

Basic Topology

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July 14, 2020

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1 Introduction

1.1 Abstract spaces

We ask for a set X and for each point x of X a nonempty collection of subsets of X , called neighbourhoods of x . These neighbourhoods are required to satisfy four axioms

1. x lies in each of its neighbourhoods
2. The intersection of two neighbourhoods of x is itself a neighbourhood of x
3. If N is a neighbourhood of x and if U is a subset of X which contains N , then U is a neighbourhood of x
4. If N is a neighbourhood of x and if \dot{N} denotes the set $\{z \in N \mid N \text{ is a neighbourhood of } z\}$, then \dot{N} is a neighbourhood of x . (The set \dot{N} is called the **interior** of N)

This whole structure is called a **topological space**. The assignment of a collection of neighbourhoods satisfying axioms (1) \rightarrow (4) to each point $x \in X$ is called a **topology** on the set X .

Let X and Y be topological spaces. A function $f : X \rightarrow Y$ is **continuous** if for each point $x \in X$ and each neighbourhood N of $f(x)$ in Y the set $f^{-1}(N)$ is a neighbourhood of x in X . A function $h : X \rightarrow Y$ is called a **homeomorphism** if it is one-one, onto, continuous and has a continuous inverse. When such a function exists, X and Y are called **homeomorphic** spaces

Example 1.1. 1. Let X be a topological space and let Y be a subset of X . We can define a topology on Y as follows. Given a point $y \in Y$ take the collection of its neighbourhoods in the topological space X and intersect each of these neighbourhood with Y . The resulting sets are the neighbourhoods of y in Y . We say that Y has the **subspace topology**.

Definition 1.1. A **surface** is a topological space in which each point has a neighbourhood homeomorphic to the plane, and for which any two distinct points possess disjoint neighbourhoods

2 Continuity

2.1 Open and closed sets

Let X be a topological space and call a subset O of X **open** if it is a neighbourhood of each of its points. The union of any collection of open sets is open by axiom (3) and the intersection of *finite* number of open sets is open by axiom (2).

Suppose we have a set X together with a nonempty collection of subsets of X , which we call open sets, such that any union of open sets is itself open, any finite intersection of open sets is open, and both the whole set and the empty set are open. Given a point x of X , we shall call a subset N of x a **neighbourhood of x** if we can find an open set O s.t. $x \in O \subseteq N$

We claim that this definition of neighbourhood makes X into a topological space.

Verification for axiom (4). Suppose N is a neighbourhood of x and let \dot{N} denote the set of points z s.t. N is a neighbourhood of z . Choose an open set O s.t. $x \in O \subseteq N$. Now O , being open, is a neighbourhood of each of its points, so O is contained in \dot{N} .

Definition 2.1. A **topology** on a set X is a nonempty collection of subsets of X , called open sets, such that any union of open sets is open, any finite intersection of open sets is open, and both X and the empty set are open. A set together with a topology on it is called a **topological space**

The open sets of the “usual” topology on \mathbb{R}^n are characterized as follows. A set U is open if given $x \in U$ we can always find a positive real number ϵ s.t. the ball with centre x and radius ϵ lies entirely in U .

For **discrete topology** on X , every subset of X is an open set and we call X discrete space.

A subset of a topological space is **closed** if its complement is open.

Consider the set A on \mathbb{R}^2 whose points x, y satisfy $x \geq 0$ and $y > 0$. This set is neither closed nor open. Take the space X whose points are those points $(x, y) \in \mathbb{R}^2$ s.t. $x \geq 1$ or $x \leq -1$ and whose topology is induced from \mathbb{R}^2 . The subsets of X consisting of those points with positive first coordinate is both open and closed.

Let A be a subset of a topological space X and call a point p of X a **limit point** (or accumulation point) of A if every neighbourhood of p contains at least one point of $A - \{p\}$

Example 2.1.

1. Take X to be the real line \mathbb{R} , and let A consist of the points $1/n, n = 1, 2, \dots$. Then A has exactly one limit point, namely the origin
2. X the real line, take $A = [0, 1)$. Then each point of A is a limit point of A , and in addition 1 is a limit point
3. Let $X \subseteq \mathbb{R}^3$ and let A consist of those points all of whose coordinates are rational. Then every point of \mathbb{R}^3 is a limit point of A
4. Let $A \subseteq \mathbb{R}^3$ be the set of points which have integer coordinates. Then A does not have any limit points

5. Take X to be the set of all real numbers with the so called **finite-complement topology**. Here a set is open if its complement is finite or all of X . If we now take A to be an infinite subset of X (say the set of all integers), then every point of X is a limit point of A . On the other hand a finite subset of X has no limit points in this topology

Theorem 2.2. *A set is closed if and only if it contains all its limit points*

Proof. If A is closed, its complement $X - A$ is open. Since an open set is a neighbourhood of each of its points, no point of $X - A$ can be a limit point of A .

