

Topological Spaces

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1 Topologies

1.1 Definitions

We denote $\mathcal{P}(X)$ as the power set of X .

Definition. (Topology) Let X be a set. A *topology* on X is a collection of sets $T \subseteq \mathcal{P}(X)$ such that

- (i) $\emptyset, X \in T$,
- (ii) T is closed under (possibly uncountable) unions.
- (iii) T is closed under finite intersections.

A set X with a topology T is called a *topological space* of X . An element of X is called a *point* and elements of T are called *open sets*. If $x \in U \in T$ we say U is an open neighbourhood of x . Strictly we should always denote (X, T) for a topological space, but when T is clear, we just write X for the topological space.

Definition. (Continuity) If (X, T_X) and (Y, T_Y) are topological spaces then a function $f : X \rightarrow Y$ is called *continuous* if for $U \in T_Y$, $f^{-1}(U) \in T_X$.

Definition. (Homeomorphism) A function $f : (X, T_X) \rightarrow (Y, T_Y)$ is a *homeomorphism* if it is continuous and has a continuous inverse.

Definition. If $T \subseteq T'$ are topologies on X then we say that T is *coarser* and T' is *finer*. The identity function $d : (X, T) \rightarrow (X, T')$ is continuous.

1.2 Topologies from metrics

If (X, d) is a metric space, recall that a subset $U \subseteq X$ is called *open* if for every point $x \in U$ there exists a $\varepsilon > 0$ such that $B_\varepsilon(x) \subseteq U$.

Proposition. If T_d is the subset of X which are open under the metric d , then (X, T_d) is a topological space. We will call this the topology on X induced by the metric d .

Proof. Tautologically we have that $\emptyset \in T_d$. Clearly we have that $X \in T_d$ too. Let $\{U_\alpha\}_{\alpha \in I}$ be a collection of open sets in T_d with a (possibly uncountable) index set I . Let

$$x \in \bigcup_{\alpha \in I} U_\alpha.$$

Then $x \in U_\beta$ for some $\beta \in I$, so U_β is open hence there exists a $\varepsilon > 0$ such that $B_\varepsilon \subseteq U_\beta \subseteq \bigcup_{\alpha \in I} U_\alpha$, hence $\bigcup_{\alpha \in I} U_\alpha$ is open.

Now suppose that I is finite, and $x \in \bigcap_{\alpha \in I} U_\alpha$. For each α there exists a $\varepsilon_\alpha > 0$ such that $B_{\varepsilon_\alpha}(x) \subseteq U_\alpha$. Take $\varepsilon = \inf_{\alpha \in I} \varepsilon_\alpha$, so $B_\varepsilon(x) \subseteq B_{\varepsilon_\alpha}(x) \subseteq U_\alpha$ for all α , hence we have that $B_\varepsilon(x) \subseteq \bigcap_{\alpha \in I} U_\alpha$ so it's open. Hence T is a topology. \square

Now we have lots of examples we can use for topological spaces. For example we have that topology induced by the Euclidean metric on \mathbb{R}^d which we will call the Euclidean topology. For any $X \subseteq \mathbb{R}^d$ we can have a topology induced by the Euclidean metric too, like \mathbb{Q} , $[0, 1]$, $(0, 1)$.

Proposition. If we have two metric spaces (X, d_X) , (Y, d_Y) and we have $f : X \rightarrow Y$, the f is continuous in the metric space sense if and only if it is continuous in the topological space sense (with the topologies induced by the metric d_X and d_Y respectively).

Proof. Let $f : X \rightarrow Y$ be continuous in the metric space sense. Let U be an open set in T_{d_Y} so we need to show that $f^{-1}(U)$ is open. Let $x \in f^{-1}(U)$, so $f(x) \in U$. Hence there exists an $\varepsilon > 0$ such that $B_\varepsilon(f(x)) \subseteq U$. So since f is continuous there exists a $\delta > 0$ such that if $d_X(x, x') < \delta$, then $d_Y(f(x), f(x')) < \varepsilon$. Hence $f(B_\delta(x)) \subseteq B_\varepsilon(f(x))$. So $B_\delta(x) \subseteq f^{-1}(U)$, hence $f^{-1}(U)$ is open.

