Theorem 1.6.2. \square

Theorem 1.6.3

Let A be a set. Then, there is no injection $\mathcal{P}(A) \hookrightarrow A$, and there is no surjection $A \twoheadrightarrow \mathcal{P}(A)$.

Proof. Since a surjective map can be naturally deducted from $f : B \hookrightarrow C$ (by constructing $g : C \rightarrow B$ by $g(c) \in f^{-1}(\{c\})$ for $c \in \text{Im } f$ and map c to an arbitrary element in B for $c \notin \text{Im } f$), it suffices to show $A \twoheadrightarrow \mathcal{P}(A)$ does not exist.

Let $f : A \rightarrow \mathcal{P}(A)$ be any function, and let $B := \{a \in A \mid a \notin f(a)\} \in \mathcal{P}(A)$. Suppose $B = f(a_0)$ for some $a_0 \in A$. Then, by the definition of B ,

$$a_0 \in B \iff a_0 \notin f(a_0) = B,$$

which is a contradiction. Therefore, any such f cannot be surjective. \square

1.7 Infinite Sets and the Axiom of Choice

Theorem 1.7.1

Let A be a set. TFAE

- (i) A is infinite.
- (ii) \exists injection $f : \mathbb{Z}_+ \hookrightarrow A$.
- (iii) \exists bijection $g : A \rightarrow B$ where $B \subsetneq A$.

Proof. ((i) \rightarrow (ii)) Construct $f : \mathbb{Z}_+ \rightarrow A$ recursively as following. Let $c : \mathcal{P}(A) \setminus \{\emptyset\} \rightarrow A$ be a function such that $c(A') \in A'$ for every $\emptyset \neq A' \subseteq A$. Its existence is guaranteed by Lemma 1.7.1.

- (1) $f(1) := c(A)$
- (2) $f(n+1) := c(A \setminus f([n]))$ for each $n \in \mathbb{Z}_+$.

Suppose $A \setminus f([n]) = \emptyset$ for some $n \in \mathbb{Z}_+$. Then, $A \subseteq f([n])$, and $f([n])$ is finite by Theorem 1.5.2; therefore A is finite by Theorem 1.5.1. Thus, f is well-defined and it is injective by definition.

((ii) \rightarrow (iii)) Let $f : \mathbb{Z}_+ \hookrightarrow A$ be an injection. Define $g : A \rightarrow A \setminus \{f(1)\}$ by

$$g(a) := \begin{cases} f(n+1) & \text{if } a = f(n) \text{ for some } n \in \mathbb{N}_+ \\ a & \text{if } a \notin \text{Im } f. \end{cases}$$

g is well-defined because f is injective, and it is bijective by definition.

((iii) \rightarrow (i)) This is just a contrapositive of Theorem 1.5.1. \square

Theorem 1.7.2 Axiom of Choice

Given a collection \mathcal{A} of disjoint nonempty sets, there exists a set C such that $C \subseteq \bigcup \mathcal{A}$ and $\forall A \in \mathcal{A}, |C \cap A| = 1$.

Lemma 1.7.1 Existence of a Choice Function

Given a collection \mathcal{B} of nonempty sets, there exists a function

$$c: \mathcal{B} \rightarrow \bigcup \mathcal{B}$$

such that $c(B) \in B$ for each $B \in \mathcal{B}$.

Proof. Let $\mathcal{A} := \{ \{(B, x) \mid x \in B\} \mid B \in \mathcal{B} \}$. Then, by Theorem 1.7.2, there exists $c \subseteq \mathcal{A}$ such that $c \subseteq \bigcup \mathcal{A}$ and each $B \in \mathcal{B}$ appears only once in the first coordinate in c . Therefore, c is a function such that $c(B) \in B$ for each $B \in \mathcal{B}$. \square

1.8 Well-Ordered Sets

Definition 1.8.1: Well-Ordered

A set A with an order relation is a *well-ordered* set if every nonempty subset of A has a smallest element.

Example 1.8.1

- \mathbb{Z}_+ is well-ordered.
- $\{1, 2\} \times \mathbb{Z}_+$ is well ordered with respect to the dictionary ordering.

Theorem 1.8.1

Every nonempty finite set has the order type of $[n]$, and thus it is well-ordered.

Proof. We shall first claim that, if A is a nonempty finite set, then it has a largest element. It can be proved by induction on $|A|$. If $|A| = 1$, then it is trivial. Suppose the claim holds for $|A| = n$, and suppose $|A| = n + 1$ and $a_0 \in A$. Then, $A \setminus \{a_0\}$ has a largest element a_1 . This implies A has a largest element $\max\{a_0, a_1\}$.

Now, we prove there is an order-preserving bijection $f: A \rightarrow [n]$. This will also be proven with induction. It is true when $|A| = 1$, so suppose it is true for $|A| = n \in \mathbb{Z}_+$ and let $|A| = n + 1$. By above, we may let $a_0 := \max A$. By induction hypothesis, there is an order-preserving bijection $f': A \setminus \{a_0\} \rightarrow [n]$. Define $f: A \rightarrow [n + 1]$ by

$$f(a) := \begin{cases} f'(a) & \text{if } a \neq a_0 \\ n + 1 & \text{if } a = a_0. \end{cases}$$

Then, f is an order-preserving bijection from A to $[n + 1]$. \square

Theorem 1.8.2

The Cartesian product of finitely many well-ordered sets is well-ordered with respect to the dictionary ordering.

Proof by Induction. We will prove this by induction on the number of sets. If there is one set, then it is trivial.

Assume the theorem holds for n sets. Suppose we have $n + 1$ sets A_1, A_2, \dots, A_{n+1} . Then, $\prod_{i=2}^{n+1} A_i$ is well-ordered with respect to a dictionary ordering $<_1$.

Let $<_2$ and $<_3$ be the dictionary order of $A_1 \times \prod_{i=2}^{n+1} A_i$ and $\prod_{i=1}^{n+1} A_i$, respectively. Since $(A_1 \times \prod_{i=2}^{n+1} A_i, <_2)$ and $(\prod_{i=1}^{n+1} A_i, <_3)$ has the same order type, we only need to prove that $(A_1 \times \prod_{i=2}^{n+1} A_i, <_2)$ is well-ordered.

Let $\emptyset \neq S \subseteq A_1 \times \prod_{i=2}^{n+1} A_i$. If we define $S' := \{a_1 \mid (a_1, b) \in S\} \subseteq A_1$, S' is a nonempty subset of A_1 , and therefore has $a'_1 := \min S'$. Similarly, if we define $S'' := \{b_1 \mid (a'_1, b_1) \in S\} \subseteq \prod_{i=2}^{n+1} A_i$, S'' is nonempty and has a smallest element b'_1 . Then, (a'_1, b'_1) is a smallest element of $A_1 \times \prod_{i=2}^{n+1} A_i$ with respect to $<_2$. \square

Exercise 1.8.1

$\prod_{i \in \mathbb{Z}_+} \mathbb{Z}_+$ is not well-ordered with respect to the dictionary ordering.

Solution: Let $x_{ij} := \begin{cases} 2 & \text{if } i = j \\ 1 & \text{if } i \neq j \end{cases}$ for each $i \in \mathbb{Z}_+$ and $j \in \mathbb{Z}_+$. The set $A := \{(x_{i1}, x_{i2}, \dots) \mid i \in \mathbb{Z}_+\} \subseteq \prod_{i \in \mathbb{Z}_+} \mathbb{Z}_+$ has no smallest element.

Theorem 1.8.3 Well-Ordering Theorem

If A is a set, then there exists an order relation on A that is well-ordering.

The proof of Theorem 1.8.3 involves the Axiom of Choice.

Corollary 1.8.1

There exists an uncountable well-ordered set.

Definition 1.8.2: Section

Let X be a well-ordered set. Given $\alpha \in X$, let

$$S_\alpha := \{x \in X \mid x < \alpha\}.$$

S_α is called the *section* of X by α .

Lemma 1.8.1

There exists a well-ordered set A with the largest element Ω , such that

- section S_Ω of A is uncountable, and,
- for every $\alpha \in A \setminus \{\Omega\}$, section S_α of A is countable.

Proof. By Corollary 1.8.1, there exists an uncountable well-ordered set B . Let $C := \{1, 2\} \times B$ be a set with a dictionary ordering. C is well-ordered by Theorem 1.8.2.

Let $S := \{\alpha \in C \mid \text{section } S_\alpha \text{ of } C \text{ is uncountable}\} \subseteq C$. We may let $\Omega := \min S$. Then, the set $\overline{S_\Omega} = S_\Omega \cup \{\Omega\}$ satisfies the two conditions. \square

Theorem 1.8.4

If A is a countable subset of S_Ω (in Lemma 1.8.1), then A has an upper bound in S_Ω .

Proof. For each $a \in A$, the section S_a is countable; therefore, the union $B := \bigcup_{a \in A} S_a$ is also countable by Exercise 1.6.1.

Since S_Ω is uncountable, we may take an $x \in S_\Omega \setminus B$. If it were $x < a$ for some $a \in A$, then x would be contained in S_a , which is a subset of B , $\#$. Therefore, $x \in S_\Omega$ is an upper bound of A . \square

Chapter 2

Topological Spaces and Continuous Functions

2.1 Topological Spaces

Definition 2.1.1: Topology and Topological Space

A *topology* on a set X is a collection \mathcal{T} of subsets of X such that

- (i) $\emptyset, X \in \mathcal{T}$
- (ii) $\{U_i \mid i \in J\} \subseteq \mathcal{T} \implies \bigcup_{i \in J} U_i \in \mathcal{T}$
- (iii) $\{U_1, U_2, \dots, U_n\} \subseteq \mathcal{T} \implies \bigcap_{i=1}^n U_i \in \mathcal{T}$

We say (X, \mathcal{T}) is a *topological space*, and each element $U \in \mathcal{T}$ is called an *open set*.

Example 2.1.1 (Discrete Topology and Trivial Topology)

- If X is any set, the collection of all subsets of X , $\mathcal{P}(X)$, is a topology on X ; it is called the *discrete topology*.
- $\{\emptyset, X\}$ is also an topology on X ; we shall call it the *trivial topology*.

Example 2.1.2 (Finite Complement Topology)

Let X be any set. Then, $\mathcal{T} := \{U \subseteq X \mid X \setminus U \text{ is finite}\} \cup \{\emptyset\}$ is a topology.

- (i) $\emptyset, X \in \mathcal{T}$ ✓
- (ii) If $\{U_\alpha\}_{\alpha \in J} \subseteq \mathcal{T}$, then $X \setminus \bigcup_{\alpha \in J} U_\alpha = \bigcap_{\alpha \in J} (X \setminus U_\alpha)$ is finite. ✓
- (iii) If $\{U_1, U_2, \dots, U_n\} \subseteq \mathcal{T}$, $X \setminus \bigcap_{i=1}^n U_i = \bigcup_{i=1}^n (X \setminus U_i)$ is finite by Exercise 1.5.1. ✓

The topology is called the *finite complement topology*.

Example 2.1.3

If $X = \{a, b, c\}$, then $\mathcal{T} = \{\emptyset, X, \{a\}, \{a, b\}\}$ is a topology on X .

Definition 2.1.2: Finer and Coarser Topology

Let \mathcal{T} and \mathcal{T}' be topologies of a set X . If $\mathcal{T} \subseteq \mathcal{T}'$, then we say

- \mathcal{T}' is *finer* than \mathcal{T} and
- \mathcal{T} is *coarser* than \mathcal{T}' .

Also, \mathcal{T} is *comparable* to \mathcal{T}' if either $\mathcal{T} \supseteq \mathcal{T}'$ or $\mathcal{T} \subseteq \mathcal{T}'$.

2.2 Basis for a Topology

Definition 2.2.1: Basis and Topology Generated by a Basis

A *basis* for X is a collection \mathcal{B} of subsets of X such that:

- (i) $\forall x \in X, \exists B \in \mathcal{B}, x \in B$ (i.e., $X = \bigcup \mathcal{B}$) and
- (ii) $\forall B_1, B_2 \in \mathcal{B}, (x \in B_1 \cap B_2 \implies \exists B_3 \in \mathcal{B}, x \in B_3 \subseteq B_1 \cap B_2)$.

The topology \mathcal{T} generated by \mathcal{B} is the collection defined by

$$\mathcal{T} := \{U \subseteq X \mid \forall x \in U, \exists B \in \mathcal{B}, x \in B \subseteq U\}.$$

Note:-

If \mathcal{B} is a basis for X and \mathcal{T} is the topology generated by \mathcal{B} , then $\mathcal{B} \subseteq \mathcal{T}$.

Lemma 2.2.1

If \mathcal{T} is the topology generated by basis \mathcal{B} for X , then \mathcal{T} is a topology on X .

Proof.

- (i) $\emptyset \in \mathcal{T}$ by vacuous truth, and $X \in \mathcal{T}$ follows directly from (i) in Definition 2.2.1. ✓
- (ii) Let $\mathcal{U} := \{U_\alpha\}_{\alpha \in J} \subseteq \mathcal{T}$. Then, $x \in \bigcup \mathcal{U}$ implies $\exists \alpha \in J, x \in U_\alpha$. Since $U_\alpha \in \mathcal{T}$, there is $B \in \mathcal{B}$ such that $x \in B \subseteq U_\alpha \subseteq \bigcup \mathcal{U}$. This means $\bigcup \mathcal{U} \subseteq \mathcal{T}$. ✓
- (iii) It is enough to prove it for two sets U_1 and U_2 in \mathcal{T} . Let $x \in U_1 \cap U_2$. (If $U_1 \cap U_2 = \emptyset$, then it is done.) By the definition of \mathcal{T} , there are B_1 and B_2 in \mathcal{B} such that $x \in B_1 \subseteq U_1$ and $x \in B_2 \subseteq U_2$. Since $x \in B_1 \cap B_2$, there is $B_3 \in \mathcal{B}$ such that $x \in B_3 \subseteq B_1 \cap B_2 \subseteq U_1 \cap U_2$. Thus, it implies $U_1 \cap U_2 \in \mathcal{T}$. ✓

□

Lemma 2.2.2

If \mathcal{T} is the topology generated by basis \mathcal{B} for X , then \mathcal{T} is the collection of all unions of elements of \mathcal{B} . In other words, $\mathcal{T} = \{\bigcup \mathcal{U} \mid \mathcal{U} \subseteq \mathcal{B}\}$.

