

MA3201

Topology

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1 Introduction

1.1 Topological spaces

Definition 1.1. A topology on some set X is a family τ of subsets of X , satisfying the following.

1. $\emptyset, X \in \tau$.
2. All unions of elements from τ are in τ .
3. All finite intersections of elements from τ are in τ .

The sets from τ are declared to be open sets in the topological space (X, τ) .

Example. Any set X admits the indiscrete topology $\tau_{id} = \{\emptyset, X\}$, as well as the discrete topology $\tau_d = \mathcal{P}(X)$. Both of these are trivial examples.

Example. Let X be a set. The cofinite topology on X is the collection of complements of finite sets, along with the empty set. Note that when X is finite, this is simply the discrete topology.

Definition 1.2. Let τ, τ' be two topologies on the set X . We say that τ is finer than τ' if τ has more open sets than τ' . In such a case, we also say that τ' is coarser than τ .

1.2 Topological bases

Definition 1.3. Let (X, τ) be a topological space. We say that $\beta \subseteq \tau$ is a base of the topology τ such that every open set $U \in \tau$ is expressible as a union of elements from β .

Definition 1.4. Let X be a set, and let β be a collection of subsets of X satisfying the following.

1. For every $x \in X$, there exists $x \in B \in \beta$.
2. For every $x \in X$ such that $x \in B_1 \cap B_2$, $B_1, B_2 \in \beta$, there exists $B \in \beta$ such that $x \in B \subseteq B_1 \cap B_2$.

Then, β generates a topology on X , namely the collection of all unions of elements of β .

Lemma 1.1. Let τ be a topology on X , and let $\beta \subseteq \tau$ be a collection of open sets. Then, β is a basis of τ , or generates τ , if for every $x \in U \in \tau$, there exists $B \in \beta$ such that $x \in B \subseteq U$.

Example. The collection of all open balls in \mathbb{R}^n form a basis of the usual topology.

Lemma 1.2. *Let X be equipped with the topologies τ and τ' , and let β and β' be the respective bases of these topologies. Then, τ is finer than τ' if and only if given $x \in B' \in \beta'$, there exists $x \in B \in \beta$ such that $B \subseteq B'$.*

Example. The collections of open balls in \mathbb{R}^n generate the same topology as the collection of all open rectangles in \mathbb{R}^n .

Example. Consider the topologies on \mathbb{R} generated by the following bases.

1. $\beta_1 = \{(a, b) : a, b \in \mathbb{R}, a < b\}$.
2. $\beta_2 = \{[a, b) : a, b \in \mathbb{R}, a < b\}$.
3. $\beta_3 = \{(a, b) : a, b \in \mathbb{R}, a < b\} \cup \{(a, b) \setminus K\}$ where $K = \{1/n : n \in \mathbb{Z}\}$.

We call the topology generated by β_2 the lower limit topology, denoted \mathbb{R}_ℓ . The topology generated by β_3 is denoted \mathbb{R}_K . Both of these are strictly finer than the standard topology.

Definition 1.5. A sub-basis for some topology on X is a collection ρ of subsets of X whose union is the whole of X . The topology generated by ρ is defined to be the topology generated by the collection of all finite intersections of elements of ρ .

1.3 Product topology

Definition 1.6. Let $(X_1, \tau_1), (X_2, \tau_2)$ be topological spaces. Then $\tau_1 \times \tau_2$ generates the product topology on $X_1 \times X_2$.

Example. The product topology on $\mathbb{R} \times \mathbb{R}$, where \mathbb{R} is equipped with the standard topology, coincides with the standard topology on \mathbb{R}^2 .

Lemma 1.3. *If β_1, β_2 are bases of the topologies τ_1, τ_2 , then $\beta_1 \times \beta_2$ and $\tau_1 \times \tau_2$ generate the same product topology.*

Proof. Given $(x_1, x_2) \in U$ where $U \subseteq X_1 \times X_2$ is open in the product topology, recall that U can be written as a union of the basic open sets $U_{1i} \times U_{2i}$, where $U_{1i} \in \tau_1$ and $U_{2i} \in \tau_2$. Suppose that $(x_1, x_2) \in U_1 \times U_2$. Thus, we can choose $B_1 \in \beta_1, B_2 \in \beta_2$ such that $x_1 \in B_1 \subseteq U_1$ and $x_2 \in B_2 \subseteq U_2$. Thus, $(x_1, x_2) \in B_1 \times B_2 \subseteq U_1 \times U_2 \subseteq U$. \square

Definition 1.7. The projection maps are defined as $\pi_i: X_1 \times \cdots \times X_k \rightarrow X_i, (x_1, \dots, x_k) \mapsto x_i$.