Now let's do the converse and suppose that $f : X \rightarrow Y$ is continuous in the topological sense. Fix some $x \in X$ and $\varepsilon > 0$. Consider $B_\varepsilon(f(x))$ which is open in Y . Then $f^{-1}(B_\varepsilon(f(x)))$ is in T_{d_X} . It contains x so there exists a $\delta > 0$ such that $x \in B_\delta(x)$, so

$$d_X(x, x') < \delta \implies d_Y(f(x), f(x')) < \varepsilon.$$

So f is continuous in the metric sense. □

Definition. Let (X, T) be a topological space and $x_1, x_2, \dots \in X$ say. We say that x_n converges to x if for every open neighbourhood U of x there exists a N such that $x_n \in U$ for all $n \geq N$.

Proposition. If (X, d) is a metric space with topology T_d then a sequence (x_n) converges in the metric sense if and only if it converges in the topological sense.

Proof. Suppose it converges in the metric sense to x . Then for all $\varepsilon > 0$ there exists a N such that for all $n \geq N$ we have that $x_n \in B_\varepsilon(x)$. If U is a neighbourhood of x then there is some ε such that the ball of radius ε centred at x is contained in U . Conversely if (x_n) converges in the topological sense to x , let $\varepsilon > 0$ and consider the open ball centred at x with radius ε . Now $B_\varepsilon(x)$ is an open neighbourhood of x so there exists an integer N such that $x_n \in B_\varepsilon(x)$ for all $n > N$. Hence (x_n) converges to x in the metric sense. □

Consider \mathbb{R} and $(0, 1)$ with the Euclidean metric and topology. Then the two spaces are related, by the function $(0, 1) \rightarrow \mathbb{R}$ by $\tan^{-1} x$ which is invertible. Hence we say the two spaces are homeomorphic, and $\mathbb{R} \cong (0, 1)$. However the two spaces are not isometric since \mathbb{R} is not complete under the Euclidean metric and $(0, 1)$ is not. Hence the property of completeness is not a topological property: it is a property induced by the metric.

Definition. (Discrete topology) Let X be a set. The *discrete* topology is the topology $T_{\text{discrete}} = \mathcal{P}(X)$ (so every set is open).

Remark. Any function from (X, T_{discrete}) to any space is continuous. This topology can be induced by the discrete metric, where $d(x, y) = \begin{cases} 1 & x \neq y \\ 0 & x = y \end{cases}$. So $B_{\frac{1}{2}}(x) = \{x\}$ so $\{x\}$ is open, hence all

the sets are open.

Definition. (Indiscrete topology) Let X be a set. The *indiscrete* topology $T_{\text{indiscrete}} = \{\emptyset, X\}$ (as little as possible sets are open).

Remark. A function from any space to $(X, T_{\text{indiscrete}})$ is continuous. This topology does not come from a metric unless X is a singleton set. This is because if $x \neq y$ then $d(x, y) = \varepsilon > 0$, so $y \notin B_\varepsilon(x)$ and since y is arbitrary, then $B_\varepsilon(x) = \{x\} = X$.

Let $X = \{o, c\}$. Then let $T = \{\emptyset, \{o, c\}, \{o\}\}$ be a topology of X . This is called the Sierpinski space. It has the property that every sequence converges to c . A continuous function $f : T \rightarrow (X, T_{\text{Sierpinski}})$ is exactly an open subset of Y .