Proof. Let $\mathcal{T}' := \{\bigcup \mathcal{U} \mid \mathcal{U} \subseteq \mathcal{B}\}$. Since $\mathcal{B} \subseteq \mathcal{T}$ and \mathcal{T} is a topology by Lemma 2.2.1, $\mathcal{T}' \subseteq \mathcal{T}$ follows. (See (ii) in Definition 2.1.1.) Now, we shall prove $\mathcal{T} \subseteq \mathcal{T}'$.

Take any $U \in \mathcal{T}$. Then, for each $x \in U$, there is $B_x \in \mathcal{B}$ such that $x \in B_x \subseteq U$. Then, $U = \bigcup_{x \in U} B_x \in \mathcal{T}'$, hence $\mathcal{T} \subseteq \mathcal{T}'$. □

Lemma 2.2.3

Let (X, \mathcal{T}) be a topological space. If \mathcal{C} is a subset of \mathcal{T} such that

$$\forall U \in \mathcal{T}, (x \in U \implies \exists C \in \mathcal{C}, x \in C \subseteq U),$$

then \mathcal{C} is a basis for X and \mathcal{T} is the topology generated by \mathcal{C} .

Proof. We shall prove first \mathcal{C} is a basis for X .

(i) Since $X \in \mathcal{T}$, $\forall x \in X$, $\exists C \in \mathcal{C}$, $x \in C$. \checkmark

(ii) Let $C_1, C_2 \in \mathcal{C}$ and suppose $x \in C_1 \cap C_2$. Since $C_1 \cap C_2 \in \mathcal{T}$, there is $C_3 \in \mathcal{C}$ such that $x \in C_3 \subseteq C_1 \cap C_2$. \checkmark

Now let \mathcal{T}' be the topology generated by \mathcal{C} . We want to show $\mathcal{T} = \mathcal{T}'$.

For $\mathcal{T}' \subseteq \mathcal{T}$, take any $U \in \mathcal{T}'$. Then, by Lemma 2.2.2, $U = \bigcup_{\alpha \in J} C_\alpha$ where each C_α is in \mathcal{C} . Now, $U = \bigcup_{\alpha \in J} C_\alpha \in \mathcal{T}$ directly follows. The last inclusion is due to (ii) in Definition 2.1.1 and $\mathcal{C} \subseteq \mathcal{T}$. \checkmark

For $\mathcal{T} \subseteq \mathcal{T}'$, take any $U \in \mathcal{T}$. Then, for any $x \in U$, there is $C \in \mathcal{C}$ such that $x \in C \subseteq U$, therefore $U \in \mathcal{T}'$ by Definition 2.2.1. \square

Lemma 2.2.4

Let \mathcal{T} and \mathcal{T}' are topologies generated by bases \mathcal{B} and \mathcal{B}' , respectively. Then,

$$\mathcal{T} \subseteq \mathcal{T}' \iff \forall B \in \mathcal{B}, (x \in B \implies \exists B' \in \mathcal{B}', x \in B' \subseteq B).$$

Proof. (\Leftarrow) Take any $U \in \mathcal{T}$ and $x \in U$. Since \mathcal{B} generates \mathcal{T} , there is $B \in \mathcal{B}$ such that $x \in B \subseteq U$. By the supposition, there is $B' \in \mathcal{B}'$ such that $x \in B' \subseteq B \subseteq U$. This implies we can find $B' \in \mathcal{B}'$ such that $x \in B' \subseteq U$, by definition, $U \in \mathcal{T}'$. \checkmark

(\Rightarrow) Take any $B \in \mathcal{B}$ and $x \in B$. Since $B \in \mathcal{T} \subseteq \mathcal{T}'$, by definition of \mathcal{T}' , there is $B' \in \mathcal{B}'$ such that $x \in B' \subseteq B$. \checkmark \square

Example 2.2.1

Let \mathcal{B} be a set of open region inside a disk, and \mathcal{B}' be a set of open region inside a rectangle. They are bases for \mathbb{R}^2 , and topologies generated by them are the same by Lemma 2.2.4.

Definition 2.2.2: Common Topologies on \mathbb{R}

Define

- $\mathcal{B}_{\mathbb{R}} := \{(a, b) \subseteq \mathbb{R} \mid a < b\}$
- $\mathcal{B}_{\ell} := \{[a, b) \subseteq \mathbb{R} \mid a < b\}$

\mathcal{B} and \mathcal{B}' are bases for \mathbb{R} . Then,

- $\mathcal{T}_{\mathbb{R}}$, the topology generated by \mathcal{B} , is called the *standard topology* on \mathbb{R} , and
- \mathcal{T}_{ℓ} , the topology generated by \mathcal{B}_{ℓ} , is called the *lower limit topology* on \mathbb{R} .

Let $K := \{1/n \mid n \in \mathbb{Z}_+\}$ and $\mathcal{B}_K := \mathcal{B}_{\mathbb{R}} \cup \{(a, b) \setminus K \mid a < b\}$ Then, \mathcal{B}'' is a basis for \mathbb{R} and

- \mathcal{T}_K , the topology generated by \mathcal{B}_K , is called the *K-topology* on \mathbb{R} .

Lemma 2.2.5 Comparison Among the Common Topologies on \mathbb{R}

The following holds.

- (i) $\mathcal{T}_{\mathbb{R}} \subsetneq \mathcal{T}_{\ell}$ (\mathcal{T}_{ℓ} is strictly finer than $\mathcal{T}_{\mathbb{R}}$.)
- (ii) $\mathcal{T}_{\mathbb{R}} \subsetneq \mathcal{T}_K$ (\mathcal{T}_K is strictly finer than $\mathcal{T}_{\mathbb{R}}$.)
- (iii) \mathcal{T}_{ℓ} and \mathcal{T}_K are not comparable.

Proof.

- (i) For any $(a, b) \in \mathcal{B}_{\mathbb{R}}$ and $x \in (a, b)$, $[x, b) \in \mathcal{B}_{\ell}$ and $x \in [x, b) \subseteq (a, b)$. Therefore, by Lemma 2.2.4, $\mathcal{T}_{\mathbb{R}} \subseteq \mathcal{T}_{\ell}$. \checkmark
Take any $a \in \mathbb{R}$. a is in the interval $[a, b) \in \mathcal{B}_{\ell}$ but there are no open interval $(c, d) \in \mathcal{B}_{\mathbb{R}}$ such that $a \in (c, d) \subseteq [a, b)$. Therefore, by Lemma 2.2.4, $\mathcal{T}_{\ell} \not\subseteq \mathcal{T}_{\mathbb{R}}$. \checkmark
- (ii) $\mathcal{T}_{\mathbb{R}} \subseteq \mathcal{T}_K$ directly follows from $\mathcal{B}_{\mathbb{R}} \subseteq \mathcal{B}_K$. \checkmark
Although $0 \in (-1, 1) \setminus K \in \mathcal{T}_K$, there is no $(c, d) \in \mathcal{B}_{\mathbb{R}}$ such that $0 \in (c, d) \subseteq (-1, 1) \setminus K$. Therefore, by Lemma 2.2.4, $\mathcal{T}_K \not\subseteq \mathcal{T}_{\mathbb{R}}$. \checkmark
- (iii) The logics in (i) and (ii) can directly imported to prove (iii). \checkmark

□

Definition 2.2.3: Subbasis

A *subbasis* \mathcal{S} for X is a subset of $\mathcal{P}(X)$ whose union is X , i.e., $\bigcup \mathcal{S} = X$.
The *topology generated by the subbasis* \mathcal{S} is defined to be the collection of all unions of finite intersections of elements of \mathcal{S} .

Lemma 2.2.6

Let \mathcal{S} be a subbasis for X . Then, the topology generated by \mathcal{S} is a topology on X .

Proof. By Lemma 2.2.2, it is enough to show that $\mathcal{B} := \{ \bigcap_{i=1}^n S_i \mid S_i \in \mathcal{S} \}$ is a basis.

- (i) Since $\mathcal{S} \subseteq \mathcal{B}$, $X = \bigcup \mathcal{S} \subseteq \bigcup \mathcal{B} \subseteq X$. \checkmark
- (ii) Let $B_1, B_2 \in \mathcal{B}$ and $x \in B_1 \cap B_2$. Then, $B_1 = \bigcap_{i=1}^n S_i$ and $B_2 = \bigcap_{i=1}^m S'_i$ where $S_i, S'_i \in \mathcal{S}$.
Then, $B_1 \cap B_2 = (\bigcap_{i=1}^n S_i) \cap (\bigcap_{i=1}^m S'_i) \in \mathcal{B}$. \checkmark

□

2.3 The Order Topology

Definition 2.3.1: Intervals

Let X be a set with an order $<$ and $a, b \in X$ with $a < b$ are given.

- $(a, b) := \{ x \in X \mid a < x < b \}$ (open interval)
- $[a, b) := \{ x \in X \mid a \leq x < b \}$ (half-open interval)
- $(a, b] := \{ x \in X \mid a < x \leq b \}$ (half-open interval)
- $[a, b] := \{ x \in X \mid a \leq x \leq b \}$ (closed interval)

Definition 2.3.2: Order Topology

Let X has more than one element. Let \mathcal{B} be collection of

- all open intervals (a, b) in X ,
- all half-open intervals $[a_0, b)$ where a_0 is the smallest element (if a_0 exists), and
- all half-open intervals $(a, b_0]$ where b_0 is the largest element (if b_0 exists).

Then, \mathcal{B} is a basis and the topology generated by \mathcal{B} is called the *order topology*.

Lemma 2.3.1

The set \mathcal{B} above is a basis.

Proof.

- (i) Take any $x \in X$.
 - If x is the smallest, then $x \in [x, b)$ where b is some element in $X \setminus \{x\}$.
 - If x is the largest, then $x \in (a, x]$ where a is some element in $X \setminus \{x\}$.
 - Otherwise, there are some $a, b \in X \setminus \{x\}$ such that $a < x < b$ so $x \in (a, b)$. ✓
- (ii) A nonempty intersection of two basis with different types of interval is an open interval. An intersection of two basis with the same type of interval still belongs to the type of interval. ✓

□

Example 2.3.1

The order topology on \mathbb{Z}_+ is the discrete topology. $n \in (n-1, n+1) = \{n\}$ if $n > 1$ and $1 \in [1, 2) = \{1\}$.

Example 2.3.2

The order topology on \mathbb{R} is the standard topology on \mathbb{R} .

Definition 2.3.3: Ray

Let X be an order set and $a \in X$. There are four types of rays.

- $(a, \infty) := \{x \in X \mid x > a\}$ (open ray)
- $(-\infty, a) := \{x \in X \mid x < a\}$ (open ray)
- $[a, \infty) := \{x \in X \mid x \geq a\}$ (closed ray)
- $(-\infty, a] := \{x \in X \mid x \leq a\}$ (closed ray)

Note:-

Open rays are open in the order topology.

- If X has a largest element b_0 , then $(a, \infty) = (a, b_0]$.
- Otherwise, $(a, \infty) = \bigcup_{a < b} (a, b)$.

Thus, (a, ∞) is open. Similarly, $(-\infty, a)$ is open.

Note:-

Open rays form a subbasis that generates the order topology.

2.4 The Product Topology on $X \times Y$

Definition 2.4.1: Product Topology

Let X, Y be topological spaces. The *product topology* on $X \times Y$ is the topology generated by a basis

$$\mathcal{B} := \{U \times V \mid U \subseteq X \text{ and } V \subseteq Y \text{ are open}\}.$$

Theorem 2.4.1

Let \mathcal{B} be a basis for X and \mathcal{C} be a basis for Y . Then

$$\mathcal{D} := \{B \times C \mid B \in \mathcal{B} \text{ and } C \in \mathcal{C}\}$$

is a basis for the product topology of $X \times Y$.

Proof. We will exploit Lemma 2.2.3. Take any open set $W \subseteq X \times Y$ and $x \times y \in W$. Then, there is a basis element $U \times V$ of the product topology $X \times Y$ such that $x \times y \in U \times V \subseteq W$. Since U and V are open in X and Y , respectively, and $x \in U$ and $y \in V$, there are $B \in \mathcal{B}$ and $C \in \mathcal{C}$ such that $x \in B \subseteq U$ and $y \in C \subseteq V$.

Here, we find that $x \times y \in B \times C \subseteq U \times V \subseteq W$ while $B \times C \in \mathcal{D}$. Therefore, by Lemma 2.2.3, \mathcal{D} generates the product topology. \square

Definition 2.4.2: Projection

Let $\pi_1: X \times Y \rightarrow X$ and $\pi_2: X \times Y \rightarrow Y$ defined by the equations

$$\pi_1(x, y) = x$$

$$\pi_2(x, y) = y$$

The maps π_1 and π_2 are called the *projections* of $X \times Y$ onto its first and second factors, respectively.

Note:-

If $U \subseteq X$ is open, then $\pi_1^{-1}(U) = U \times Y$ is open. Similarly, if $V \subseteq Y$ is open, then $\pi_2^{-1}(V) = X \times V$ is open.