Suppose A contains all its limit points and let $x \in X - A$. Since x is not a limit point of A , we can find a neighbourhood N of x which does not meet A . So N is inside $X - A$, showing $X - A$ to be a neighbourhood of each of its points and consequently open. Therefore A is closed. \square

The union of A and all its limit points is called the **closure** of A and is written \bar{A}

Theorem 2.3. *The closure of A is the smallest closed set containing A , in other words the intersection of all closed sets which contain A*

Proof. For if $x \in X - \bar{A}$, we can find an open neighbourhood U of x which does not contain any points of A . Since an open set is a neighbourhood of each of its points, U cannot contain any of the limit points of A . Therefore we have an open set U s.t. $x \in U \subseteq X - \bar{A}$. Consequently $X - \bar{A}$ is a neighbourhood of each of its points and must be open.

Now let B be a closed set which contains A . Then every limit point of A is a limit point of B and therefore must lie in B since B is closed. This gives $\bar{A} \subseteq B$ \square

Corollary 2.4. *A set is closed if and only if it is equal to its closure*

A set whose closure is the whole space is said to be **dense** in the space

The **interior** of a set, usually written \mathring{A} , is the union of all open sets contained in A . A point lies in \mathring{A} if and only if it's a neighbourhood of A .

We define the **frontier** of A to be the $\bar{A} \cap \overline{X - A}$.

Suppose we have a topology on a set X , and a collection β of open sets s.t. every open set is a union of members of β . Then β is called a **base** for the topology and elements of β are called **basic open sets**. An equivalent formulation is to ask that given a point $x \in X$, and a neighbourhood N of x , there is always an element B of β s.t. $x \in B \subseteq N$.

Theorem 2.5. Let β be a nonempty collection of subsets of a set X . If the intersection of any finite number of members of β is always in β , and if $\bigcup \beta = X$, then β is a base for a topology on X

2.1.1 Exercise

Exercise 2.1.1. If A is a dense subset of a space X , and if O is open in X , show that $O \subseteq \overline{A \cap O}$

Proof. Suppose $O \not\subseteq \overline{A \cap O}$, then there is $x \in O$ and $x \notin \overline{A \cap O}$. Hence there is an open set U with $x \in U$ and $U \cap (A \cap O) = \emptyset$.

$$\overline{A \cap O} \cap (O - \{x\}) = \emptyset$$

But as $x \in \overline{A \cap O}$, we have

$$\overline{A \cap O} \cap O_x = \emptyset$$

and consequently, $A \cap O \cap O_x = \emptyset$. But then, setting $B = O \cap O_x$, B is open, but $A \cap B = \emptyset$ \square

Exercise 2.1.2. Show that the frontier of a set always contains the frontier of its interior. How does the frontier of $A \cup B$ relate to the frontiers of A and B

Proof. Let (X, τ) be a topological space, and let $A \subset X$. Let $x \in \text{Fr } A^\circ$. Then

$$x \in \overline{A^\circ} \cap \overline{X - A^\circ} = \overline{A^\circ} \cup \overline{(X - A) \cup (X - A^\circ)}$$

Now if $x \in \overline{A^\circ}$ and $x \in \overline{X - A}$, we are done. So suppose that $x \in \overline{A^\circ}$ and $x \in \overline{A - A^\circ}$. But then $x \in \overline{A^\circ} \cup \overline{A - A^\circ} = \overline{A}$.

$$\text{Fr}(A \cup B) \subset \text{Fr}(A) \cup \text{Fr}(B) \quad \square$$

Exercise 2.1.3. Let X be the set of real numbers and β the family of all subsets of the form $\{x \mid a \leq x < b \text{ where } a < b\}$. Prove that β is a base for a topology on X and that in this topology each member of β is both open and closed. Show that this topology does not have a countable base.