Lemma 1.4. *The collection of elements of the form $\pi_1^{-1}(U_1)$ or $\pi_2^{-1}(U_2)$, where $U_1 \in \tau_1$ and $U_2 \in \tau_2$, forms a sub-basis of the product topology on $X_1 \times X_2$.*

Proof. Note that $\pi_1^{-1}(X_1) = X_1 \times X_2$. Now it is easy to see that finite intersections of elements of the form $U_1 \times X_2$ or $X_1 \times U_2$ where U_1, U_2 are open, are all of the form $U_1 \times U_2$ which is precisely a basis of the product topology. \square

Corollary 1.4.1. *We can restrict ourselves to the sub-basis of elements of the form $\pi_1^{-1}(B_1)$ or $\pi_2^{-1}(B_2)$, where $B_1 \in \beta_1$, $B_2 \in \beta_2$ for some bases β_1, β_2 of τ_1, τ_2 .*

1.4 Subspace topology

Definition 1.8. Let (X, τ) be a topological space, and let $Y \subset X$. Then the collection $U \cap Y$ for all $U \in \tau$ comprises the subspace topology τ_Y on Y induced by the topology τ on X .

Lemma 1.5. *If β is a basis for the topology on X , and $Y \subset X$, then the collection $B \cap Y$ for all $B \in \beta$ generates the subspace topology on Y .*

Lemma 1.6. *An open set of Y is open in X if Y is open in X .*

Proof. Let $U \subset Y$ be open in Y , then $U = V \cap Y$ for some open set V in X . If additionally Y is open in X , this immediately shows that U is open in X . \square

Theorem 1.7. *Let $(X, \tau_X), (Y, \tau_Y)$ be topological spaces, and let $A \subseteq X, B \subseteq Y$. Then, there are two ways of assigning a natural topology on $A \times B$.*

1. *Take the product topology on $X \times Y$, and consider the subspace topology induced by it on $A \times B$.*
2. *Take the subspace topologies on A induced by τ_X , B induced by τ_Y , and consider the product topology generated by them on $A \times B$.*

These two methods generate the same topology on $A \times B$.

Proof. Open sets in 1 look like $(U \times V) \cap (A \times B)$, where $U \in \tau_X, V \in \tau_Y$. Open sets in 2 look like $(U' \cap A) \times (V' \cap B)$, where $U' \in \tau_X, V' \in \tau_Y$, which can be rewritten as $(U' \times V') \cap (A \times B)$. It is easy to see that these describe precisely the same sets. \square

1.5 Order topology

Definition 1.9. Let X be a set with a simple order $<$. Then the collection of sets of the form (a, b) , $[a_0, b)$, $(a, b_0]$ where a_0 is the minimal element of X , b_0 is the maximal element of X , generate the order topology on X .

Example. The order topology on \mathbb{N} is precisely the discrete topology.

Definition 1.10. Let X_1, X_2 be simply ordered sets. The dictionary order on $X_1 \times X_2$ is defined as follows: $(x_1, x_2) < (y_1, y_2)$ if $x_1 < y_1$, or if $x_1 = y_1$ and $x_2 < y_2$.

Example. Consider $X = \{1, 2\} \times \mathbb{N}$, where both $\{1, 2\}$ and \mathbb{N} are endowed with the discrete topology. Note that the product topology on X is the discrete topology.

Now consider the dictionary order on X . Here, $(1, 1)$ is the smallest element, so we can list the elements of X in ascending order. Note that every $(1, m) < (2, n)$, for all $m, n \in \mathbb{N}$. Now, note that all singletons $\{(1, m)\}$ are open in the order topology on X . The same is true for the singletons $\{(1, n)\}$ for all $n > 1$. However, the singleton $\{(2, 1)\}$ is *not* open in the order topology.

Example. Consider \mathbb{R} with the usual topology, and $X = [0, 1) \cup \{2\}$. Then, $\{2\}$ is open in the subspace topology on X , but it is not open in the order topology on X .

Lemma 1.8. The open rays of the form $(a, +\infty)$ and $(-\infty, a)$ in X form a sub-basis of the order topology on X .

Proof. Note that $(a, b) = (-\infty, b) \cap (a, +\infty)$, $[a_0, b) = (-\infty, b)$, and $(a, b_0] = (a, +\infty)$. □

Definition 1.11. Let X be a simply ordered set, and $Y \subseteq X$. Then, we say that Y is convex in X if given $a, b \in Y$ such that $a < b$, the interval $(a, b) = \{x \in X : a < x < b\} \subseteq Y$.

Theorem 1.9. Let Y be convex in X . Then, the subspace topology and the order topology on Y induced from the order topology on X coincide.

1.6 Closed sets

Definition 1.12. Let (X, τ) be a topological space. A set $F \subseteq X$ is said to be closed in X if $F^c = X \setminus F \in \tau$.

Example. The sets \emptyset, X are closed in every topological space (X, τ) .

Example. In a set equipped with the discrete topology, every set is both open and closed.

Lemma 1.10. *Arbitrary intersections, and finite unions of closed sets are closed.*

Theorem 1.11. *Let (X, τ) be a topological space, and let $Y \subset X$ be equipped with the subspace topology. Then, a set $F \subseteq Y$ is closed in Y if and only if $F = Y \cap G$, where G is closed in X .*

Proof. Let $F \subset Y$. Now, F is closed in Y , $Y \setminus F = Y \cap F^c$ is open in Y , $Y \cap F^c = Y \cap U$ where U is open in X , $F = Y \cap (Y \cap F^c)^c = Y \cap (Y \cap U)^c = Y \cap U^c$ where U^c is closed. The steps are reversible. \square

Lemma 1.12. *A closed set of Y is closed in X if Y is closed in X .*

1.7 Interiors and closures

Definition 1.13. Let $A \subseteq X$ where (X, τ) is a topological space.