Theorem 2.4.2

The collection

$$\mathcal{S} := \{\pi_1^{-1}(U) \mid U \subseteq X \text{ is open}\} \cup \{\pi_2^{-1}(V) \mid V \subseteq Y \text{ is open}\}$$

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

Proof. Let \mathcal{T} be the product topology and \mathcal{T}' be the topology generated by \mathcal{S} .

- Since $\mathcal{S} \subseteq \mathcal{T}$, every union of finite intersections in \mathcal{S} is in \mathcal{T} . Thus, $\mathcal{T}' \subseteq \mathcal{T}$. \checkmark
- Every open set of \mathcal{T} is a union of elements in $\mathcal{B} := \{U \times V \mid U \subseteq X \text{ and } V \subseteq Y \text{ are open}\}$. Noting that each $U \times V$ can be expressed as $\pi_1^{-1}(U) \cap \pi_2^{-1}(V)$, which is a finite intersection of elements in \mathcal{S} , we may conclude $\mathcal{T} \subseteq \mathcal{T}'$. \checkmark

\square

2.5 The Subspace Topology

Definition 2.5.1: Subspace Topology

Let (X, \mathcal{T}) be a topological space. If $Y \subseteq X$, then

$$\mathcal{T}_Y := \{Y \cap U \mid U \in \mathcal{T}\}$$

is called the *subspace topology* of Y and (Y, \mathcal{T}_Y) is called a *subspace* of (X, \mathcal{T}) .

Lemma 2.5.1

(Y, \mathcal{T}_Y) is a topological space.

Proof.

- (i) $\emptyset = Y \cap \emptyset$ and $Y = Y \cap X$. ✓
- (ii) If $U_\alpha \in \mathcal{T}_Y$, $\bigcup_{\alpha \in J} (Y \cap U_\alpha) = Y \cap \left(\bigcup_{\alpha \in J} U_\alpha\right) \in \mathcal{T}_Y$. ✓
- (iii) If $U_i \in \mathcal{T}_Y$, $\bigcap_{i=1}^n (Y \cap U_i) = Y \cap \left(\bigcap_{i=1}^n U_i\right) \in \mathcal{T}_Y$. ✓

□

Lemma 2.5.2

If \mathcal{B} is a basis for (X, \mathcal{T}) , then

$$\mathcal{B}_Y := \{Y \cap B \mid B \in \mathcal{B}\}$$

is a basis for the subspace topology on Y .

Proof. We will exploit Lemma 2.2.3.

Take any $U \in \mathcal{T}$ and $y \in Y \cap U$. Since $y \in U$, $\exists B \in \mathcal{B}$, $y \in B \subseteq U$, which implies $y \in Y \cap B \subseteq Y \cap U$. □

Note:-

Not all open sets in Y are open in X .

For instance, if $X = \mathbb{R}$ and $Y = [0, 1]$, Y is open in Y but not open in X .

Lemma 2.5.3

All the open sets in Y are open in X if and only if Y is open in X .

Proof. (\Rightarrow) Y is open in Y . Hence, Y is open in X .

(\Leftarrow) Let U be any open set in Y . Then, $U = Y \cap V$ for some open set V in X . Since Y is open in X , U is open in X . □

Theorem 2.5.1

If A is a subspace of X and B is a subspace of Y , then the product topology on $A \times B$ is the same as the topology $A \times B$ inherits as a subspace of $X \times Y$. In other words, the following two topologies are the same.

- (i) $X, Y \xrightarrow{\text{subspace}} A \subseteq X, B \subseteq Y \xrightarrow{\text{product}} A \times B$
- (ii) $X, Y \xrightarrow{\text{product}} X \times Y \xrightarrow{\text{subspace}} A \times B \subseteq X \times Y$

Proof. By Theorem 2.4.1,

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

is a basis for $X \times Y$. Thus,

$$\mathcal{B} := \{(A \times B) \cap (U \times V) \mid U \in \mathcal{B}_X \text{ and } V \in \mathcal{B}_Y\}$$

is a basis for (ii) by Lemma 2.5.2.

Note that $(A \times B) \cap (U \times V) = (A \cap U) \times (B \cap V)$. Also, $\{A \cap U \mid U \in \mathcal{B}_X\}$ and $\{B \cap V \mid V \in \mathcal{B}_Y\}$ are bases for A and B . Thus, \mathcal{B} is also a basis for (i) by Theorem 2.4.1. \square

Wrong Concept 2.1: Order Topology and Subspace Topology

Unlike product topology and subspace topology, order topology and subspace topology are not associative. Let X be an ordered set and $Y \subseteq X$.

$$\begin{aligned} \text{(i)} \quad & Y \xrightarrow{\text{order}} Y \\ \text{(ii)} \quad & X \xrightarrow{\text{order}} X \xrightarrow{\text{subspace}} Y \subseteq X \end{aligned}$$

Then, will those be the same?

Example 1. Consider $X = \mathbb{R}$ and $Y = [0, 1]$. Then, the subspace topology of the order topology X has a basis of

$$\mathcal{B}_{[0,1]} = \{[0, 1] \cap (a, b) \mid a < b\},$$

which is in fact the order topology on Y . In this case, (i) = (ii).

Example 2. Consider $X = \mathbb{R}$ and $Y = [0, 1] \cup \{2\}$. Then, $\{2\}$ is an open in (ii) since $\{2\} = Y \cap (1.5, 2.5)$. But, there is no basis of the order topology on Y such that contains 2 and is a subset of $\{2\}$. Thus, in this case, (i) \neq (ii).

Example 3. Consider $X = \mathbb{R}^2$ and $Y = I^2$ where $I = [0, 1]$. Then, $\{1/2\} \times (1/2, 1]$ is an open set in (ii) since it is $(\{1/2\} \times (1/2, 3/2)) \cap I^2$. But it is not an open set in (i) since there is no basis that contain $(1/2, 1)$ and is a subset of $\{1/2\} \times (1/2, 1]$.

Definition 2.5.2: Convex Subset

Given an ordered set X and $Y \subseteq X$, Y is called *convex* if

$$\forall a, b \in Y, (a < b \implies (a, b) \subseteq Y).$$

Theorem 2.5.2

Let X be an ordered set with the ordered topology. If $Y \subseteq X$ is convex, then the order topology on Y is the same as the subspace topology.

Proof. We will make use of the fact that open rays form a subbasis that generates the order topology.

First, every open ray of (i) is an open ray of the subspace (ii).

$$\{x \in Y \mid x > a\} = \{x \in X \cap Y \mid x > a\},$$

for example. Therefore, (ii) is finer than (i).

Now, take any open ray in X , $(a, \infty)_X = \{x \in X \mid x > a\}$, for instance. Then, let

$$\begin{aligned} R &\triangleq (a, \infty)_X \cap Y \\ &= \{y \in Y \mid y > a\} = (a, \infty)_Y. \end{aligned}$$

If $a \in Y$, then R is an open ray in Y .

Now consider the case $a \notin Y$. If R is nonempty then there is some $y_0 \in R$. Take any $y \in Y$. If $y_0 < y$, then $y \in R$ since $a < y_0 < y$. If $y < y_0$, it implies $a < y < y_0$ because $y < a < y_0$ with $y, y_0 \in Y$ implies $a \in Y$ by the convexity of Y . Therefore, $y \in R$. So, if $a \notin Y$, it is either $R = \emptyset$ or $R = Y$.

Combining the cases, we get the fact that the intersection of Y and an arbitrary open ray in X is an open ray in Y , an empty set, or the whole Y .

This is the final step. Take any open set U in the ordered topology X . Then, $U = \bigcup_{\alpha \in J} U_\alpha$ where $U_\alpha \neq \emptyset$ is a finite intersection of open rays in X . Noting that $U \cap Y$ is a general form of an open set in Y , we get $U \cap Y = \bigcup_{\alpha \in J} (U_\alpha \cap Y)$, which implies either $U \cap Y = Y$ or $U \cap Y$ is a union of finite intersections of an open ray in Y . \square

Corollary 2.5.1

Let X be an ordered set with the ordered topology. The subspace topology of $Y \subseteq X$ is finer than the order topology on Y .

2.6 Closed Sets and Limit Points

2.6.1 Closed Sets

Definition 2.6.1: Closed Set

Let X be a topological space. A subset $A \subseteq X$ is *closed* if $X \setminus A$ is open.

Example 2.6.1

- $[a, b] \subseteq \mathbb{R}$ is closed since $(-\infty, a) \cup (b, \infty)$ is open.
- $[a, b] \times [c, d] \subseteq \mathbb{R}^2$ is closed.
- In discrete topology on X , every subset of X is closed.
- If $Y = [0, 1] \cup (2, 3) \subseteq \mathbb{R}$, $[0, 1]$ and $(2, 3)$ are both open and closed in Y .

Theorem 2.6.1

Let X be a topological space. Then the following conditions hold.

- \emptyset and X are closed.
- Arbitrary intersections of closed sets are closed.
- Finite unions of closed sets are closed.

Proof.

- $X \setminus \emptyset = X$ and $X \setminus X = \emptyset$ are open. \checkmark
- Let $\{A_\alpha\}_{\alpha \in J}$ be a collection of closed sets. Then,

$$X \setminus \bigcap_{\alpha \in J} A_\alpha = \bigcup_{\alpha \in J} (X \setminus A_\alpha).$$

is open since each $X \setminus A_\alpha$ is open. \checkmark

(iii) Let $\{A_i\}_{i=1}^n$ be a collection of closed sets. Then,

$$X \setminus \bigcup_{i=1}^n A_i = \bigcap_{i=1}^n (X \setminus A_i).$$

is open since it is a finite intersection of open sets. ✓

□

Theorem 2.6.2

Let X be a topological space and $Y \subseteq X$. Then $A \subseteq Y$ is closed in Y if and only if there is a closed set B in X such that $A = Y \cap B$.

Proof. (\Leftarrow) Let B be a closed set of X such that $A = Y \cap B$. Then, $X \setminus B$ is open in X and $Y \cap (X \setminus B) = Y \setminus A$ is open in Y . Thus, A is closed in Y .

(\Rightarrow) Since $Y \setminus A$ is open in Y , $Y \setminus A = Y \cap U$ for some open set U in X . Then, $A = Y \cap (X \setminus U)$ where $X \setminus U$ is closed in X . □

Theorem 2.6.3

If Y is closed in X , then every closed sets of Y are closed in X if and only if Y is closed in X .

Proof. Proof is analogous to the proof of Lemma 2.5.3. □

Definition 2.6.2: Interior and Closure of a Set

Given a subset A of a topological space (X, \mathcal{T}) ,

- the *interior* of A is $\mathring{A} \triangleq \bigcup \{U \subseteq X \mid U \in \mathcal{T} \text{ and } U \subseteq A\}$, and
- the *closure* of A is $\bar{A} \triangleq \bigcap \{V \subseteq X \mid X \setminus V \in \mathcal{T} \text{ and } A \subseteq V\}$.

Note:-

- $\mathring{A} \subseteq A \subseteq \bar{A}$
- \mathring{A} is open, and \bar{A} is closed.
- \mathring{A} is the largest open set contained in A , and \bar{A} is the smallest closed set containing A .

Theorem 2.6.4

Let Y be a subspace of X and $A \subseteq Y$. Let \bar{A} and \bar{A}_Y denote the closures of A in X and Y , respectively. Then,

$$\bar{A} \cap Y = \bar{A}_Y.$$

Proof. (\supseteq) $\bar{A} \cap Y$ is closed in Y by Theorem 2.6.2. Thus, $\bar{A}_Y \subseteq \bar{A} \cap Y$.

(\subseteq) $\bar{A}_Y = B \cap Y$ for some closed set B in X by Theorem 2.6.2. Also, $\bar{A} \subseteq B$ holds. Therefore, $\bar{A}_Y = B \cap Y \subseteq \bar{A} \cap Y$. □

Definition 2.6.3: Intersection and Neighborhood

- Given two sets A and B , we say A and B *intersect* if $A \cap B \neq \emptyset$.
- An open set containing $x \in X$ is called an *open neighborhood* of x .

Theorem 2.6.5

Let $A \subseteq X$ where X is a topological space. The following hold.

- (i) $x \in \bar{A}$ if and only if every neighborhood of x intersects A .
- (ii) Let \mathcal{B} be a basis for X . Then, $x \in \bar{A}$ if and only if every $B \in \mathcal{B}$ containing x intersects A .

Proof.

- (i) We will prove the contrapositive " $x \notin \bar{A} \iff \exists$ neighborhood U of x , $U \cap A = \emptyset$ ".
 (\Rightarrow) $U \triangleq X \setminus \bar{A}$ is a neighborhood of x . We find that $U \cap A = \emptyset$ since $A \subseteq \bar{A}$. \checkmark
 (\Leftarrow) Suppose a neighborhood U of x satisfies $U \cap A = \emptyset$. It implies $A \subseteq X \setminus U$. Since $X \setminus U$ is closed, $\bar{A} \subseteq X \setminus U$ also holds. Since $x \in U$, $x \in \bar{A}$ may never hold. \checkmark
- (ii) (\Rightarrow) A basis element that contains x is a neighborhood of x . \checkmark
 (\Leftarrow) Follows from the definition of basis. (See Definition 2.2.1.) \checkmark

□

Example 2.6.2

- If $A = (0, 1/2) \subseteq \mathbb{R}$, then $\bar{A} = [0, 1/2]$.
- If $A = \{1/n \mid n \in \mathbb{Z}_+\} \subseteq \mathbb{R}$, then $\bar{A} = A \cup \{0\}$.
- If $A = \mathbb{Q} \subseteq \mathbb{R}$, then $\bar{A} = \mathbb{R}$.
- If $A = \mathbb{Z} \subseteq \mathbb{R}$, then $\bar{A} = \mathbb{Z}$.