Proof. Suppose this topology has a countable base $\{B_n\}_{n \in \omega}$. Define the function $f : \mathbb{R} \rightarrow \mathbb{N}$ as follows: for each $x \in \mathbb{R}$, let $f(x) = n$ s.t. $B_n \subset [x, 1 + x)$

Suppose $x < y$ and $f(x) = f(y)$. Hence $[x, x + 1) \subset [y, y + 1)$, a contradiction \square

Exercise 2.1.4. Show that if X has a countable base for its topology, then X contains a countable dense subset. A space whose topology has a countable base is called a **second countable** space. A space which contains a countable dense subset is said to be **separable**.

Proof. Let $\{B_n\}_{n \in \omega}$ be a countable base for τ . By the Axiom of Choice, let A be the elements of elements $\{a_i\}_{i \in \omega}$ s.t. $a_i \in B_i$. The claim is that $\bar{A} = X$

Let $\mathcal{O} \in \tau$. Then $\mathcal{O} = \bigcup_j B_j$. Now, as $A = \bigcup_i x_i$, we have $A \cap \mathcal{O} \neq \emptyset$. \square

2.2 Continuous functions

Theorem 2.6. *A function from X to Y is continuous if and only if the inverse image of each open set of Y is open in X*

A continuous function is often called a **map**

Theorem 2.7. *The composition of two maps is a map*

Theorem 2.8. *Suppose $f : X \rightarrow Y$ is continuous, and let $A \subseteq X$ have the subspace topology. Then the restriction $f|_A : A \rightarrow Y$ is continuous*

Theorem 2.9. *The following are equivalent*

1. $f : X \rightarrow Y$ is a map
2. If β is a base for the topology of Y , the inverse image of every member of β is open in X
3. $\overline{f(A)} \subseteq \overline{f(A)}$ for any subset A of X
4. $f^{-1}(B) \subseteq f^{-1}(\bar{B})$ for any subset B of Y
5. The inverse image of each closed set in Y is closed in X

Proof. (2) \rightarrow (3). $f(A) \subseteq \overline{f(A)}$. If $x \in \bar{A} - A$ and $f(x) \notin f(A)$. If N is a neighbourhood of $f(x)$ we can find a basic open set B in β s.t. $f(x) \in B \subseteq N$. $f^{-1}(B)$ is open and is therefore a neighbourhood of x . But x is a limit point of A , which means that $f^{-1}(B)$ must contain a point of A . So B , and therefore N , contains a point of $f(A)$.

$$(3) \rightarrow (4). \overline{f(f^{-1}(B))} \subseteq f f^{-1}(\bar{B}) \Leftrightarrow \overline{f(f^{-1}(B))} \subseteq \overline{f f^{-1}(B)}$$

$$(4) \rightarrow (5). f^{-1}(B) \subseteq f^{-1}(\bar{B}) = f^{-1}(B). \quad \square$$