1. The interior of A is defined as the union of all open sets contained in A . This is denoted by A° .
2. The closure of A is defined as the intersection of all closed sets containing A . This is denoted by \overline{A} .

Remark. The interior of a set is open, and the closure of a set is closed.

Lemma 1.13. *Let $Y \subset X$ be topological spaces, and let $A \subseteq Y$. Also let $\overline{A}_X, \overline{A}_Y$ denote the closures of A in X, Y respectively. Then, $\overline{A}_Y = \overline{A}_X \cap Y$.*

Theorem 1.14. *Let $A \subset X$. Then,*

1. $x \in \overline{A}$ if and only if every open set containing x has non-empty intersection with A .
2. $x \in \overline{A}$ if and only if every basic open set containing x has non-empty intersection with A , given that the topology on X is generated by those basic open sets.

Definition 1.14. Let $A \subseteq X$ where (X, τ) is a topological space. We say that $x \in X$ is a limit point of X if for every open set U containing x , the deleted neighbourhood $U \setminus \{x\}$ has non-empty intersection with A . The set of limit points of A is denoted by A' .

Example. Let X be a set endowed with the discrete topology. Then, given any set $A \subseteq X$, we have $A' = \emptyset$.

Lemma 1.15. *A closed set contains all its limit points.*

Proof. Let $F \subseteq X$ be closed in X , and let $x \in F'$. Then given any open set containing x , we have $U \cap F \supseteq (U \setminus \{x\}) \cap F \neq \emptyset$, hence $x \in \overline{F} = F$. \square

Lemma 1.16. *Let $A \subseteq X$ where (X, τ) is a topological space. Then, $\overline{A} = A \cup A'$.*

Proof. It is clear that $\overline{A} \supseteq A \cup A'$. Now pick $x \in \overline{A}$. If $x \notin A$, then we know that given any open neighbourhood U of x , we have non-empty $U \cap A$. Furthermore, this intersection can never contain x , hence $x \in A'$. This proves that $\overline{A} \subseteq A \cup A'$. \square

1.8 Convergence of sequences

Definition 1.15. Let $\{x_n\}_{n=1}^\infty$ be a sequence of points from (X, τ) , and let $x \in X$. We say that this sequence converges to x , denoted $x_n \rightarrow x$, if every open neighbourhood of x contains the tail of this sequence. In other words, given $U \in \tau$ such that $x \in U$, there must exist $N \in \mathbb{N}$ such that $x_n \in U$ for all $n \geq N$.

Example. Let $X = \{a, b, c\}$, and $\tau = \{\emptyset, \{b\}, \{a, b\}, \{b, c\}, X\}$. Then, the constant sequence of b 's converges to all three points a, b, c .

Example. Let $X = \mathbb{R}$, and τ be the collection of all intervals $(-a, a)$ together with \emptyset, \mathbb{R} . Then, the constant sequence of 0's converges to every point in \mathbb{R} .

Definition 1.16. Let (X, τ) be a topological space. We say that this topological space is Hausdorff if given any two distinct points $x, y \in X$, there exist open sets $U, V \in \tau$ such that $x \in U$, $y \in V$, and $U \cap V = \emptyset$.

Example. The real numbers under the standard topology is Hausdorff.

Theorem 1.17. *Let (X, τ) be a Hausdorff topological space, and let $\{x_n\}_{n=1}^{\infty}$ be a sequence of points in X . Then, this sequence can converge to at most one point in X .*

Proof. Suppose that $\{x_n\}_{n=1}^{\infty}$ converges to distinct points $x, y \in X$. Then there exist disjoint open neighbourhoods U, V such that $x \in U, y \in V$. Convergence means that both U and V contain a tail of the sequence, which is a contradiction. \square

Lemma 1.18. *The singleton sets in a Hausdorff space are closed.*

Proof. Let $x \in X$ where (X, τ) is Hausdorff. Pick $y \neq x$, whence there exist $U_y, V_y \in \tau$, such that $x \in U_y, y \in V_y$, and $U_y \cap V_y = \emptyset$. In particular, $\{x\} \cap V_y = \emptyset$. We now have

$$X \setminus \{x\} = \bigcup_{y \neq x} V_y,$$

which is open. \square

Theorem 1.19. *The topology induced by a metric is Hausdorff.*

Proof. Given a metric space X and distinct points $x, y \in X$, we set $r = |x - y|$, $U = B(x, r/3)$, $V = B(y, r/3)$. \square

2 Continuous maps

Definition 2.1. Let $f: X \rightarrow Y$ be a function between the topological spaces (X, τ_X) and (Y, τ_Y) . We say that f is continuous if for every $U \in \tau_Y$, we have $f^{-1}(U) \in \tau_X$. In other words, the pre-image of every open set in Y must be open in X .