2.6.2 Limit Points

Definition 2.6.4: Limit Point

Let $A \subseteq X$ and $x \in X$. The point x is a *limit point* of A if every neighborhood of x intersects A in some point other than x . The set of limit points of A is denoted by A' .

Note:-

Equivalently, x is a limit point of A if $x \in \overline{A \setminus \{x\}}$ thanks to Theorem 2.6.5.

Theorem 2.6.6

Let $A \subseteq X$ where X is a topological space. Then

$$\bar{A} = A \cup A'.$$

Proof. (\supseteq) We only need to show $A' \subseteq \bar{A}$. For every $x \in A'$, $x \in \bar{A}$ due to Theorem 2.6.5. \checkmark

(\subseteq) Let $x \in \bar{A} \setminus A$. By definition, every neighborhood of x intersects A while x cannot be in the intersection since $x \notin A$. Thus, $x \in A'$. \checkmark

□

Corollary 2.6.1

Let $A \subseteq X$ where X is a topological space. Then A is closed if and only if $A' \subseteq A$.

Proof. (\Rightarrow) $A = \bar{A} = A \cup A'$ and it implies $A' \subseteq A$. \checkmark

(\Leftarrow) $\bar{A} = A \cup A' = A$ and \bar{A} is closed. \checkmark

□

Definition 2.6.5: Convergence of a Sequence

Let X be a topological space. Then, a sequence $\{x_n\}$ in X converges to $x \in X$ if, for every neighborhood U of x , there exists $N \in \mathbb{Z}_+$ such that $x_n \in U$ for all $n \geq N$.

Note:-

The point to which a sequence converges may not be unique in general. If $X = \{a, b, c\}$ and $\mathcal{T} = \{\emptyset, X, \{b\}, \{a, b\}, \{b, c\}\}$, the sequence $x_n = b$ may converge to a , b , or c as any neighborhood of a or c contains b .

2.6.3 Hausdorff Spaces

Definition 2.6.6: Hausdorff Space

A topological space (X, \mathcal{T}) is called a *Hausdorff space* if for each pair x_1 and x_2 of distinct points of X , there exist neighborhoods U_1 and U_2 of x_1 and x_2 , respectively, that are disjoint. In other words,

$$\forall x_1, x_2 \in X, (x_1 \neq x_2 \implies \exists U_1, U_2 \in \mathcal{T}, x_1 \in U_1 \wedge x_2 \in U_2 \wedge U_1 \cap U_2 = \emptyset).$$

Theorem 2.6.7

Every finite point set in a Hausdorff space X is closed.

Proof. It suffices to prove that every singleton of X is closed since closedness of finite point set will be naturally driven by Theorem 2.6.1.

If $|X| \leq 1$, then it is done. Now, let x and y be distinct elements in X . Then, there are disjoint open sets U and V such that $x \in U$ and $y \in V$. Therefore, x and y are not limit points of each other. Thus, there are at most one limit point of $\{x\}$. (If it exists, it must be x .) Thus, $\{x\}' \subseteq \{x\}$; $\{x\}$ is closed by Corollary 2.6.1. \square

Definition 2.6.7: T_1 Axiom

A topological space X is said to satisfy T_1 axiom if every singleton in X is closed.

Note:-

Theorem 2.6.7 implies that every Hausdorff space satisfies T_1 axiom.

Note:-

T_1 axiom is strictly weaker than being a Hausdorff space.

- \mathbb{R} in the finite complement topology satisfies T_1 axiom. Every singleton $\{x\}$ is closed since $\mathbb{R} \setminus \{x\}$ is open.
- However, it is not a Hausdorff space. Suppose $x, y \in \mathbb{R}$ with $x \neq y$ and there are disjoint open set U and V such that $x \in U$ and $y \in V$. Then, since $U \cap V = \emptyset$, $\mathbb{R} = \mathbb{R} \setminus (U \cap V) = (X \setminus U) \cup (X \setminus V)$, which is impossible since $X \setminus U$ and $X \setminus V$ are finite.

Theorem 2.6.8

Let X be a space satisfying the T_1 axiom; let $A \subseteq X$. Then $x \in A'$ if and only if every neighborhood of x contains infinitely many points of A .

Proof. (\Rightarrow) Let $x \in A'$ and suppose some neighborhood U of x intersects A in finitely many points. Then, it also intersects $A \setminus \{x\}$ in finitely many points; let us denote them x_1, x_2, \dots, x_m . Noting that $\{x_1, x_2, \dots, x_m\}$ is closed as X satisfies T_1 axiom, $X \setminus \{x_1, x_2, \dots, x_m\}$ is a neighborhood of x but does not intersect $A \setminus \{x\}$, contradicting that x is a limit point of A .

(\Leftarrow) Let U be any neighborhood of x . Then, U intersects A in infinitely many points by assumption, and thus it intersects $A \setminus \{x\}$ in infinitely many points. Therefore, x is a limit point of A . \square

Theorem 2.6.9

If X is a Hausdorff space, then there is at most one point of X to which a sequence of points of X converges.

Proof. Suppose $\{x_n\}$ is a sequence in X that converges to x . If $y \neq x$, we may find disjoint neighborhoods U and V of x and y , respectively. Then, U has all but finitely many points of x_n , but V cannot. Therefore, y cannot be a point that $\{x_n\}$ converges to. \square

Note:-

The finite complement topology on \mathbb{R} is not a Hausdorff.

Let $\{x_n\}$ be a sequence that has no points infinitely repeated in $\{x_n\}$. Then, $\{x_n\}$ converges to every point in \mathbb{R}^n .

2.7 Continuous Functions

2.7.1 Continuity of a Function

Definition 2.7.1: Continuity of a Function

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

Note:-

To prove a function $f : X \rightarrow Y$ is continuous, it is enough to prove that every basis of Y has an open preimage in X . Then, for every open $V = \bigcup_{\alpha \in J} B_\alpha \subseteq Y$, it follows that

$$f^{-1}(V) = \bigcup_{\alpha \in J} f^{-1}(B_\alpha)$$

is open in X .

If the topology on Y is given by a subbasis, it is even sufficient to prove every preimage of subbasis element is open. Then, for every basis $B = \bigcap_{i=1}^n S_i$, it follows that

$$f^{-1}(B) = \bigcap_{i=1}^n f^{-1}(S_i)$$

is open in X .

Theorem 2.7.1

Let X and Y be topological spaces. TFAE

- (i) f is continuous.

- (ii) For every subset A of X , $f(\bar{A}) \subseteq \overline{f(A)}$.
- (iii) For every closed set B of Y , the set $f^{-1}(B)$ is closed in X .
- (iv) For each $x \in X$ and each neighborhood V of $f(x)$, there is a neighborhood U of x such that $f(U) \subseteq V$.

Proof. ((i) \implies (ii)) Take any $x \in \bar{A}$. Let V be any neighborhood of $f(x)$. Then, $f^{-1}(V)$ is a neighborhood of x . Since $x \in \bar{A}$, by Theorem 2.6.5, $f^{-1}(V)$ intersects A ; $A \cap f^{-1}(V) \neq \emptyset$. Therefore, since $\emptyset \neq f(A \cap f^{-1}(V)) = f(A) \cap f(f^{-1}(V)) \subseteq f(A) \cap V$, V intersects $f(A)$; by Theorem 2.6.5, $f(x) \in \overline{f(A)}$ as V was arbitrary. Therefore, $f(\bar{A}) \subseteq \overline{f(A)}$.

((ii) \implies (iii)) Let B be closed in Y and let $A \triangleq f^{-1}(B)$. Then, $f(A) = f(f^{-1}(B)) \subseteq B$. Therefore, if $x \in \bar{A}$, $f(x) \in f(\bar{A}) \subseteq \overline{f(A)} \subseteq \bar{B} = B$; which implies $x \in f^{-1}(B) = A$. This means $\bar{A} \subseteq A$, thus A is closed.

((iii) \implies (i)) Let V be an open set of Y . Let $B \triangleq Y \setminus V$. Then

$$f^{-1}(B) = f^{-1}(Y) \setminus f^{-1}(V) = X \setminus f^{-1}(V)$$

is closed as B is closed. Thus, $f^{-1}(V) = X \setminus f^{-1}(B)$ is open.

((i) \implies (iv)) For every neighborhood V of $f(x)$, $U = f^{-1}(V)$ is the neighborhood of x that satisfies $f(U) \subseteq V$.

((iv) \implies (i)) Let V be an open set of Y . Then, for each $x \in f^{-1}(V)$, since V is a neighborhood of $f(x)$, there exists a neighborhood U_x of x that satisfies $f(U_x) \subseteq V$. Then, $U_x \subseteq f^{-1}(f(U_x)) \subseteq f^{-1}(V)$. Therefore, $f^{-1}(V) = \bigcup_{x \in f^{-1}(V)} U_x$ is open in X . \square

2.7.2 Homeomorphisms

Definition 2.7.2: Homeomorphism

Let X and Y be topological spaces $f : X \rightarrow Y$ be a bijection. f is called a *homeomorphism* if both f and f^{-1} are continuous.

Note:-

Since the inverse image under f^{-1} is exactly the image under f , “ f^{-1} is continuous” implies “ $f(U)$ is open for all open U in X .” So, f is a homeomorphism if and only if it is a bijection such that $U \subseteq X$ is open in X if and only if $f(U)$ is open in Y .

Note:-

If f is a homeomorphism between X and Y , then $\mathcal{T}_Y = \{f(U) \mid U \in \mathcal{T}_X\}$ and $\mathcal{T}_X = \{f^{-1}(V) \mid V \in \mathcal{T}_Y\}$.

Therefore, any property of X that is entirely expressed in terms of the topology of X yields, via the correspondence f , the corresponding property for the space Y . Such a property of X is called *topological property* of X .

Homeomorphism preserves topological properties.

Definition 2.7.3: Open Map and Closed Map

Let X and Y be topological spaces $f : X \rightarrow Y$ be a function.

- f is said to be an *open map* if $f(U)$ is open for all open $U \subseteq X$ in X .
- f is said to be a *closed map* if $f(U)$ is closed for all closed $U \subseteq X$ in X .

Definition 2.7.4: Topological Imbedding

Let X and Y be topological spaces $f: X \hookrightarrow Y$ be an injection. Then, $f': X \rightarrow f(X)$ obtained by restriction is a bijection. If f' is a homeomorphism in which the topology of $\text{Im } f$ is given as the subspace topology, f is said to be a *topological imbedding*, or simply an *imbedding*, of X in Y .

2.7.3 Constructing Continuous Functions

Theorem 2.7.2 Rules for Constructing Continuous Functions

Let X , Y , and Z be topological spaces.

- (i) (*Constant Function*) If $f: X \rightarrow Y$ has a singleton $f(X)$, f is continuous.
- (ii) (*Inclusion*) If A is a subspace of X , the inclusion function $j: A \rightarrow X$ is continuous.
- (iii) (*Composites*) If $f: X \rightarrow Y$ and $g: Y \rightarrow Z$ are continuous, then the map $g \circ f$ is continuous.
- (iv) (*Restricting the Domain*) If $f: X \rightarrow Y$ is continuous, and if A is a subspace of X , then the restricted function $f|_A: A \rightarrow Y$ is continuous.
- (v) (*Restricting or Expanding the Codomain*) Let $f: X \rightarrow Y$ be continuous. If Z is a subspace of Y and $f(X) \subseteq Z$, then the function $g: X \rightarrow Z$ obtained by restricting the range of f is continuous. If Z is a space having Y as a subspace, then the function $h: X \rightarrow Z$ obtained by expanding the range of f is continuous.
- (vi) (*Local Formulation of Continuity*) The map $f: X \rightarrow Y$ is continuous if X is a union of open sets U_α such that $f|_{U_\alpha}$ is continuous for each α .

Proof.

- (i) Let $f(x) = y_0$ for every $x \in X$ for some fixed $y_0 \in Y$. Then, for each (open) set $V \subseteq Y$,

$$f^{-1}(V) = \begin{cases} X & \text{if } y_0 \in V \\ \emptyset & \text{if } y_0 \notin V \end{cases}$$

is always open in X .

- (ii) If U is open in X , then $f^{-1}(U) = U \cap A$ is open in A (by definition).
- (iii) If U is open in Z , then $g^{-1}(U)$ is open in Y , and thus $(g \circ f)^{-1}(U) = f^{-1}(g^{-1}(U))$ is open in X .
- (iv) $f|_A = f \circ j$ where $j: A \rightarrow X$ is the inclusion function. Therefore, $f|_A$ is continuous by (ii) and (iii).
- (v) First, suppose $f(X) \subseteq Z \subseteq Y$. Take any open set $W \subseteq Z$ of Z . Then, $W = V \cap Z$ for some open set V in Y . Because $f(X) \subseteq Z$ and $f(x) = g(x)$ for all $x \in X$,

$$f^{-1}(V) = f^{-1}(V \cap Z) = f^{-1}(W) = g^{-1}(W).$$

Thus, $g^{-1}(W)$ is open in X as f is continuous.

We get h is continuous from noting that $h = j \circ f$ where $j: Y \rightarrow Z$ is the inclusion function.

- (vi) Let $X = \bigcup_{\alpha \in J} U_\alpha$ in which, for each $\alpha \in J$, U_α is an open set in X such that $f|_{U_\alpha}$ is continuous. Let V be an open set in Y . Then

$$f^{-1}(V) \cap U_\alpha = (f|_{U_\alpha})^{-1}(V)$$

for each $\alpha \in J$; $f^{-1}(V) \cap U_\alpha$ is open in X since $f|_{U_\alpha}$ is continuous. Therefore,

$$f^{-1}(V) = f^{-1}(V) \cap X = f^{-1}(V) \cap \left(\bigcup_{\alpha \in J} U_\alpha \right) = \bigcup_{\alpha \in J} (f^{-1}(V) \cap U_\alpha)$$

is open in X .