Let $X = \mathbb{R}$ we'll define the right order topology on X as

$$T_{\text{ord}} = \{(a, \infty) \mid -\infty \leq a \leq \infty\}.$$

Let $\{(a, \infty)\}_{a \in I}$ be a collect of elements of T_{ord} . Then

$$\bigcup_{a \in I} (a, \infty) = (\inf_{a \in I} a, \infty) \in T_{\text{ord}}.$$

Similarly for finite I ,

$$\bigcap_{a \in I} (a, \infty) = (\max_{a \in I} a, \infty) \in T_{\text{ord}}$$

1.3 Bases and subbases

Definition. (Basis) Let T be a topology of X . A *basis*, $B \subseteq T$ for T is a subcollection such that every element of T is a union of elements in B .

Definition. (Subbasis) Let T be a topology of X . A *subbasis*, $S \subseteq T$ for T is a subcollection such that every element of T is a union of sets which are finite intersections of elements of S .

Lemma. Let $f : (X, T_X) \rightarrow (Y, T_Y)$ and $S \subseteq T_Y$ is a subbasis. If $f^{-1}(U)$ is open for all $U \in S$ then f is continuous.

Proof. If $V \subseteq T_Y$, then $V = \bigcup_{a \in I} V_a$ where $V_a \in \bigcap_{b \in J_a} U_{a,b}$ with $U_{a,b} \in S$ and J_a finite. Then

$$f^{-1}(V) = \bigcup_{a \in I} V_a = \bigcup_{a \in I} \left(\bigcap_{b \in J_a} f^{-1}(U_{a,b}) \right) \in T_X,$$

by the axioms of the topology. □

Consider the Euclidean topology on \mathbb{R}^n . The collection $B = \{B_r(x) \mid x \in \mathbb{R}^n, r > 0\}$ is a basis. Likewise the collection of n -cubes everywhere are also a basis. Interestingly the set $QB \subseteq B$ with balls at rational points with rational radii is also a basis. This is interesting since QB is countable while B is uncountable and $\mathcal{P}(\mathbb{R}^n)$ is \aleph_2 .

Definition. (Closed set) Let (X, T) be a topological space. A subset $C \subseteq X$ is *closed* if $X \setminus C \in T$.

Proposition. Let (X, T) be a topological space and $\mathcal{F} = \{C \subseteq X \mid C \text{ closed}\}$. Then

- (i) $\emptyset, X \in \mathcal{F}$;
- (ii) \mathcal{F} is closed under (possibly uncountable) intersections;
- (iii) \mathcal{F} is closed under finite unions.

Proposition. A function $f : X \rightarrow Y$ between topological spaces is continuous if and only if the preimage of every closed set is closed.

Definition. Let (X, T) be a topological space. Let $A \subseteq X$ be a subset of X . Then

- (i) The closure \bar{A} is the smallest (by inclusion) closed set containing A so

$$\bar{A} = \bigcap_{S \text{ closed}, A \subseteq S} S.$$

- (ii) We say that A is dense in X if $A = \bar{A}$.
- (iii) The interior $\overset{\circ}{A}$ is the largest open set contained in A so

$$\overset{\circ}{A} = \bigcup_{S \text{ open}, S \subseteq A} S.$$

Definition. (Limit point) Let X be a topological space and $A \subseteq X$. A *limit point* of A is a point in X which is a limit of a sequence in A .

Proposition. If C is a closed subset of (X, T) , then the limit points of C lie in C .

Proof. Let $\{x_n\}$ be a sequence in C with limit x_∞ . If $x_\infty \notin C$, then $x_\infty \in X \setminus C$ which is open. Then if $x_n \rightarrow x_\infty$ then we should have that $x_n \in X \setminus C$ for $n \geq N$ but $x_n \in C$ so $x_n \notin X \setminus C$ which is a contradiction. \square

Corollary. A limit point of a A lies in \bar{A} .