Lemma 2.1. *A function $f: X \rightarrow Y$ is continuous if and only if given a base β of Y , we have $f^{-1}(U) \in \tau_X$ for every $U \in \beta$.*

Example. The identity function $\text{id}: \mathbb{R}_\ell \rightarrow \mathbb{R}$ is continuous, while the identity function $\text{id}: \mathbb{R} \rightarrow \mathbb{R}_\ell$ is not. This is because the topology on \mathbb{R}_ℓ is strictly finer than that on \mathbb{R} .

Lemma 2.2. *A function $f: X \rightarrow Y$ is continuous if and only if for every closed set $F \subseteq Y$, we have $f^{-1}(F)$ closed in X .*

Lemma 2.3. *A function $f: X \rightarrow Y$ is continuous if and only if given any $x \in X$ and an open set $V \subseteq Y$ such that $f(x) \in V$, there exists an open set $U \subseteq X$ such that $x \in U, f(U) \subseteq V$.*

Theorem 2.4. *The composition of continuous functions is continuous.*

2.1 Restricting and enlarging the domain

Lemma 2.5. *Let $f: X \rightarrow Y$ be continuous, and let $A \subset X$. Then the restriction of f to A is continuous.*

Theorem 2.6. *Let $f: X \rightarrow Y$, and let X be the union of the collection of open sets $\{A_\lambda\}_{\lambda \in \Lambda}$. If the restrictions of f to each A_λ are continuous, then f is continuous.*

Proof. Pick $x \in X$, hence $x \in A_\lambda$ for some $\lambda \in \Lambda$. Now if $f(x) \in V \subset Y$, where V is open in Y , then the continuity of the restriction of f to A_λ gives us an open set $U \subseteq A_\lambda$ such that $f(U) \subseteq V$. Finally since A_λ is open in X , so is U . \square

Definition 2.2. Let X be the union of the collection of open sets $\{A_\lambda\}_{\lambda \in \Lambda}$. We say that this collection is a locally finite cover of X if given $x \in X$, there exists a neighbourhood U of x such that $U \cap A_\lambda$ is non-empty for only finitely many $\lambda \in \Lambda$.

Theorem 2.7. *Let $f: X \rightarrow Y$, and let $\{F_\lambda\}_{\lambda \in \Lambda}$ be a locally finite collection of closed sets covering X . If the restrictions of f to each F_λ are continuous, then f is continuous.*

Corollary 2.7.1 (Pasting lemma). *Let $X = A \cup B$, with A, B closed in X . Let $f: A \rightarrow Y$, $g: B \rightarrow Y$ be continuous, with $f(x) = g(x)$ on $A \cap B$. Then the function $h: X \rightarrow Y$, defined by $x \mapsto f(x)$ on A and $x \mapsto g(x)$ on B , is continuous.*

Definition 2.3. A path is a continuous function $\gamma: [0, 1] \rightarrow X$.

Lemma 2.8. *Two paths γ_1, γ_2 can be concatenated when $\gamma_1(1) = \gamma_2(0)$.*

2.2 Homeomorphisms

Definition 2.4. Let $f: X \rightarrow Y$ be a function between the topological spaces (X, τ_X) and (Y, τ_Y) . We say that f is a homeomorphism if f is continuous, f is bijective, and f^{-1} is continuous. We also say that X and Y are homeomorphic when such a homeomorphism between them exists.

Example. The interval $(-1, 1)$ is homeomorphic to \mathbb{R} ; for instance, the map $x \mapsto \tan(\pi x/2)$ on $(-1, 1)$ is a homeomorphism. A simpler construction is the map $x \mapsto x/(1 - x^2)$.

2.3 Projection maps

Theorem 2.9. *The projection maps $\pi_i: X_1 \times \cdots \times X_k \rightarrow X_i$ are continuous, when the domain is equipped with the product topology. Furthermore, the product topology is the coarsest topology on the domain for which the projection maps are continuous.*

Lemma 2.10. *Let $f: A \rightarrow X_1 \times \cdots \times X_k$, where the co-domain is equipped with the product topology. Then, f is continuous if and only if the component functions $f_i = \pi_i \circ f$ are continuous.*

Proof. Note that if f is continuous, the compositions $\pi_i \circ f$ are immediately continuous. Conversely suppose that each f_i is continuous, and write

$$f(t) = (f_1(t), \dots, f_k(t)).$$

The sets $U_1 \times \cdots \times U_k$, where each $U_i \subseteq X_i$ is open, form a basis of the co-domain. Furthermore, their pre-images under f are $f_1^{-1}(U_1) \cap \cdots \cap f_k^{-1}(U_k)$, which are open in A . This shows that f is continuous. \square

Definition 2.5. Let J be an arbitrary index set. A J -tuple of elements in a set X is a function $x: J \rightarrow X$, formally denoted $(x_\alpha)_{\alpha \in J}$. If $\{X_\alpha\}_{\alpha \in J}$ is a family of sets, their Cartesian product is defined as

$$\prod_{\alpha \in J} X_\alpha = \{x: J \rightarrow \bigcup_{\alpha \in J} X_\alpha : x_\alpha \in X_\alpha\}.$$

Remark. The fact that we can choose an element from each set in an uncountable collection relies on the Axiom of Choice.