□

Theorem 2.7.3 The Pasting Lemma

Let $X = A \cup B$ be a topological space, where A and B are closed in B . Let $f: A \rightarrow Y$ and $g: B \rightarrow Y$ be continuous. If $f(x) = g(x)$ for every $x \in A \cap B$, then the function $h: X \rightarrow Y$ defined by

$$h(x) \triangleq \begin{cases} f(x) & \text{if } x \in A \\ g(x) & \text{if } x \in B \end{cases}$$

is continuous.

Proof. Let C be a closed subset of Y . Now

$$f^{-1}(C) = f^{-1}(C) \cup g^{-1}(C).$$

Since f and g are continuous and C is closed, $f^{-1}(C)$ and $g^{-1}(C)$ are closed by Theorem 2.7.1. Thus, $h^{-1}(C)$ is closed. □

Note:-

Theorem 2.7.3 holds if A and B are both open. It is, nonetheless, a special case of (vi) of Theorem 2.7.2.

Note:-

Theorem 2.7.3 does not hold if A is open and B is closed. For instance, the function $h: A \cup B \rightarrow \mathbb{R}$, where $A = (-\infty, 0)$ and $B = [0, \infty)$, defined by

$$h(x) \triangleq \begin{cases} x - 2 & \text{if } x \in A \\ x + 2 & \text{if } x \in B \end{cases}$$

is not continuous since $h^{-1}((1, 3)) = [0, 1)$ is not open.

Theorem 2.7.4 Maps Into Products

Let $f: A \rightarrow X \times Y$ be given by

$$f(a) = f_1(a) \times f_2(b).$$

Then f is continuous if and only if the functions

$$f_1: A \rightarrow X \quad \text{and} \quad f_2: A \rightarrow Y$$

are continuous.

Proof. (\Rightarrow) We first show that the projections $\pi_1: X \times Y \rightarrow X$ and $\pi_2: X \times Y \rightarrow Y$ are continuous. For each open sets $U \subseteq X$ and $V \subseteq Y$, $\pi_1^{-1}(U) = U \times Y$ and $\pi_2^{-1}(V) = X \times V$ are open; π_1 and π_2 are continuous.

Then, noting that $f_1 = \pi_1 \circ f$ and $f_2 = \pi_2 \circ f$, we conclude f_1 and f_2 are continuous.

(\Leftarrow) For any basis element $U \times V$ in $X \times Y$,

$$\begin{aligned} f^{-1}(U \times V) &= \{a \in A \mid f(a) \in U \times V\} \\ &= \{a \in A \mid f_1(a) \in U \text{ and } f_2(a) \in V\} \\ &= f_1^{-1}(U) \cap f_2^{-1}(V). \end{aligned}$$

Thus, $f^{-1}(U \times V)$ is open since $f_1^{-1}(U)$ and $f_2^{-1}(V)$ are open. \square

2.8 The Product Topology

Definition 2.8.1: Box Topology

Let $\{X_\alpha\}_{\alpha \in J}$ be an indexed family of topological spaces. The topology generated by the basis

$$\mathcal{B} = \left\{ \prod_{\alpha \in J} U_\alpha \mid \forall \alpha \in J, U_\alpha \text{ is open in } X_\alpha \right\}$$

for the product $\prod_{\alpha \in J} X_\alpha$ is called the *box topology*.

Note:-

The collection \mathcal{B} is indeed a basis for $\prod_{\alpha \in J} X_\alpha$. $\bigcup \mathcal{B} = \prod_{\alpha \in J} X_\alpha$ holds since $\prod_{\alpha \in J} X_\alpha \in \mathcal{B}$. Also, an intersection of two basis elements is another basis element. This can be shown by

$$\left(\prod_{\alpha \in J} U_\alpha \right) \cap \left(\prod_{\alpha \in J} V_\alpha \right) = \prod_{\alpha \in J} (U_\alpha \cap V_\alpha).$$

Definition 2.8.2: Projection

Let $\{X_\alpha\}_{\alpha \in J}$ be an indexed family of sets. Let

$$\pi_\beta: \prod_{\alpha \in J} X_\alpha \rightarrow X_\beta$$

be defined by

$$(x_\alpha)_{\alpha \in J} \mapsto x_\beta$$

for each $\beta \in J$. Then, π_β is called the *projection mapping* associated with the index β .

Definition 2.8.3: Product Topology

Let $\{X_\alpha\}_{\alpha \in J}$ be an indexed family of topological spaces. Let \mathcal{S}_β denote the collection

$$\mathcal{S}_\beta = \{ \pi_\beta^{-1}(U_\beta) \mid U_\beta \text{ is open in } X_\beta \}$$

and let

$$\mathcal{S} = \bigcup_{\alpha \in J} \mathcal{S}_\alpha.$$

The topology generated by the subbasis \mathcal{S} for $\prod_{\alpha \in J} X_\alpha$ is called the *product topology*. In this topology, $\prod_{\alpha \in J} X_\alpha$ is called a *product space*.

Note:-

A typical basis of the product topology has a form of

$$B = \pi_{\beta_1}^{-1}(U_{\beta_1}) \cap \pi_{\beta_2}^{-1}(U_{\beta_2}) \cap \cdots \cap \pi_{\beta_n}^{-1}(U_{\beta_n})$$

where $\beta_i \in J$ and U_{β_i} is open in X_{β_i} for each $i \in [n]$. Since $\pi_{\beta_1}^{-1}(U_{\beta_1}) \cap \pi_{\beta_2}^{-1}(U_{\beta_2}) = \pi_{\beta_1}^{-1}(U_{\beta_1} \cap U_{\beta_2})$, without loss of generality, β_i 's are mutually different. This means,

$$B = \prod_{\alpha \in J} U_\alpha$$

where $U_\alpha = \begin{cases} U_{\beta_i} & \text{if } \alpha = \beta_i \text{ for some } i \in [n] \\ X_\alpha & \text{otherwise.} \end{cases}$ In other words, a basis element is a product of U_α 's where U_α is an open set of X_α for finitely many indices and $U_\alpha = X_\alpha$ for the remaining indices.

Note:-

- For finite products, i.e., for finite J , the box topology and the product topology on $\prod_{\alpha \in J} X_\alpha$ are the same.
- In general, the box topology is finer than the product topology since the basis of the box topology contains the basis of the product topology.

Theorem 2.8.1

Suppose the topology on each space X_α is given by a basis \mathcal{B}_α . Then,

$$\mathcal{B}_1 = \left\{ \prod_{\alpha \in J} B_\alpha \mid \forall \alpha \in J, B_\alpha \in \mathcal{B}_\alpha \right\}$$

is a basis for the box topology on $\prod_{\alpha \in J} X_\alpha$.

Moreover,

$$\mathcal{B}_2 = \left\{ \prod_{\alpha \in J} B_\alpha \mid B_\alpha \in \mathcal{B}_\alpha \text{ for finitely many } \alpha \text{'s and } B_\alpha = X_\alpha \text{ for remaining indices} \right\}$$

is a basis for the product topology on $\prod_{\alpha \in J} X_\alpha$.

Proof. The basis for the box topology in Definition 2.8.1 has B_1 as a subset. Thus, the box

topology is finer than the topology generated by B_1 .

Also, for any basis element $\prod_{\alpha \in J} U_\alpha$ of the box topology and $x \in \prod_{\alpha \in J} U_\alpha$, since $x_\alpha \in U_\alpha$, there exists some $B_\alpha \in \mathcal{B}_\alpha$ such that $x_\alpha \in B_\alpha \subseteq U_\alpha$. Thus, $x \in \prod_{\alpha \in J} B_\alpha \subseteq \prod_{\alpha \in J} U_\alpha$; the topology generated by B_1 is finer than the box topology by Lemma 2.2.4.

Every element in \mathcal{B}_2 is a basis element of the product topology. Thus, \mathcal{B}_2 generates a product which is coarser than the product topology.

Let $B = \prod_{\alpha \in J} U_\alpha$ be a basis of the product topology and $x \in B$. Then, $U_\alpha = X_\alpha$ for all but finitely many many indices; let $\alpha_1, \alpha_2, \dots, \alpha_n$ denote indices where $U_\alpha \neq X_\alpha$. Then, for each $i \in [n]$, since $x_{\alpha_i} \in U_{\alpha_i}$, there exists basis element $B_{\alpha_i} \in \mathcal{B}_{\alpha_i}$ such that $x_{\alpha_i} \in B_{\alpha_i} \subseteq U_{\alpha_i}$. Thus, $x \in \prod_{\alpha \in J} B_\alpha \subseteq B$ where $B_\alpha = X_\alpha$ if $\alpha \notin \{\alpha_1, \alpha_2, \dots, \alpha_n\}$. \square

Theorem 2.8.2

Let A_α be a subspace of X_α for each $\alpha \in J$. Then $\prod_{\alpha \in J} A_\alpha$ is a subspace of $\prod_{\alpha \in J} X_\alpha$, if both products are given in the box topology, or if both products are given in the product topology.

Proof. (For box topology) The box topology on $\prod_{\alpha \in J} A_\alpha$ has a basis of

$$\left\{ \prod_{\alpha \in J} (A_\alpha \cap U_\alpha) \mid U_\alpha \text{ is open in } X_\alpha \right\},$$

which is exactly equal to the subspace topology of $\prod_{\alpha \in J} A_\alpha$,

$$\left\{ \left(\prod_{\alpha \in J} A_\alpha \right) \cap \left(\prod_{\alpha \in J} U_\alpha \right) \mid U_\alpha \text{ is open in } X_\alpha \right\}.$$

(For product topology) It is analogous; the theorem comes inherently from the fact that $\prod (A_\alpha \cap U_\alpha) = \left(\prod A_\alpha \right) \cap \left(\prod U_\alpha \right)$. \square

Theorem 2.8.3

If each space X_α is a Hausdorff space, then $\prod_{\alpha \in J} X_\alpha$ is a Hausdorff space in both the box and the product topologies.

Proof. Let $x, y \in \prod_{\alpha \in J} X_\alpha$ with $x \neq y$. Then, there is some index $\alpha_0 \in J$ such that $x_{\alpha_0} \neq y_{\alpha_0}$. Then, since X_{α_0} is Hausdorff, there are disjoint neighborhoods U and V in X_{α_0} of x_{α_0} and y_{α_0} , respectively. Then, $x \in \prod_{\alpha \in J} U_\alpha$ and $y \in \prod_{\alpha \in J} V_\alpha$ where

$$U_\alpha \triangleq \begin{cases} U & \text{if } \alpha = \alpha_0 \\ X_\alpha & \text{otherwise} \end{cases} \quad \text{and} \quad V_\alpha \triangleq \begin{cases} V & \text{if } \alpha = \alpha_0 \\ X_\alpha & \text{otherwise} \end{cases}.$$

As $\prod_{\alpha \in J} U_\alpha$ and $\prod_{\alpha \in J} V_\alpha$ are open in both topologies, they are disjoint neighborhoods of x and y in both topologies. \square

Theorem 2.8.4

Let $\{X_\alpha\}_{\alpha \in J}$ be an indexed family of spaces and $A_\alpha \subseteq X_\alpha$ for each $\alpha \in J$. Then

$$\prod_{\alpha \in J} \overline{A_\alpha} = \overline{\prod_{\alpha \in J} A_\alpha}$$

in both the box and the product topologies.

Proof. (\subseteq) Let $x \in \prod_{\alpha \in J} \overline{A_\alpha}$. Let $U = \prod_{\alpha \in J} U_\alpha$ be a basis element (for either the box or the product topology) that contains x . For each $\alpha \in J$, since $x_\alpha \in \overline{A_\alpha}$ and U_α is a neighborhood of x , $U_\alpha \cap A_\alpha \neq \emptyset$ by Theorem 2.6.5. This implies

$$\left(\prod_{\alpha \in J} A_\alpha\right) \cap U = \left(\prod_{\alpha \in J} A_\alpha\right) \cap \left(\prod_{\alpha \in J} U_\alpha\right) = \prod_{\alpha \in J} (A_\alpha \cap U_\alpha) \neq \emptyset$$

Since the choice of U was arbitrary, by Theorem 2.6.5, $x \in \overline{\prod_{\alpha \in J} A_\alpha}$.

(\supseteq) Let $x \in \overline{\prod_{\alpha \in J} A_\alpha}$. Fix any $\alpha_0 \in J$, and let U_{α_0} be a neighborhood of x_{α_0} in X_{α_0} . Since $\pi_{\alpha_0}^{-1}(U_{\alpha_0})$ is a neighborhood of x (in both topologies), $\pi_{\alpha_0}^{-1}(U_{\alpha_0}) \cap \prod_{\alpha \in J} A_\alpha \neq \emptyset$ by Theorem 2.6.5. In particular, at the α_0^{th} index, $U_{\alpha_0} \cap A_{\alpha_0} \neq \emptyset$. Thus, $x_{\alpha_0} \in \overline{A_{\alpha_0}}$.

Therefore, $x \in \prod_{\alpha \in J} \overline{A_\alpha}$. □

Note:-

Theorem 2.8.2, Theorem 2.8.3, and Theorem 2.8.4 illustrate the common property of the box and the product topologies. We are now going to investigate the *differences* that makes the product topology more useful.

Theorem 2.8.5

Let $f : A \rightarrow \prod_{\alpha \in J} X_\alpha$ be given by the equation

$$f(a) = (f_\alpha(a))_{\alpha \in J},$$

where $f_\alpha : A \rightarrow X_\alpha$ for each α . Let $\prod_{\alpha \in J} X_\alpha$ have the product topology. Then f is continuous if and only if each f_α is continuous.