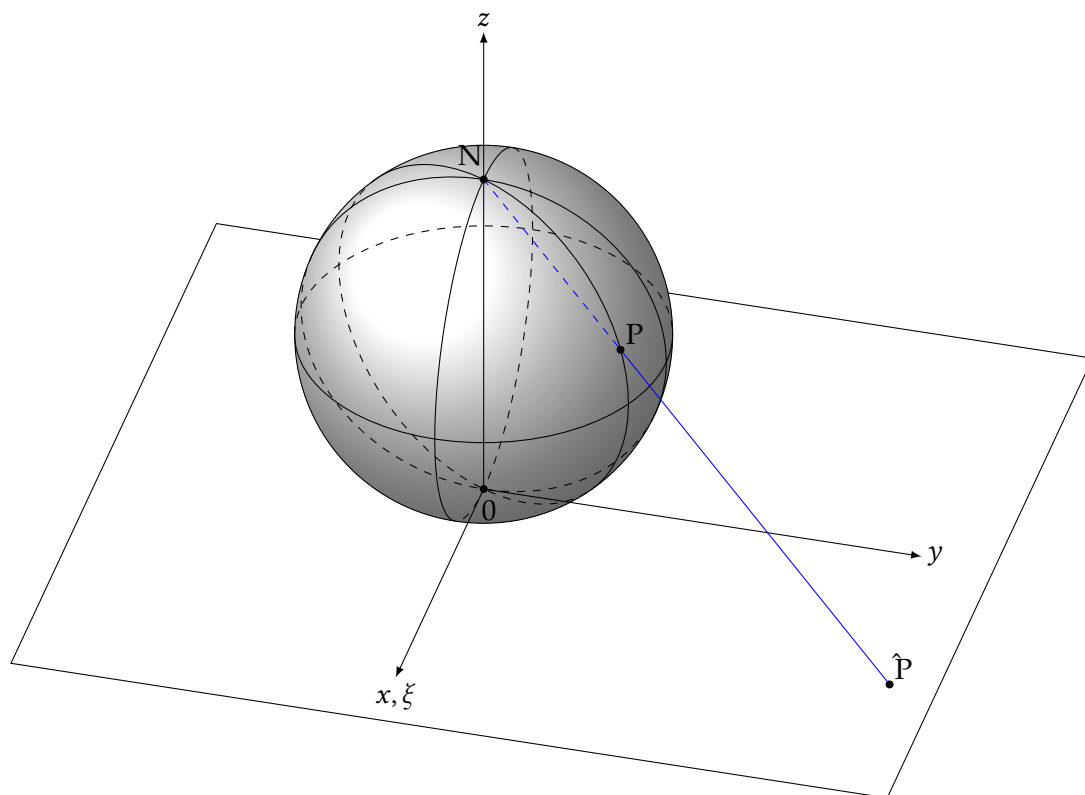
Example 2.2. Let C denote the unit circle in the complex plane, taken with the subspace topology, and give the interval $[0, 1)$ the induced topology from the real line. Define $f : [0, 1) \rightarrow C$ by $f(x) = e^{2\pi i x}$. f is continuous. We can take the set of all open segments of the circle as a base for the topology on C . Now if S is such a segment and if S does not contain the complex number 1, then $f^{-1}(S)$ is just an open interval of the form (a, b) where $0 < a < b < 1$. If S does happen to contain 1, then $f^{-1}(S)$ has the form $[0, a) \cup (b, 1)$, where $0 < a < b < 1$. This is open in $[0, 1)$ because it is the intersection of the open set $(-1, a) \cup (b, 1)$ of the real line with $[0, 1)$.

However its inverse is not continuous. Take O to be the interval $[0, 1/2)$; this is open in $[0, 1)$ but its image is not open in C

A **homeomorphism** $h : X \rightarrow Y$ is a function which is continuous, one-one, and onto, and which has continuous inverse. From Theorem 2.6 we see that a set O is open iff $h(O)$ is open. Therefore, h induces a one-one onto correspondence between the topologies of X and Y

Example 2.3. Let S^n denote the n -dimensional sphere whose points are those of \mathbb{R}^{n+1} which have distance 1 from the origin, taken with the subspace topology. We claim that removing a single point from S^n gives a space homeomorphic to \mathbb{R}^n .

Which point we remove is irrelevant because we can rotate any point of S^n into any other; for convenience we choose to remove the point $p = (0, \dots, 0, 1)$. Now the set of points of \mathbb{R}^{n+1} , which have zero as their final coordinate, when given the induced topology, is clearly homeomorphic to \mathbb{R}^n . We define a function $h : S^n - \{p\} \rightarrow \mathbb{E}$, called **stereographic projection** as follows. If $x \in S^n - \{p\}$, then $h(x)$ is the point of intersection of \mathbb{R}^n and the straight line determined by x and p



By a **disc** we mean any space homeomorphic to the closed unit disc D in \mathbb{R}^2 . C stands for the unit circle. If A is a disc, and if $h : A \rightarrow D$ is a homeomorphism, then $h^{-1}(C)$ is called the **boundary** of A and is written ∂A .

Lemma 2.10. *Any homeomorphism from the boundary of a disc to itself can be extended to a homeomorphism of the whole disc*

Proof. Let A be a disc and choose a homeomorphism $h : A \rightarrow D$. Given a homeomorphism $g : \partial A \rightarrow \partial A$, we can easily extend $hgh^{-1} : C \rightarrow C$ to a homeomorphism of all of D as follows. Send 0 to 0 , and if $x \in D - \{0\}$ send x to the point $\|x\| hgh^{-1}(x/\|x\|)$. In other words extend conically \square

Lemma 2.11. *Let A and B be discs which intersect along their boundaries in an arc. Then $A \cup B$ is a disc.*

Proof. Let γ denote the arc $A \cap B$, and use α, β for the complementary arcs in the boundaries of A and B . We construct a homeomorphism from $A \cup B$ to D with the aid of lemma 2.10