Definition 2.6. Let $\{X_\alpha\}_{\alpha \in J}$ be a collection of topological spaces. The topology generated by $\prod_{\alpha \in J} U_\alpha$, where each $U_\alpha \subseteq X_\alpha$ is open, is called the box topology on $\prod_{\alpha \in J} X_\alpha$.

Definition 2.7. Let $\{X_\alpha\}_{\alpha \in J}$ be a collection of topological spaces. The topology generated by the sub-basis $\pi_\alpha^{-1}(U_\alpha)$, where each $U_\alpha \subseteq X_\alpha$ is open, is called the product topology on $\prod_{\alpha \in J} X_\alpha$.

Remark. The basic open sets are of the form $\pi_{\alpha \in J} U_\alpha$, where all but finitely many $U_\alpha = X_\alpha$. Thus, this is a coarser topology than the box topology.

Lemma 2.11. *Let $\prod_{\alpha \in J} X_\alpha$ be equipped with the box or product topology. Then, $\overline{\prod A_\alpha} = \prod \overline{A_\alpha}$, where each $A_\alpha \subseteq X_\alpha$.*

Lemma 2.12. *Let $f: A \rightarrow \prod_{\alpha \in J} X_\alpha$, where the co-domain is equipped with the product topology. Then, f is continuous if and only if the component functions $f_\alpha = \pi_\alpha \circ f$ are continuous.*

Remark. This fails when $\prod_{\alpha \in J}$ is equipped with the box topology. Consider $f: \mathbb{R} \rightarrow \prod_{n=1}^{\infty} \mathbb{R}$, $x \mapsto (x, x, \dots)$. Then, the product $\prod_{n=1}^{\infty} (-1/n, 1/n)$ is open in the box topology, but its pre-image under f is $\bigcap_{n=1}^{\infty} (-1/n, 1/n) = \{0\}$, which is not open in \mathbb{R} .

3 Metric spaces

Definition 3.1. A metric space (X, d) is a set equipped with a metric $d: X \times X \rightarrow \mathbb{R}$, such that

1. $d(x, y) = 0$ if and only if $x = y$.
2. $d(x, y) = d(y, x)$.
3. $d(x, z) \leq d(x, y) + d(y, z)$.

Definition 3.2. An open ball in a metric spaces is the set of points

$$B(x, r) = \{y \in X : d(x, y) < r\}.$$

Lemma 3.1. *The collection of open balls in a metric space generates its standard topology.*

Example. Consider a set X , equipped with the metric

$$d: X \times X \rightarrow \mathbb{R}, \quad (x, y) \mapsto \begin{cases} 0, & \text{if } x = y, \\ 1, & \text{if } x \neq y. \end{cases}$$

Then, this metric induces the discrete topology on X .

3.1 Metrizable spaces

Definition 3.3. A topological space (X, τ) is called metrizable if there exists a metric $d: X \times X \rightarrow \mathbb{R}$ which induces the topology τ on X .

Definition 3.4. Let $A \subseteq X$. The diameter of A is defined to be

$$\text{diam}(A) = \sup\{d(x, y) : x, y \in A\}.$$

If $\text{diam}(A)$ is finite, we say that A is bounded.

Example. The metric

$$(x, y) \mapsto \frac{|x - y|}{1 + |x - y|}$$

generates the standard topology on \mathbb{R} . Note that \mathbb{R} is unbounded in the standard metric, but bounded in this one.

Definition 3.5. Let (X, d) be a metric space. Then the standard bounded metric corresponding to d is defined as

$$\bar{d}: X \times X \rightarrow \mathbb{R}, \quad (x, y) \mapsto \min\{d(x, y), 1\}.$$

Lemma 3.2. Both d and \bar{d} generate the same topology.

Theorem 3.3. The product topology on $\mathbb{R}^\omega = \mathbb{R} \times \mathbb{R} \times \dots$ is metrizable, using the metric

$$D(x, y) = \sup_n \left\{ \frac{1}{n} \bar{d}(x, y) \right\}.$$

Lemma 3.4. Let $A \subseteq X$, let $x \in X$, and let the sequence $\{x_n\}_{n \in \mathbb{N}}$, $x_n \in A$ converge with $x_n \rightarrow x$. Then, $x \in \bar{A}$.

Remark. The converse holds if X is metrizable.

Example. Consider $X = \mathbb{R}^\omega$ equipped with the box topology. Choose $A = \{(x_1, x_2, \dots) : x_i > 0\}$. Then, $0 = (0, 0, \dots) \in \bar{A}$; this is clear from the fact that any open set around 0 contains the basic open set $\prod_i (a_i, b_i)$ with $a_i < 0 < b_i$. However, there is no sequence $\{x_n\}_{n \in \mathbb{N}}$, $x_n \in A$, such that $x_n \rightarrow 0$. Note that if this were the case, then each $x_n = (x_{n1}, x_{n2}, \dots)$. Now, $B = \prod_i (-x_{ii}, x_{ii})$ contains none of the points x_n , since the n th coordinate of B eliminates the point n .