For an example $\overline{\mathbb{Q}} = \mathbb{R}$ since any real number is a limit of a sequence of rational numbers. We have that $\overline{(0, 1)} = [0, 1]$ too. The cocountable topology on \mathbb{R} is the topology $T_{\text{countable}} = \{\emptyset\} \cup \{\mathbb{R} \setminus C \mid C \text{ countable}\}$. Let $\{x_n\}$ be a sequence in \mathbb{R} , for $x \in \mathbb{R}$ consider $\{x\} \cup \{\mathbb{R} - \{x_n\}\}$ is open and contains x . If $x_n \rightarrow x$, then x_n must be in a U for all $n \geq N$ so $x_n = x$ for all $n \geq N$. Hence the convergent sequences are exactly the eventually constant sequences with the limits being the value they are eventually constant to. So the limit points of a set A are A under this topology. However almost all A is not closed. For example $(0, 1)$ is not closed since $\mathbb{R} \setminus (0, 1)$ is not countable. But the closure of $(0, 1)$ must be closed, so it must be \mathbb{R} hence the sense of limit points and closure are actually two very different properties in topology instead of metric spaces.

1.4 Hausdorff spaces

Definition. (Hausdorff) A space (X, T) is *Hausdorff* if for $x \neq y \in X$ there are open neighbourhoods $x \in U, y \in V$ with $U \cap V = \emptyset$.

Remark. This is the notion that points are separated by open sets.

Lemma. If the topology T is induced by a metric then it is Hausdorff.

Proof. If $x \neq y$ then $d(x, y) = s > 0$. So consider $U = B_{s/2}(x)$ and $V = B_{s/2}(y)$. The triangle inequality shows that $U \cap V = \emptyset$ and we know all balls are open. \square

Proposition. If a space is Hausdorff then a sequence in X has at most 1 limit.

Proof. Let (x_n) be a sequence in X . Suppose it has limits $y \neq z \in X$. Let U and V be disjoint local neighbourhoods for y and z respectively. Then $x_n \in U$ for all $n \geq N_1$ and $x_n \in V$ for all $n \geq N_2$. So if we take that $N = \max\{N_1, N_2\}$ then for all $n \geq N$, we have that $x_n \in U \cap V$ which is empty, hence we have a contradiction. \square

Proposition. If (X, T) is Hausdorff then points are closed.

Proof. Let $x \in X$. We want to show that $\{x\} = \overline{\{x\}}$. Let $y \neq x$. Let U, V be disjoint neighbourhoods of x and y respectively. We know that $x \in X \setminus V$ which is closed. Hence $\overline{\{x\}} \subseteq X \setminus V$. But $y \notin V$, so y is not in the closure of $\{x\}$ hence the closure of $\{x\}$ is just $\{x\}$, so $\{x\}$ is closed. \square

Let's see an example. Let X be an infinite set and consider the cofinite topology on X . Take two non-empty open sets, so

$$(X \setminus F) \cap (X \setminus F') = X \setminus (F \cup F')$$

which is non-empty since $F \cup F'$ is finite and X is infinite so the set on the RHS is non-empty hence the space is not Hausdorff.

1.5 Defining new topologies on existing ones

We have three main ways to define new topologies when given a topology already.

1.5.1 The subspace topology

Definition. (Subset topology) Let (X, T_X) be a topological space. Let $Y \subseteq X$ a subset. The *subset topology* on Y is

$$T|_Y = \{Y \cap U \mid U \in T\}.$$

Definition. (Subspace) A subspace of (X, T) is a subset equipped with the subspace topology.

Proposition. The subset topology is a topology.

Proof. Simple exercise of the axioms. \square

Proposition. The inclusion map $\iota : (Y, T|_Y) \rightarrow (X, T)$ is continuous. In fact $T|_Y$ is the constant topology on Y such that the inclusion map is continuous.

Proof. Let $U \in T$ then $\iota^{-1}(U) = U \cap Y \in T|_Y$ by definition. So it is continuous. Suppose $\iota : (Y, T') \rightarrow (X, T)$ is continuous. For $U \in T$, $\iota^{-1}(U) \in T'$ so $T|_Y \subseteq T'$. \square

A further point of view, a function $f : (z, T_z) \rightarrow (Y, T|_Y)$ is continuous if and only if $\iota \circ f$ is continuous.