Proof. (\Rightarrow) For each $\alpha \in J$, since π_α is continuous, $f_\alpha = \pi_\alpha \circ f$ is continuous by (iii) of Theorem 2.7.2.

(\Leftarrow) Let $\pi_\alpha^{-1}(U_\alpha)$ be any subbasis element of the product topology. Since $\pi_\alpha \circ f = f_\alpha$, $f^{-1}(\pi_\alpha^{-1}(U_\alpha)) = f_\alpha^{-1}(U_\alpha)$ is open. Thus, f is continuous. □

Note:-

It still holds in the box topology that, if f is continuous, then each f_α is continuous. The proof is exactly the same.

However, the converse does not hold. If we let $f : \mathbb{R} \rightarrow \mathbb{R}^\omega$ (where \mathbb{R} is in the standard topology) defined by

$$f(t) = (t, t, t, \dots),$$

the coordinate functions $f_n : \mathbb{R} \rightarrow \mathbb{R}$ defined by $f_n(t) = t$ are continuous. However, f is not continuous. The set

$$U = \prod_{n \in \mathbb{Z}_+} \left(-\frac{1}{n}, \frac{1}{n}\right)$$

is open in \mathbb{R}^ω endowed with the box topology. However, its inverse image $f^{-1}(U) = \{0\}$ is not open in \mathbb{R} .

2.9 The Metric Topology

Definition 2.9.1: Metric

A *metric* on a set X is a function

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

having the following properties.

- (i) (*Positive Definiteness*) $d(x, y) \geq 0$ for all $x, y \in X$; equality holds if and only if $x = y$.
- (ii) (*Symmetry*) $d(x, y) = d(y, x)$ for all $x, y \in X$.
- (iii) (*Triangle Inequality*) $d(x, z) \leq d(x, y) + d(y, z)$ for all $x, y, z \in X$.

Definition 2.9.2: Epsilon-Ball

Given a metric d on X and $\varepsilon \in \mathbb{R}_+$, the set

$$B_d(x, \varepsilon) = \{y \in X \mid d(x, y) < \varepsilon\}$$

is called the ε -ball centered at x . Sometimes, we write $B(x, \varepsilon)$ if no confusion arises.

Lemma 2.9.1

Let d be a metric on a set X . If $y \in B(x, \varepsilon)$, then there is some $\delta \in \mathbb{R}_+$ such that $y \in B(y, \delta) \subseteq B(x, \varepsilon)$.

Proof. Let $\delta = \varepsilon - d(x, y)$. ($\delta \in \mathbb{R}_+$, indeed.) Then, if $z \in B(y, \delta)$, $d(x, z) \leq d(x, y) + d(y, z) < d(x, y) + (\varepsilon - d(x, y)) = \varepsilon$. Thus, $B(y, \delta) \subseteq B(x, \varepsilon)$. \square

Definition 2.9.3: Metric Topology

If d is a metric on the set X , then the topology generated by the basis

$$\mathcal{B} = \{B_d(x, \varepsilon) \mid x \in X \text{ and } \varepsilon \in \mathbb{R}_+\}$$

is called the *metric topology induced by d* .

Note:-

\mathcal{B} is actually a basis for X . The first condition can be easily check by noting that $x \in B(x, 1)$ for every $x \in X$.

To check the second condition, let $y \in B(x_1, \varepsilon_1) \cap B(x_2, \varepsilon_2)$. Then, by Lemma 2.9.1, there are $\delta_1, \delta_2 \in \mathbb{R}_+$ such that $B(y, \delta_1) \subseteq B(x_1, \varepsilon_1)$ and $B(y, \delta_2) \subseteq B(x_2, \varepsilon_2)$. If we take $\delta_0 \triangleq \min\{\delta_1, \delta_2\}$, $y \in B(y, \delta_0) \subseteq B(x_1, \varepsilon_1) \cap B(x_2, \varepsilon_2)$.

Definition 2.9.4: Metrizability and Metric Space

If X is a topological space, X is said to be *metrizable* if there exists a metric d on X that induces the topology of X . A *metric space* is a metrizable space X together with a specific metric d that gives the topology of X .

Definition 2.9.5: Boundedness

Let (X, d) be a metric space. A subset of A of X is said to be *bounded* if

$$\exists M \in \mathbb{R}, \forall a_1, a_2 \in A, d(a_1, a_2) \leq M.$$

Note:-

Boundedness is not a topological property as it depends on the metric. For instance, \mathbb{R} can be metrizable by two metrics:

$$d_1(x, y) = |x - y| \quad \text{and} \quad d_2(x, y) = \min\{|x - y|, 1\}.$$

(Both are metrics and induce the standard topology on \mathbb{R} .) However, \mathbb{R} is not bounded with respect to d_1 , but is bounded with respect to d_2 .

Definition 2.9.6: Diameter

Let (X, d) be a metric space. if $\emptyset \neq A \subseteq X$, the *diameter* of A is defined to be

$$\text{diam} A \triangleq \sup\{d(a_1, a_2) \mid a_1, a_2 \in A\}.$$

Theorem 2.9.1

Let (X, d) be a metric space. Define $\bar{d}: X \times X \rightarrow \mathbb{R}$ by

$$\bar{d}(x, y) = \min\{d(x, y), 1\}.$$

Then \bar{d} is a metric on X that induces the same topology as d .

Proof. The positive definiteness and the symmetry is direct. Let us check the triangle inequality.

Take any $x, y, z \in X$. Since $\bar{d}(x, z) \leq 1$ always holds, we get the triangle inequality in the case of $\bar{d}(x, y) \geq 1$ or $\bar{d}(y, z) \geq 1$.

In the other case, i.e., $\bar{d}(x, y) < 1$ and $\bar{d}(y, z) < 1$, it holds that $\bar{d}(x, y) = d(x, y)$ and $\bar{d}(y, z) = d(y, z)$. This implies

$$\bar{d}(x, z) \leq d(x, z) \leq d(x, y) + d(y, z) = \bar{d}(x, y) + \bar{d}(y, z),$$

which completes the proof that \bar{d} is a metric on X .

Now, note that, in any metric space,

$$\{B_d(x, \varepsilon) \mid x \in X \text{ and } \varepsilon \in \mathbb{R}_+\}$$

and

$$\{B_d(x, \varepsilon) \mid x \in X \text{ and } \varepsilon \in (0, 1)\}$$

generates the same topology. Therefore, it follows that d and \bar{d} generates the same topology on X , because the collections of ε -balls with $\varepsilon < 1$ under these two metrics are the same. \square

Definition 2.9.7: Standard Bounded Metric

Let (X, d) be a metric space. Define $\bar{d}: X \times X \rightarrow \mathbb{R}$ by

$$\bar{d}(x, y) = \min\{d(x, y), 1\}.$$

Then, \bar{d} is a metric on X and is called the *standard bounded metric corresponding to d* .

Definition 2.9.8: Norm, Euclidean Metric and Square Metric

Given $\mathbf{x} = (x_1, x_2, \dots, x_n) \in \mathbb{R}^n$, we define the *norm* of \mathbf{x} by the equation.

$$\|\mathbf{x}\| = (x_1^2 + x_2^2 + \dots + x_n^2)^{1/2};$$

and we define the *euclidean metric* d on \mathbb{R}^n by the equation

$$d(\mathbf{x}, \mathbf{y}) = \|\mathbf{x} - \mathbf{y}\| = [(x_1 - y_1)^2 + \dots + (x_n - y_n)^2]^{1/2}.$$

We define the *square metric* ρ on \mathbb{R}^n by the equation

$$\rho(\mathbf{x}, \mathbf{y}) = \max\{|x_1 - y_1|, \dots, |x_n - y_n|\}.$$

Note:-

The proof that ρ is a metric is trivial but for the triangle inequality. Since, for each $i \in [n]$,

$$|x_i - z_i| \leq |x_i - y_i| + |y_i - z_i| \leq \rho(\mathbf{x}, \mathbf{y}) + \rho(\mathbf{y}, \mathbf{z}),$$

it holds that

$$\rho(\mathbf{x}, \mathbf{z}) \leq \rho(\mathbf{x}, \mathbf{y}) + \rho(\mathbf{y}, \mathbf{z}).$$

Lemma 2.9.2

Let d and d' be two metrics on the set X ; let \mathcal{T} and \mathcal{T}' be the topologies they induce, respectively. Then,

$$\mathcal{T} \subseteq \mathcal{T}' \iff \forall (x, \varepsilon) \in X \times \mathbb{R}_+, \exists \delta \in \mathbb{R}_+, B_{d'}(x, \delta) \subseteq B_d(x, \varepsilon).$$

Proof. (\Rightarrow) Take any $x \in X$ and $\varepsilon \in \mathbb{R}_+$. Since $B_d(x, \varepsilon)$ is a basis element of \mathcal{T} , by Lemma 2.2.4, there is a basis element B' of \mathcal{T}' such that $x \in B' \subseteq B_d(x, \varepsilon)$. By Lemma 2.9.1, there is some $B_{d'}(x, \delta)$ such that $x \in B_{d'}(x, \delta) \subseteq B'$.

(\Leftarrow) Let $x \in X$; let B be any basis element of \mathcal{T} that contains x . By Lemma 2.9.1, there is some $B_d(x, \varepsilon)$ such that $B_d(x, \varepsilon) \subseteq B$. By supposition, there exists $\delta \in \mathbb{R}_+$ such that $x \in B_{d'}(x, \delta) \subseteq B_d(x, \varepsilon)$. Thus, by Lemma 2.2.4, \mathcal{T}' is finer than \mathcal{T} . \square

Theorem 2.9.2

The topologies on \mathbb{R}^n induced by d and ρ are the same as the product topology on \mathbb{R}^n .

Proof. Let \mathcal{T}_d and \mathcal{T}_ρ be the topologies induced by d and ρ , respectively. Let $\mathcal{T}_{\mathbb{R}^n}$ be the product topology on \mathbb{R}^n .

$(\mathcal{T}_d = \mathcal{T}_\rho)$ Let $\mathbf{x} = (x_1, \dots, x_n)$ and $\mathbf{y} = (y_1, \dots, y_n)$. Let $M \in [n]$ such that $|x_M - y_M| = \rho(\mathbf{x}, \mathbf{y})$.

Then,

$$\begin{aligned}\rho(\mathbf{x}, \mathbf{y})^2 &= |x_M - y_M|^2 \leq \sum_{i=1}^n (x_i - y_i)^2 = d(\mathbf{x}, \mathbf{y})^2 \\ &\leq \sum_{i=1}^n (x_M - y_M)^2 = n\rho(\mathbf{x}, \mathbf{y})^2;\end{aligned}$$

thus

$$\rho(\mathbf{x}, \mathbf{y}) \leq d(\mathbf{x}, \mathbf{y}) \leq \sqrt{n}\rho(\mathbf{x}, \mathbf{y}).$$

Therefore, we get, for every $\mathbf{x} \in \mathbb{R}^n$ and $\varepsilon \in \mathbb{R}_+$,

$$B_d(\mathbf{x}, \varepsilon) \subseteq B_\rho(\mathbf{x}, \varepsilon) \quad \text{and} \quad B_\rho(\mathbf{x}, \varepsilon/\sqrt{n}) \subseteq B_d(\mathbf{x}, \varepsilon).$$

By Lemma 2.9.2, one is finer than the other; $\mathcal{T}_d = \mathcal{T}_\rho$.

($\mathcal{T}_\rho = \mathcal{T}_{\mathbb{R}^n}$) $\mathcal{T}_\rho \subseteq \mathcal{T}_{\mathbb{R}^n}$ is direct since every basis element

$$B_\rho(\mathbf{x}, \varepsilon) = (x_1 - \varepsilon, x_1 + \varepsilon) \times \cdots \times (x_n - \varepsilon, x_n + \varepsilon)$$

of \mathcal{T}_ρ is a basis element of $\mathcal{T}_{\mathbb{R}^n}$, by Lemma 2.2.4, $\mathcal{T}_\rho \subseteq \mathcal{T}_{\mathbb{R}^n}$.

To prove the other containment, take any $\mathbf{x} \in \mathbb{R}^n$ and let $B = \prod_{i=1}^n (a_i, b_i)$ be a basis element of $\mathcal{T}_{\mathbb{R}^n}$ that contains \mathbf{x} . For each $i \in [n]$, let $\varepsilon_i = \min\{x_i - a_i, b_i - x_i\}$. Then, $(x_i - \varepsilon_i, x_i + \varepsilon_i) \subseteq (a_i, b_i)$ for all $i \in [n]$. Thus, it follows that $\mathbf{x} \in B_\rho(\mathbf{x}, \min_{i=1}^n \varepsilon_i) \subseteq B$; $\mathcal{T}_{\mathbb{R}^n} \subseteq \mathcal{T}_\rho$ by Lemma 2.2.4. \square

Corollary 2.9.1

The product topology on \mathbb{R}^n is metrizable.

Theorem 2.9.3

Given an index set J and given points $\mathbf{x} = (x_\alpha)_{\alpha \in J}$ and $\mathbf{y} = (y_\alpha)_{\alpha \in J}$ of \mathbb{R}^J , let us define $\bar{\rho}: \mathbb{R}^J \times \mathbb{R}^J \rightarrow \mathbb{R}$ by

$$\bar{\rho}(\mathbf{x}, \mathbf{y}) = \sup\{\bar{d}(x_\alpha, y_\alpha) \mid \alpha \in J\}$$

where \bar{d} is the standard bounded metric on \mathbb{R} . Then, $\bar{\rho}$ is a metric on \mathbb{R}^J .