Corollary 3.4.1. \mathbb{R}^ω equipped with the box topology is not metrizable.

4 Compactness

Definition 4.1. Let X be a topological space. We say that X is compact if every open cover of X has a finite subcover.

Lemma 4.1. Let $Y \subseteq X$. Then, Y is compact if and only if every open cover of Y by open sets in X has a finite subcover.

4.1 Compact subspaces

Lemma 4.2. *All compact sets in a metric space are bounded.*

Proof. Let $K \subseteq X$ be compact. Then, K admits an open cover of open balls $B(0, n)$ from which we can extract a finite subcover; however, this can be reduced to just one open ball $B(0, N)$ for some N . Thus $K \subset B(0, N)$ is bounded. \square

Lemma 4.3. *A closed subset of a compact space is compact.*

Proof. Let K be compact, and $F \subseteq K$ be closed. Consider an open cover $\{U_\alpha\}_{\alpha \in J}$ of F . By adding $K \setminus F$ to this collection, we have an open cover of K , from which we can extract a finite subcover $U_{i_1}, U_{i_2}, \dots, U_{i_k}, K \setminus F$. By discarding the latter, we have found a finite subcover of F . \square

Lemma 4.4. *In a Hausdorff space, every compact set is closed.*

Proof. Let X be Hausdorff, and $K \subseteq X$ be compact. Fix $x_0 \in X \setminus K$, and note that given any $y \in K$, there exist open neighbourhoods U_y, V_y such that $x_0 \in U_y$, $y \in V_y$, $U_y \cap V_y = \emptyset$. Thus, the collection of all such $\{V_y\}_{y \in K}$ is an open cover of K , from which we can extract a finite subcover V_{y_1}, \dots, V_{y_k} . Corresponding to this, $x_0 \in U_{y_1} \cap \dots \cap U_{y_k} \subseteq X \setminus K$. Thus, x_0 lies in the interior of $X \setminus K$. This shows that $X \setminus K$ is open, hence K is closed. \square

Theorem 4.5. *The image of a compact space under a continuous map is compact.*

Lemma 4.6. *Let $f: X \rightarrow Y$ be a continuous bijection. If X is compact and Y is Hausdorff, then f is a homeomorphism.*

Proof. We need only show that f is a closed map; now every closed set $F \subseteq X$ is compact because X is compact, hence $f(F) \subseteq Y$ is compact. Since Y is Hausdorff, the compact set $f(F)$ is closed. \square

4.2 Products of compact spaces

Lemma 4.7 (Tube lemma). *Let X, Y be topological spaces, and let Y be compact. Let $x_0 \in X$, and let $\{x_0\} \times Y \subset N \subseteq X \times Y$ where N is open. Then, there exists an open set $W \subseteq X$ such that $\{x_0\} \times Y \subseteq W \times Y \subseteq N$.*

Proof. Note that $\{x_0\} \times Y$ is compact, being homeomorphic to Y . Thus, it can be covered with basic open sets $U_1 \times V_1, \dots, U_k \times V_k$ such that each $U_i \times V_i \subset N$. Simply set $W = U_1 \cap \dots \cap U_k$. \square

Theorem 4.8. *Let X, Y be compact topological spaces. Then, $X \times Y$ is compact.*

Proof. Let $\{U_\alpha\}_{\alpha \in J}$ be an open cover of $X \times Y$. Pick $x \in X$, whence $\{x\} \times Y$ is compact and admits a finite subcover $U_{x i_1}, \dots, U_{x i_k}$. Denote their union by U_x ; the tube lemma guarantees an open set $W_x \subseteq X$ such that $\{x\} \times Y \subseteq W_x \times Y \subseteq U_x$. Now, the collection $\{W_x\}_{x \in X}$ is an open cover of X , hence admits a finite subcover W_{x_1}, \dots, W_{x_n} . This also means that $W_{x_1} \times Y, \dots, W_{x_n} \times Y$ is a finite cover of Y . However, each $W_{x_i} \times Y \subseteq U_{x_i}$ can be covered by finitely many U_α , which means that we have a finite subcover of $X \times Y$. \square

4.3 Euclidean spaces

Lemma 4.9. *Let X be a simply ordered set with the least upper bound property. Then, the intervals $[a, b]$ are compact.*

Theorem 4.10 (Heine-Borel). *Compact sets of \mathbb{R}^n are precisely those which are closed and bounded.*

4.4 Limit point compactness

Definition 4.2. Let X be a topological space. We say that X is limit point compact if every infinite subset of X has a limit point.