Lemma. (Gluing Lemma) Let $f : X \rightarrow Y$ be a function between topological spaces.

- (i) If $\{U_\alpha\}_{\alpha \in I}$ are open subsets which cover X and each $f|_{U_\alpha} : U_\alpha \rightarrow Y$ are continuous (where U_α is given the subspace topology) then f is continuous.
- (ii) If $\{C_\alpha\}_{\alpha \in I}$ is a finite collection of closed sets containing X and $f|_{C_\alpha} : C_\alpha \rightarrow Y$ is continuous for each $\alpha \in I$ then f is continuous.

Proof. Let $V \subseteq Y$ be open. We want to show that $f^{-1}(V)$ is open. We know that

$$\begin{aligned} f^{-1}(V) &= (f^{-1}(V)) \cap X = f^{-1}(V) \cap \left(\bigcup_{\alpha \in I} U_\alpha \right) \\ &= \bigcup_{\alpha \in I} f^{-1}(V) \cap U_\alpha \end{aligned}$$

Since $f|_{U_\alpha}$ are continuous, we have that $f^{-1}|_{U_\alpha}(V)$ is open in U_α in the subspace topology. So there exists a W open in X such that $f^{-1}|_{U_\alpha}(V) = U_\alpha \cap W$ hence this is the intersection on open subsets of X so is open in X , hence since the union of open subsets is open $f^{-1}(V)$ is open, so f continuous.

The second part can be proved the same using the closed set definition of continuity. \square

If (X, d) is a metric space with topology T_d and $Y \subseteq X$ then $T_d|_Y$ is the topology induced by $d|_Y$.

1.5.2 The quotient topology

Definition. (Quotient topology) Let (X, T_X) be a topological space, \sim an equivalence relation on X and X/\sim is the set of equivalence classes, and $\pi : X \rightarrow X/\sim$ the equivalence map. The *quotient topology* on X/\sim is

$$T_{X/\sim} = \{U \subset X/\sim \mid \pi^{-1}(U) \in T_X\}.$$

Proposition. $T_{X/\sim}$ is indeed a topology.

Proof. $\emptyset = \pi^{-1}(\emptyset) \in T_X$ so $\emptyset \in T_{X/\sim}$. $X = \pi^{-1}(X/\sim) \in T_X$ so $X/\sim \in T_{X/\sim}$. Let $\{U_\alpha\}$ be a collection of sets of $T_{X/\sim}$, then

$$\pi^{-1}\left(\bigcup_{\alpha \in I} U_\alpha\right) = \bigcup_{\alpha \in I} \pi^{-1}(U_\alpha),$$

and $\pi^{-1}(U_\alpha) \in T_X$, so the union is too. Hence $\bigcup_{\alpha \in I} U_\alpha \in T_{X/\sim}$. We have a similar proof for finite intersections. \square

Proposition. The quotient map $\pi : (X, T_X) \rightarrow (X/\sim, T_{X/\sim})$ is continuous and $T_{X/\sim}$ is the finest topology for which this is true.

Proof. This is a tautology. \square

An alternative characterisation of the quotient topology is that $f : X/\sim \rightarrow Y$ is continuous if and only if $f \circ \pi : X \rightarrow Y$ is continuous.

Definition. For a continuous function $g : (X, T_X) \rightarrow (Y, T_Y)$ is a *quotient map* if it is surjective and $U \in T_Y \iff g^{-1}(U) \in T_X$.
Given, this construct \sim on X by $x \sim x' \iff g(x) = g(x')$. There is an induced function $G : X/\sim \rightarrow Y$ sending $G([x]) = g(x)$.

Remark. This function G is a bijection and continuous with a continuous inverse. This means that G is a homeomorphism, so $X/\sim \cong Y$.