Proof. The positive definiteness and the symmetry is direct. Let us check the triangle inequality.

Let $\mathbf{x}, \mathbf{y}, \mathbf{z} \in \mathbb{R}^J$. For each $\alpha \in J$, it holds that

$$\bar{d}(x_\alpha, z_\alpha) \leq \bar{d}(x_\alpha, y_\alpha) + \bar{d}(y_\alpha, z_\alpha) \leq \bar{\rho}(\mathbf{x}, \mathbf{y}) + \bar{\rho}(\mathbf{y}, \mathbf{z}).$$

Therefore, $\bar{\rho}(\mathbf{x}, \mathbf{z}) \leq \bar{\rho}(\mathbf{x}, \mathbf{y}) + \bar{\rho}(\mathbf{y}, \mathbf{z})$. \square

Definition 2.9.9: Uniform Metric and Uniform Topology

Given an index set J , $\bar{\rho}$ in the Theorem 2.9.3 is called the *uniform metric* on \mathbb{R}^J , and the topology it induces is called the *uniform topology*.

Theorem 2.9.4

The uniform topology on \mathbb{R}^J is finer than the product topology and coarser than the

box topology. Moreover, they are all strict when J is infinite. In other words,

$$\mathcal{T}_{\text{product}} \subseteq \mathcal{T}_{\text{uniform}} \subseteq \mathcal{T}_{\text{box}}$$

They are strict if J is infinite.

Proof. ($\mathcal{T}_{\text{product}} \subseteq \mathcal{T}_{\text{uniform}}$) Let $B = \prod_{\alpha \in J} U_\alpha$ be a basis element of the product topology and $\mathbf{x} \in B$. Let $\alpha_1, \alpha_2, \dots, \alpha_n$ be the indices such that $U_{\alpha_i} \neq \mathbb{R}$. Then, for each $i \in [n]$, there exists $\varepsilon_i \in \mathbb{R}_+$ such that $B_{\bar{d}}(x_{\alpha_i}, \varepsilon_i) \subseteq U_{\alpha_i}$. Let $\varepsilon \triangleq \min_{i=1}^n \varepsilon_i$. Then, $B_{\bar{\rho}}(\mathbf{x}, \varepsilon) \subseteq B$. The result follows from Lemma 2.2.4. ✓

($\mathcal{T}_{\text{uniform}} \subseteq \mathcal{T}_{\text{box}}$) Let B be any basis element of the uniform topology and $\mathbf{x} \in B$. Then, Lemma 2.9.1 implies that there is some ε -ball centered at \mathbf{x} such that $B_{\bar{\rho}}(\mathbf{x}, \varepsilon) \subseteq B$. Then, $\prod_{\alpha \in J} (x_\alpha - \varepsilon/2, x_\alpha + \varepsilon/2)$ is an open neighborhood of \mathbf{x} which is contained in B . ✓

($\mathcal{T}_{\text{product}} \not\subseteq \mathcal{T}_{\text{uniform}}$ if J is infinite) Let $0 < \varepsilon < 1$ and $\mathbf{x} \in \mathbb{R}^J$. Then, $\mathbf{x} \in B_{\bar{\rho}}(\mathbf{x}, \varepsilon)$ but there is no basis element of the product topology that is contained in $B_{\bar{\rho}}(\mathbf{x}, \varepsilon)$. By Lemma 2.2.4, the product topology is not finer than the uniform topology. ✓

($\mathcal{T}_{\text{uniform}} \not\subseteq \mathcal{T}_{\text{box}}$ if J is infinite.) Let $U \triangleq \prod_{\alpha \in J} (0, 2)$, which is a basis element of the box topology. There is an injective function $f: \mathbb{Z}_+ \hookrightarrow J$ by Theorem 1.7.1. Let $\mathbf{x} \in U$ where

$$x_\alpha = \begin{cases} 1/n & \text{if } \exists n \in \mathbb{N}_+, f(n) = \alpha \\ 1 & \text{otherwise.} \end{cases}$$

Then, no basis element that contains \mathbf{x} can be contained in U . If otherwise, there is an $B_{\bar{\rho}}(\mathbf{x}, \varepsilon') \subseteq U$ by Lemma 2.9.1. However, there exists $\alpha_0 \in J$ such that $f(n) = \alpha_0$ where $n\varepsilon' > 2$, which implies $x_{\alpha_0} = 1/n < \varepsilon'/2$. ✓

Let $\mathbf{x}' \in \mathbb{R}^J$ defined by

$$x'_\alpha = \begin{cases} x_{\alpha_0} - \varepsilon'/2 & \text{if } \alpha = \alpha_0 \\ x_\alpha & \text{otherwise.} \end{cases}$$

Then, $\mathbf{x}' \in B_{\bar{\rho}}(\mathbf{x}, \varepsilon')$ but $x'_{\alpha_0} - \varepsilon'/2 < 0$; $\mathbf{x}' \notin U$. This contradicts $B_{\bar{\rho}}(\mathbf{x}, \varepsilon') \subseteq U$. ✓

□

Theorem 2.9.5 Countable Product of Metrizable Spaces Is Metrizable

Let X_n be a metric space with metric d_n for each $n \in \mathbb{Z}_+$. Let \bar{d}_n be the standard bounded metric corresponding to d_n . If $\mathbf{x}, \mathbf{y} \in \prod_{i \in \mathbb{Z}_+} X_i$, define

$$D(\mathbf{x}, \mathbf{y}) = \sup \left\{ \frac{\bar{d}_i(x_i, y_i)}{i} \mid i \in \mathbb{Z}_+ \right\}.$$

Then D is a metric that induces the product topology on $\prod_{i \in \mathbb{Z}_+} X_i$.

Proof. (D is a metric on $\prod_{i \in \mathbb{Z}_+} X_i$.) The positive definiteness and the symmetry of D is direct. Note that, for each $i \in \mathbb{Z}_+$,

$$\frac{\bar{d}_i(x_i, z_i)}{i} \leq \frac{\bar{d}_i(x_i, y_i)}{i} + \frac{\bar{d}_i(y_i, z_i)}{i} \leq D(\mathbf{x}, \mathbf{y}) + D(\mathbf{y}, \mathbf{z}).$$

Thus,

$$D(\mathbf{x}, \mathbf{z}) = \sup \left\{ \frac{\bar{d}_i(x_i, z_i)}{i} \mid i \in \mathbb{Z}_+ \right\} \leq D(\mathbf{x}, \mathbf{y}) + D(\mathbf{y}, \mathbf{z}). \quad \checkmark$$

($\mathcal{T}_{\text{metric}} \subseteq \mathcal{T}_{\text{product}}$) Let B be any ε' -ball in the metric topology and let $\mathbf{x} \in B$. Then, by Lemma 2.9.1, there exists $\varepsilon \in \mathbb{R}_+$ such that $B_D(\mathbf{x}, \varepsilon) \subseteq B$. Take $N \in \mathbb{Z}_+$ such that $\varepsilon N > 1$. Let V be the basis element for the product topology defined by

$$V \triangleq B_{\bar{d}_1}(x_1, \varepsilon) \times \cdots \times B_{\bar{d}_N}(x_N, \varepsilon) \times X_{n+1} \times X_{n+2} \times \cdots.$$

Note that, given any $\mathbf{y} \in \mathbb{R}^\omega$ and $i \geq N$, $\frac{\bar{d}_i(x_i, y_i)}{i} \leq \frac{1}{N}$. Thus, when $\mathbf{y} \in V$,

$$D(\mathbf{x}, \mathbf{y}) \leq \max \left\{ \frac{\bar{d}_1(x_1, y_1)}{1}, \frac{\bar{d}_2(x_2, y_2)}{2}, \dots, \frac{\bar{d}_N(x_N, y_N)}{N}, \frac{1}{N} \right\} < \varepsilon.$$

Thus, $\mathbf{x} \in V \subseteq B_D(\mathbf{x}, \varepsilon) \subseteq B$. Now, Lemma 2.2.4 tells the result. \checkmark

($\mathcal{T}_{\text{metric}} \supseteq \mathcal{T}_{\text{product}}$) Let $B = \prod_{i \in \mathbb{Z}_+} U_i$ be a basis element of the product topology and $\mathbf{x} \in B$. Let i_1, i_2, \dots, i_n be the indices such that $U_{i_k} \neq X_{i_k}$ for each $k \in [n]$.

For each $k \in [n]$, since U_{i_k} is open, there exists $\varepsilon_k \in (0, 1)$ such that $B_{\bar{d}_{i_k}}(x_{i_k}, \varepsilon_k) \subseteq U_{i_k}$. Let $\varepsilon \triangleq \min_{k=1}^n (\varepsilon_k / i_k)$.

Now we claim that $B_D(\mathbf{x}, \varepsilon) \subseteq U$. Let $\mathbf{y} \in B_D(\mathbf{x}, \varepsilon)$. Then, for all $k \in [n]$,

$$\bar{d}_{i_k}(x_{i_k}, y_{i_k}) \leq i_k \cdot D(\mathbf{x}, \mathbf{y}) < i_k \varepsilon \leq \varepsilon_k < 1.$$

It follows that $y_{i_k} \in B_{\bar{d}_{i_k}}(x_{i_k}, \varepsilon_k)$; therefore $\mathbf{y} \in B$. \checkmark □

Corollary 2.9.2

\mathbb{R}^ω with the product topology is metrizable.

2.10 The Metric Topology (continued)

Theorem 2.10.1 The ε - δ Definition of Continuity

Let $f : X \rightarrow Y$; let X and Y be metrizable with metrics d_X and d_Y , respectively. Then, f is continuous if and only if

$$\forall x \in X, \forall \varepsilon \in \mathbb{R}_+, \exists \delta \in \mathbb{R}_+, \forall y \in Y, (d_X(x, y) < \delta \implies d_Y(f(x), f(y)) < \varepsilon).$$

Proof. (\implies) Given $x \in X$ and $\varepsilon \in \mathbb{R}_+$, the set $f^{-1}(B(f(x), \varepsilon))$ is open and contains x . Thus, there is some δ -ball $B(x, \delta)$ centered at x such that $x \in B(x, \delta) \subseteq f^{-1}(B(f(x), \varepsilon))$. \checkmark

(\impliedby) Let V be open in Y ; we claim that $f^{-1}(V)$ is open in X . Let $x \in f^{-1}(V)$. Since $f(x) \in V$, there is some ε -ball $B(f(x), \varepsilon)$ such that $B(f(x), \varepsilon) \subseteq V$. By the supposition, there is some $\delta \in \mathbb{R}_+$ such that $f(B(x, \delta)) \subseteq B(f(x), \varepsilon)$. Thus, $x \in B(x, \delta) \subseteq f^{-1}(B(f(x), \varepsilon)) \subseteq f^{-1}(V)$. This implies $f^{-1}(V)$ is open by definition. \checkmark □

Definition 2.10.1: Local Basis

A space X is said to have a *local basis at the point* $x \in X$ if there is a countable collection \mathcal{U} of open neighborhoods of x such that any neighborhood U of x contains at least one of element of \mathcal{U} .

Definition 2.10.2: First Countable Axiom

A space X satisfies the *first countable axiom* if it has countable local basis at each point.

Note:-

Any metrizable space satisfies the first countable axiom. For each $x \in X$, $\{B_d(x, 1/n) \mid n \in \mathbb{Z}_+\}$ is a countable local basis at x .

Lemma 2.10.1 The Sequence Lemma

Let X be a topological space; let $A \subseteq X$. If there is a sequence of points in A converging to x , then $x \in \bar{A}$. Moreover, the converse holds if X satisfies the first countable axiom.

Proof. (\Rightarrow) Suppose $x_n \rightarrow x$ and $x_n \in A$. This means every neighborhood U of x intersects A , so $x \in \bar{A}$ by Theorem 2.6.5. \checkmark

(\Leftarrow) Let $\{U_n\}_{n \in \mathbb{Z}_+}$ be a local basis for x . Set $B_n \triangleq \bigcap_{i=1}^n U_i$ so that $B_1 \supseteq B_2 \supseteq \cdots$. Since $x \in \bar{A}$ and $x \in B_n$ is open, we may take $x_n \in A \cap B_n$.

We want to show that $x_n \rightarrow x$. Take any neighborhood U of x . Then, it contains U_{n_0} for some $n_0 \in \mathbb{Z}_+$. Then, for all $n \geq n_0$, $x_n \in U_{n_0} \subseteq U$. \checkmark \square

Lemma 2.10.2

Let X and Y be topological spaces. If $f: X \rightarrow Y$ is continuous, then for every convergent sequence $x_n \rightarrow x$, the sequence $f(x_n)$ converges to $f(x)$. The converse also holds if X satisfies the first countable axiom.

Proof. (\Rightarrow) Let V be a neighborhood of $f(x)$ in Y . Then, $f^{-1}(V)$ is a neighborhood of x in X since f is continuous. Since $x_n \rightarrow x$, there is some $n_0 \in \mathbb{Z}_+$ such that $x_n \in f^{-1}(V)$ whenever $n \geq n_0$, i.e., $f(x_n) \in V$ whenever $n \geq n_0$. \checkmark

(\Leftarrow) We claim that $f(\bar{A}) \subseteq \overline{f(A)}$ for any $A \subseteq X$, and thus f is continuous by Theorem 2.7.1. Let $x \in \bar{A}$. Then, by Lemma 2.10.1, there is a sequence $\{x_n\}_{n \in \mathbb{Z}_+} \subseteq A$ that converges to x . Then, by assumption, the sequence $\{f(x_n)\}_{n \in \mathbb{Z}_+}$ in $f(A)$ converges to $f(x)$. By Lemma 2.10.1, $f(x) \in \overline{f(A)}$. \checkmark \square

Lemma 2.10.3

The addition, subtraction, and multiplication operations are continuous functions from $\mathbb{R} \times \mathbb{R}$ into \mathbb{R} ; and the quotient operation is a continuous function from $\mathbb{R} \times (\mathbb{R} \setminus \{0\})$ into \mathbb{R} .