Lemma 4.11. *A compact space is limit point compact.*

Proof. Let X be compact, and let $A \subseteq X$ have no limit points. Then, $A = A \cup A' = \bar{A}$ is closed in X , hence compact. Now given any $a \in A$, we know that a is not a limit point of A , hence we can choose an open neighbourhood U_a such that $U_a \cap A = \{a\}$. The collection $\{U_a\}_{a \in A}$ is now an open cover of A , and hence admits a finite subcover U_{a_1}, \dots, U_{a_k} . Let U denote their union, whence $A = A \cap U = \{a_1, \dots, a_k\}$ is finite. \square

Example. Let $X = \mathbb{N} \times \{0, 1\}$, where \mathbb{N} has the discrete topology, and $\{0, 1\}$ has the indiscrete topology. Then, every subset of X has a limit point; indeed, given any $\{(n, b)\}$, we have a limit point $(n, 1 - b)$. However, X is clearly not compact, since the open cover of sets $\{n\} \times \{0, 1\}$ does not admit any finite subcover.

Theorem 4.12. *Let X be a metrizable space. Then, X is limit point compact if and only if it is compact.*

5 Connectedness

Definition 5.1. Let X be a topological space, and let $U, V \subseteq X$ be open, non-empty, disjoint, with $U \cup V = X$. We say that U, V form a separation of X .

Definition 5.2. A topological space X is said to be connected if it admits no separation.

Lemma 5.1. *A topological space X is connected if and only if the only subsets that are both open and closed in it are \emptyset, X .*

Lemma 5.2. *Let X be a topological space, and let $Y \subseteq X$ be a subspace. Then, a separation of Y is a pair of open sets $A, B \subseteq X$ such that $\overline{A} \cap B = \emptyset$, $A \cap \overline{B} = \emptyset$.*

Lemma 5.3. *Let C, D form a separation of X , and let $Y \subseteq X$ be a connected subspace. Then, either $Y \subseteq C$, $Y \subseteq D$.*

Lemma 5.4. *The union of a collection of connected spaces with a common point is connected.*

Proof. Let $\{X_\alpha\}_{\alpha \in J}$ be a collection of connected spaces, with the common point x_0 , and let X be their union. Suppose that U, V is a separation of X ; then each of the connected X_α must be contained in one of U, V . However, since all X_α share the common point x_0 , they must all lie in the same half, say U , forcing $V = \emptyset$, a contradiction. \square

Lemma 5.5. *Let $A \subseteq X$ be connected, and let $A \subseteq B \subseteq \overline{A}$. Then, B is connected.*

Theorem 5.6. *The image of a connected space under a continuous maps is connected.*

Theorem 5.7. *A finite Cartesian product of connected spaces is connected.*

Proof. Let X, Y be connected spaces. Fix $(a, b) \in X \times Y$. Now, $X \times \{b\}$ is connected, being homeomorphic to X . Furthermore, each $\{x\} \times Y$ is connected, for each $x \in Y$. Now, the set $T_x = \{x\} \times Y \cup X \times \{b\}$ is connected, being the union of connected spaces with the common point (x, b) . Finally, the union of all such T_x is connected, being the union of connected spaces with the common point (a, b) . This union is just $X \times Y$, which is thus connected. \square

Example. The countable product \mathbb{R}^ω with the box topology is disconnected. Consider

$$A = \text{set of all bounded sequences}, \quad B = \text{set of all unbounded sequences}.$$

Now, $A \cap B = \emptyset$, $A \cup B = \mathbb{R}^\omega$, $A, B \neq \emptyset$. It can also be shown that A, B are open.

Example. The countable product \mathbb{R}^ω with the product topology is connected. To show this, define

$$\tilde{R}^n = \{(x_1, \dots, x_n, 0, 0, \dots) : x_i \in \mathbb{R}\}.$$

Then, set $X = \bigcup_{n=1}^{\infty} \tilde{R}^n$, and note that since each $\tilde{R}^n \cong \mathbb{R}^n$ is connected with all of them sharing the common point $(0, 0, \dots)$, X must be connected. We now show that $\overline{X} = \mathbb{R}^\omega$. Indeed, given $x = (x_1, x_2, \dots) \in \mathbb{R}^\omega$, an open neighbourhood of x looks like $U = U_1 \times U_2 \times \dots$, where all but finitely many $I_i = \mathbb{R}$. In other words, there exists sufficiently large $N \in \mathbb{N}$ such that for all $n \geq N$, $U_n = \mathbb{R}$. Thus, the point $(x_1, x_2, \dots, x_n, 0, 0, \dots) \in U \cap \tilde{R}^N$.

Lemma 5.8. *The closed intervals $[a, b] \subset \mathbb{R}$ are connected.*

5.1 Path connectedness

Definition 5.3. A topological space X is said to be path connected if there exists a path joining any two points in X . In other words, given $a, b \in X$, there always exists a continuous map $\gamma: [0, 1] \rightarrow X$ such that $\gamma(0) = a$, $\gamma(1) = b$.