Let's see an example on \mathbb{R} . Consider $x \sim y \iff x - y \in \mathbb{Z}$. What is \mathbb{R}/\sim ? Consider $f : \mathbb{R} \rightarrow \mathbb{R}^2$ defined by $x \rightarrow (\sin(2\pi x), \cos(2\pi x))$. This is a continuous map so $f : \mathbb{R} \rightarrow S^1 \subseteq \mathbb{R}^2$ is also continuous and surjective. By periodicity $x \sim y \iff f(x) = f(y)$, so we get $F : \mathbb{R}/\sim \rightarrow S^1$ which we can check is a homeomorphism.

Now take the example $X = \mathbb{R} \times \{0, 1\} \subseteq \mathbb{R}^2$ with the standard subspace topology. Let $(x, i) \sim (y, j) \iff (x, i) = (y, j) \text{ or } x = y \neq 0$. We can then think of X/\sim is a line with two origins. We cannot draw X/\sim since it is not Hausdorff. Any neighbourhood of $[(0, 0)]_\sim$ intersects any neighbourhood of $[(1, 0)]_\sim$ so not Hausdorff. Hence it is not subspace of any Euclidean space.

1.5.3 The product topology

For sets X, Y the projections functions are

$$\begin{aligned} \pi_X : X \times Y &\rightarrow X \\ (x, y) &\rightarrow x \end{aligned}$$

and

$$\begin{aligned} \pi_Y : X \times Y &\rightarrow Y \\ (x, y) &\rightarrow y \end{aligned}$$

Definition. (Product topology) Let (X, T_X) and (Y, T_Y) be topological spaces. Then *product topology* on $X \times Y$ consists of open sets $U \subseteq X \times Y$ such that for $(x, y) \in U$ there

is a $V \in T_X$ and $W \in T_Y$ such that $(x, y) \in V \times W \in U$.

Proposition. This indeed is a topology and the sets $V \times W$ are a basis for $T_{X \times Y}$.

Proof. Tautologically, we have that $\emptyset \in T_{X \times Y}$. Taking $V = X, W = Y$ we have that $X \times Y \in T_{X \times Y}$. For a collection $\{U_\alpha\}_{\alpha \in I}$ of elements of $T_{X \times Y}$, let $(x, y) \in \bigcup_{\alpha \in I} U_\alpha$. Then $(x, y) \in U_\beta$ for $\beta \in I$ so there exists neighbourhoods of x, y with their product a subset of $U_\beta \subseteq \bigcup_{\alpha \in I} U_\alpha \in T_{X \times Y}$. If I is finite and $(x, y) \in \bigcap_{\alpha \in I} U_\alpha$. Then $(x, y) \in V_\alpha \times W_\alpha \subseteq U_\alpha$ for each $\alpha \in I$. So $(x, y) \in (\bigcap_{\alpha} V_\alpha) \times (\bigcap_{\alpha} W_\alpha) \in \bigcap_{\alpha} U_\alpha$ and since these intersections are finite, these intersections are open. \square

Proposition. The projection maps

$$\pi_X : (X \times Y, T_{X \times Y}) \rightarrow (X, T_X) \quad \pi_Y : (X \times Y, T_{X \times Y}) \rightarrow (Y, T_Y)$$

are continuous and $T_{X \times Y}$ is the coarsest topology for which this is true.

Proof. Let $V \in T_X$. Then $\pi_X^{-1}(V) = V \times Y$, so this is open. Hence π_X, π_Y are continuous.

Suppose that T' is a topology on $X \times Y$ such that π_X and π_Y are continuous, then $\pi_X^{-1}(V) = V \times Y$ is open and $\pi_Y^{-1}(W) = X \times W$ is open. So $V \times W$ is open in T' , so $T_{X \times Y} \subseteq T'$. \square

The universal property of the product topology is that the function

$$f : (Z, T_Z) \rightarrow (X \times Y, T_{X \times Y})$$

is continuous if and only if $\pi_X \circ f : (Z, T_Z) \rightarrow (X, T_X)$ and $\pi_Y \circ f : (Z, T_Z) \rightarrow (Y, T_Y)$ are continuous. Equivalently, if f is componentwise continuous.