Theorem 2.10.2

If X is a topological space, and if $f, g: X \rightarrow \mathbb{R}$ are continuous, then $f + g$, $f - g$, and $f \cdot g$ are continuous. If $g(x) \neq 0$ for all x , then f/g is continuous.

Proof. The map $h: X \rightarrow \mathbb{R} \times \mathbb{R}$ defined by

$$h(x) = f(x) \times g(x)$$

is continuous by Theorem 2.8.5. The function $f + g$ equals the composite of h and the addition operation

$$+: \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R};$$

therefore $f + g$ is continuous by (iii) of Theorem 2.7.2. It is similar for $f - g$, $f \cdot g$, and f/g . \square

Definition 2.10.3: Uniform Convergence

Let $\{f_n\} \subseteq X \rightarrow Y$ be a sequence of functions from the set X to the metric space Y . Let d be the metric for Y . We say that the sequence $\{f_n\}$ converges uniformly to the function $f : X \rightarrow Y$ if

$$\forall \varepsilon \in \mathbb{R}_+, \exists N \in \mathbb{Z}_+, \forall n \in \mathbb{Z}_+ (n \geq N \implies \forall x \in X, d(f_n(x), f(x)) < \varepsilon).$$

Note:-

Uniformity of convergence depends not only on the topology of Y but also on its metric.

Theorem 2.10.3 Uniform Limit Theorem

Let $\{f_n\} \subseteq X \rightarrow Y$ be a sequence of continuous functions from the topological space X to the metric space Y . If $\{f_n\}$ converges uniformly to f , then f is continuous.

Proof. Let V be open in Y . We want to show that $f^{-1}(V)$ is open. Take any $x_0 \in f^{-1}(V)$. Let $y_0 \triangleq f(x_0) \in V$. Since $f^{-1}(V)$ is open, there exists $\varepsilon \in \mathbb{R}_+$ such that $B(y_0, \varepsilon) \subseteq f^{-1}(V)$. By uniform convergence,

$$\exists N \in \mathbb{Z}_+, \forall x \in X, d(f_N(x), f(x)) < \varepsilon/4.$$

where d is the metric on Y . Moreover, since f_N is continuous, $U = f_N^{-1}(B(f_N(x_0), \varepsilon/2))$ is a neighborhood of x_0 .

Thus, for each $x \in U$,

$$\begin{aligned} d(y_0, f(x)) &\leq d(f(x_0), f_N(x_0)) + d(f_N(x_0), f_N(x)) + d(f_N(x), f(x)) \\ &< \varepsilon/4 + \varepsilon/2 + \varepsilon/4 = \varepsilon. \end{aligned}$$

Thus, we have $x_0 \in U \subseteq f^{-1}(V)$; $f^{-1}(V)$ is open. \square

Theorem 2.10.4

$\{f_n\} \subseteq X \rightarrow \mathbb{R}$ converges uniformly to $f : X \rightarrow \mathbb{R}$ if and only if $\{f_n\}$ converges to f in the uniform topology.

Proof. (\implies) Let U be any neighborhood of f in the uniform topology. Then, there is an ε -ball $B_{\overline{\rho}}(f, \varepsilon)$ centered at f which is contained in U . By the uniform convergence, there is some $N \in \mathbb{Z}_+$ such that

$$\forall n \in \mathbb{Z}_+, (n \geq N \implies \forall x \in X, d(f_n(x), f(x)) < \varepsilon/2).$$

Thus, for all $n \geq N$, $\overline{\rho}(f_n, f) \leq \varepsilon/2 < \varepsilon$, i.e., $f_n \in B_{\overline{\rho}}(f, \varepsilon) \subseteq U$. \checkmark

(\impliedby) Take any $\varepsilon \in \mathbb{R}_+$. By the convergence in the uniform topology, there exists some $N \in \mathbb{Z}_+$ such that

$$\forall n \in \mathbb{Z}_+, (n \geq N \implies f_n \in B_{\overline{\rho}}(f, \varepsilon)).$$

This implies, whenever $n \geq N$, $\forall x \in X, d(f_n(x), f(x)) < \varepsilon$. \checkmark \square

Corollary 2.10.1

\mathbb{R}^ω with the box topology is not metrizable.

Proof. Let $A = (\mathbb{R}_+)^{\omega}$ be a subset of \mathbb{R}^{ω} . Then, $\mathbf{0}$ is a limit point of A . To see this, let

$$B = (a_1, b_1) \times (a_2, b_2) \times \cdots$$

be any basis element that contains $\mathbf{0}$. Then,

$$(b_1/2, b_2/2, \dots) \in A \cap B.$$

However, there is no sequence of points of A that converge to $\mathbf{0}$. To see this, let $\{\mathbf{a}_n\}_{n \in \mathbb{Z}_+}$ be a sequence of points in A where

$$\mathbf{a}_n = (a_{n1}, a_{n2}, \dots, a_{in}, \dots).$$

Let $B' = \prod_{n \in \mathbb{Z}_+} (-a_{nn}, a_{nn})$ is a neighborhood of $\mathbf{0}$ but no \mathbf{a}_n is in B' ; $\{\mathbf{a}_n\}$ does not converge to $\mathbf{0}$.

Thus, by Lemma 2.10.1, \mathbb{R}^{ω} does not satisfy the first countable axiom, and thus is not metrizable. \square

Corollary 2.10.2

\mathbb{R}^J with uncountable J in the product topology is not metrizable.

Proof. Let $A = \{(x_{\alpha})_{\alpha \in J} \mid x_{\alpha} = 1 \text{ for all but finitely many } \alpha\}$.

Let $\prod_{\alpha \in J} U_{\alpha}$ be a basis that contains $\mathbf{0}$ and suppose $U_{\alpha} \neq \mathbb{R}$ for $\alpha \in \{\alpha_1, \alpha_2, \dots, \alpha_n\}$. Define $(y_{\alpha})_{\alpha \in J}$ by

$$y_{\alpha} \triangleq \begin{cases} 0 & \text{if } \alpha = \alpha_i \text{ for some } i \in [n] \\ 1 & \text{otherwise.} \end{cases}$$

Then, $(y_{\alpha})_{\alpha \in J} \in A \cap \prod_{\alpha \in J} U_{\alpha}$. Hence, $\mathbf{0} \in \bar{A}$ by Theorem 2.6.5.

Now, we shall prove that no sequence in A converges to $\mathbf{0}$. Let $\{\mathbf{a}_n\}_{n \in \mathbb{Z}_+}$ be a sequence in A . For each $n \in \mathbb{Z}_+$, let

$$J_n \triangleq \{\alpha \in J \mid (\mathbf{a}_n)_{\alpha} \neq 1\}.$$

Since each J_n is finite, and since $\bigcup_{n \in \mathbb{Z}_+} J_n$ is thus countable, we may take $\beta \in J \setminus (\bigcup_{n \in \mathbb{Z}_+} J_n)$. For such β , it is $(\mathbf{a}_n)_{\beta} = 1$ for all $n \in \mathbb{Z}_+$. This implies that $\mathbf{a}_n \notin \pi_{\beta}^{-1}((-1, 1))$ for each $n \in \mathbb{Z}_+$ while $\pi_{\beta}^{-1}((-1, 1))$ is a neighborhood of $\mathbf{0}$; $\{\mathbf{a}_n\}_{n \in \mathbb{Z}_+}$ does not converge to $\mathbf{0}$. Thus, \mathbb{R}^J is not metrizable by Lemma 2.10.1. \square

2.11 The Quotient Topology

Definition 2.11.1: Quotient Map

Let X and Y be topological spaces. A map $p: X \rightarrow Y$ is called a *quotient map* if

- (i) p is surjective and
- (ii) $V \subseteq Y$ is open in $Y \iff p^{-1}(V)$ is open in X .

Note:-

A quotient map is continuous.

Definition 2.11.2: Saturated Set

A subset C of X is *saturated* (with respect to the surjective map $p: X \rightarrow Y$) if

$$\forall y \in Y, (p^{-1}(\{y\}) \cap C \neq \emptyset \implies p^{-1}(\{y\}) \subseteq C).$$

In other words, C is saturated if $C = p^{-1}(V)$ for some $V \subseteq Y$.

Note:-

Here is the proof of their equivalence.

- Suppose $C = p^{-1}(V)$ for some $V \subseteq Y$. Let $y \in Y$ and suppose it satisfies $p^{-1}(\{y\}) \cap C \neq \emptyset$. Thus,

$$p^{-1}(\{y\}) \cap p^{-1}(V) = p^{-1}(V \cap \{y\}) \neq \emptyset;$$

$y \in V$. Hence, $p^{-1}(\{y\}) \subseteq p^{-1}(V) = C$.

- For the converse, let

$$\begin{aligned} V &\triangleq \{y \in Y \mid p^{-1}(\{y\}) \cap C \neq \emptyset\} \\ &= \{y \in Y \mid p^{-1}(\{y\}) \subseteq C\} \end{aligned}$$

The second equality follows from the hypothesis.

If $p(x) \in V$ where $x \in X$, by definition of V , $x \in p^{-1}(p(\{x\})) = p^{-1}(\{p(x)\}) \subseteq C$. This proves $p^{-1}(V) \subseteq C$.

For the other containment, let $x \in C$. Then, $\{p(x)\} \cap p(C) \neq \emptyset$, and thus

$$\emptyset \neq p^{-1}(\{p(x)\} \cap p(C)) = p^{-1}(\{p(x)\}) \cap p^{-1}(p(C)) \subseteq p^{-1}(\{p(x)\}) \cap C$$

is nonempty; $p(x) \in V$ by definition of V . This proves $C \subseteq p^{-1}(V)$. □

Lemma 2.11.1

Let X and Y be topological spaces. A surjective, continuous map $p: X \rightarrow Y$ is a quotient map if and only if $p(C)$ is open for every saturated open set $C \subseteq X$.

Proof. The continuity is equivalent to \Rightarrow of Definition 2.11.1 (ii), and ‘sending every saturated open set to an open set’ is equivalent to \Leftarrow of Definition 2.11.1 (ii). □

Lemma 2.11.2

Let X and Y be topological spaces and $p: X \rightarrow Y$ be surjective and continuous. Then, if p is an open map or is a closed map, p is a quotient map.

Proof. If p is open, then the result follows directly from Lemma 2.11.1.

Suppose p is closed and let $V \subseteq Y$ such that $p^{-1}(V)$ is open in X . Then, $X \setminus p^{-1}(V)$ is closed, and thus,

$$p(X \setminus p^{-1}(V)) = p(X) \setminus p(p^{-1}(V)) = Y \setminus V$$

is closed in Y . The last equality comes from Example 1.1.2. Thus, V is open in Y . □

Example 2.11.1

Let $A = ([0, \infty) \times \mathbb{R}) \cup (\mathbb{R} \times \{0\})$ be a subspace of $X = \mathbb{R}^2$ endowed with the standard topology. Let $\pi: A \rightarrow \mathbb{R}$ be the projection onto its first factor, i.e.,

$$\pi(x \times y) = x.$$

Since π is surjective and $\pi^{-1}(V) = (V \times \mathbb{R}) \cap A$ for each $V \subseteq \mathbb{R}$, π is a quotient map when \mathbb{R} is endowed with the standard topology.

However, it is not open as $\pi((\mathbb{R} \times (0, 1)) \cap A) = [0, \infty)$ is not open. It is also not closed as, if we let $C = \{x \times 1/x \mid x \in \mathbb{R}_+\}$, $p(C) = (0, \infty)$ is not closed although C is closed in A .

This shows that the converses of Lemma 2.11.2 are not true.

Theorem 2.11.1

If X is a space and A is a set and if $p: X \rightarrow A$ is a surjective map, then there exists a unique topology \mathcal{T} on A relative to which p is a quotient map. Moreover,

$$\mathcal{T} = \{V \subseteq A \mid p^{-1}(V) \text{ is open in } X\}.$$

Proof. First, we shall prove that \mathcal{T} is a topology.

(i) $p^{-1}(\emptyset) = \emptyset$ and $p^{-1}(A) = X$ are open in X ; thus $\emptyset, A \in \mathcal{T}$. ✓

(ii) For any $\{V_\alpha\}_{\alpha \in J} \subseteq \mathcal{T}$, $p^{-1}(\bigcup_{\alpha \in J} V_\alpha) = \bigcup_{\alpha \in J} p^{-1}(V_\alpha)$ is open in X . Thus, $\bigcup_{\alpha \in J} V_\alpha \in \mathcal{T}$. ✓

(iii) For any $\{V_i\}_{i=1}^n \subseteq \mathcal{T}$, $p^{-1}(\bigcup_{i=1}^n V_i) = \bigcup_{i=1}^n p^{-1}(V_i)$ is open in X . Thus, $\bigcup_{i=1}^n V_i \in \mathcal{T}$. ✓

p is a quotient map relative to \mathcal{T} . The surjectivity is given by definition, and the continuity is direct from the definition. Moreover, if $p^{-1}(U)$ is open in X where $U \subseteq A$, by the definition of \mathcal{T} , $U \in \mathcal{T}$. ✓

To prove the uniqueness, let \mathcal{T}' be a topology on A relative to which p is a quotient map. Then,

$$V \in \mathcal{T} \iff p^{-1}(V) \text{ is open in } X \iff V \in \mathcal{T}';$$

$$\mathcal{T} = \mathcal{T}'. \quad \checkmark$$

□