Lemma 5.9. *All path connected spaces are connected.*

Proof. Note that if $X = U \cup V$ is a separation of the path connected space X , then $[0, 1] = \gamma^{-1}(U) \cup \gamma^{-1}(V)$ is a separation of the connected interval $[0, 1]$, a contradiction. \square

Lemma 5.10. *The image of a path connected space under a continuous map is path connected.*

Example. The unit sphere S^{n-1} is path connected. Note that the map

$$f: \mathbb{R}^n \setminus \{0\} \rightarrow S^{n-1}, \quad x \mapsto x/\|x\|$$

is continuous and surjective. Thus, it maps the path connected set $\mathbb{R}^n \setminus \{0\}$ to S^{n-1} , which must be path connected.

Example. The set \overline{S} , called the topologist's sine curve, is connected but not path connected.

$$S = \{(x, \sin(1/x)) : 0 < x \leq 1\}.$$

Note that S is the continuous image of the connected interval $(0, 1]$, hence connected. This further shows that \overline{S} is connected. Now,

$$\overline{S} = S \cup \{(0, y) : -1 \leq y \leq 1\}.$$

However, \overline{S} is not path connected, since there exists no path joining $(0, 0)$ and $(1/\pi, 0)$. Indeed, given any path $\gamma: [0, 1] \rightarrow \overline{S}$ starting at $(0, 0)$, it cannot escape $\{0\} \times [-1, 1]$. To see this, write $\gamma = (\gamma_1, \gamma_2)$, $\gamma_2(0) = 0$. By continuity of γ_2 , we can choose $\delta > 0$ such that $|\gamma_2(t)| < 1/2$ for all $0 \leq t \leq \delta$. Suppose that $\gamma_1(t^*) = \tau > 0$ for some $0 \leq t \leq \delta$. By the intermediate value theorem, γ_1 takes all the values between 0 and τ in the interval $[0, t^*]$. Choose N such that $2/\pi(2N+1) < \tau$. Again, there must exist some $0 < t_0 < t^*$ such that $\gamma_1(t_0) = 2/\pi(2N+1)$. Now, $\gamma_2(t_0) = \sin(1/\gamma_1(t_0)) = 1 > 1/2$, a contradiction. This means that $\gamma_1(t) = 0$ for all $t \in [0, \delta]$.

6 Quotient topology

Definition 6.1. Let X be a topological space, and let \sim be an equivalence relation on X . Then X/\sim denotes the set of all equivalence classes with respect to \sim . Its elements are of the form $[x] = \{y \in X : x \sim y\}$, for $x \in X$. Define the map

$$\pi: X \rightarrow X/\sim, \quad x \mapsto [x].$$

The quotient topology on X/\sim is the finest topology such that π is continuous. In other words, $U \subseteq X/\sim$ is open if $\pi^{-1}(U)$ is open in X .

Lemma 6.1. Let $f: X \rightarrow Y$ be a continuous surjection, with X compact and Y Hausdorff. Define an equivalence relation \sim on X such that $x \sim x' \Leftrightarrow f(x) = f(x')$. Then, $g: X/\sim \rightarrow Y$, $[x] \mapsto f(x)$ is a homeomorphism.

Example. Consider the interval $[0, 1]$, with the equivalence relation \sim which identifies $0 \sim 1$, and leaves all other points undisturbed. Then, the quotient space $[0, 1]/\sim$ is homeomorphic to the circle S^1 .

Note that the quotient map on $[0, 1]$ is not open, since the image of the open set $[0, 1/2)$ is not open in $[0, 1]/\sim$.

Example. Let $X = \mathbb{R}^{n+1} \setminus \{0\}$, and define an equivalence relation on X which identifies points on the same line through the origin together. Then, the resulting quotient space is called the real projective space, denoted \mathbb{RP}^n .

Example. Let S^n denote the n -sphere in \mathbb{R}^{n+1} , and define an equivalence relation on S^n which identifies antipodal points. Then, the resulting quotient space is also \mathbb{RP}^n . The quotient map here is an open map.

Lemma 6.2. *Let $f: X \rightarrow Y$ be an open, continuous, surjective map. Define an equivalence relation \sim on X such that $x \sim x' \Leftrightarrow f(x) = f(x')$. Then, $g: X/\sim \rightarrow Y$, $[x] \mapsto f(x)$ is a homeomorphism.*

Example. By defining f as a composition of maps $\mathbb{R}^n \setminus \{0\} \rightarrow S^n \rightarrow S^n/\sim$, it can be shown that \mathbb{RP}^n is compact.

6.1 One-point compactification

Definition 6.2. Let X be a compact topological space, and let $A \subset X$ be closed. The one-point compactification of $X \setminus A$ is defined by

$$Y = (X \setminus A) \cup \{\infty\},$$

with the topology

$$\tau_Y = \{U \subseteq X \setminus A \text{ is open}\} \cup \{Y \setminus C \text{ where } C \text{ is compact in } X \setminus A\}.$$

Lemma 6.3. *If X is compact, Hausdorff, then so is the one-point compactification Y of $X \setminus A$.*

Lemma 6.4. *Let X be a compact, Hausdorff space and $A \subseteq X$ be a closed set. Define \sim on X by identifying $x \sim x'$ whenever $x, x' \in A$ and leaving the remaining points undisturbed. Then, X/\sim is homeomorphic to the one-point compactification $Y = X \setminus A \cup \{\infty\}$.*