The y axis in the plane divides up D as the union of two discs D_1 and D_2 . We label the three arcs which together make up the boundaries of D_1 and D_2 as α , β and γ . Both α and β are homeomorphic to the closed unit interval $[0, 1]$, so we can find a homeomorphism from α to β . We first extend this over γ , to give a homeomorphism from $\alpha \cup \gamma$ to $\beta \cup \gamma$; then over A to give a homeomorphism from A to D_1 , which take γ to γ' , using lemma 2.10. \square

2.2.1 Exercise

Exercise 2.2.1. If $f : \mathbb{R} \rightarrow \mathbb{R}$ is a map, show that the set of points which are left fixed by f is a closed subset of \mathbb{R} . If g is a continuous real-valued function on X show that the set $\{x \mid g(x) = 0\}$ is closed

Proof. Define $f_0(x) = f(x) - x$ \square

Exercise 2.2.2. Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be a map and define its graph $\Gamma_f : \mathbb{R} \rightarrow \mathbb{R}^2$ by $\Gamma_f(x) = (x, f(x))$. Show that Γ_f is continuous and that its image (taken with the topology induced from \mathbb{R}^2) is homeomorphic to \mathbb{R}

Proof. The function $p_1 : \text{im } \Gamma_f \rightarrow \mathbb{R}$ defined by $(x, f(x)) \mapsto x$ is the desired homeomorphism \square

Exercise 2.2.3. What topology must X have if every real-valued function defined on X is continuous

Proof. Discrete topology. It suffices to show points in X are open

Fix $x \in X$ and define $f : X \rightarrow \mathbb{R}$ by

$$f(y) = \begin{cases} f(x) = 0 \\ f(y) = 1 \end{cases} \quad y \neq x$$

Then $f^{-1}((-0.5, 0.5)) = \{x\}$ \square

Exercise 2.2.4. An **open map** is one which sends open sets to open sets: a **closed map** takes closed sets to closed sets. Which of the following maps are open or closed

1. The exponential map $x \mapsto e^{ix}$ from the real line to the circle
2. The folding map $f : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ given by $(x, y) \mapsto (x, |y|)$
3. The map which winds the plane three times on itself given in terms of complex numbers, by $z \mapsto z^3$

Proof. 1.

2. not open. closed.
3. open. closed

□

2.3 A space-filling curve

2.4 The Tietze extension theorem

Let X be a topological space and A a subspace of X . Given a real-valued continuous function defined on A , it is natural to ask whether or not we can always extend it to all of X .

Definition 2.12. A **metric** or **distance function** on a set X is a real-valued function d defined on the cartesian product $X \times X$ s.t. for all $x, y, z \in X$

1. $d(x, y) \geq 0$ with equality iff $x = y$
2. $d(x, y) = d(y, x)$
3. $d(x, y) + d(y, z) \geq d(x, z)$

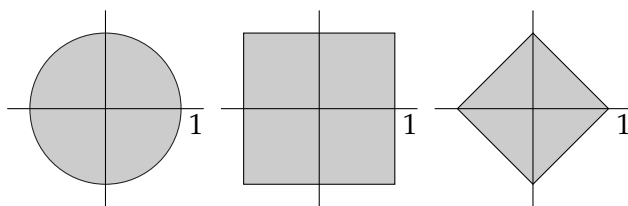
A set together with a metric on it is called a **metric space**

A metric on a set gives rise to a topology on the set as follows. Let d be a metric on the set X . Given $x \in X$, the set $\{y \in X \mid d(x, y) \leq \epsilon\}$ is called the **ball of radius ϵ** , or ϵ -ball, centered at the point x , and is denoted by $B(x, \epsilon)$. We define a subset O of X to be **open** if given $x \in O$ we can find a positive real number ϵ s.t. $B(x, \epsilon) \subset O$.

Different metrics on a set may give the same topology. For example, we can make the underlying set of points of euclidean n -space into a metric space in three different ways as follows. Write $\mathbf{x} = (x_1, \dots, x_n) \in \mathbb{R}^n$, define:

1. $d_1(\mathbf{x}, \mathbf{y}) = \sqrt{(x_1 - y_1)^2 + \dots + (x_n - y_n)^2}$
2. $d_2(\mathbf{x}, \mathbf{y}) = \max_{1 \leq i \leq n} |x_i - y_i|$
3. $d_3(\mathbf{x}, \mathbf{y}) = |x_1 - y_1| + \dots + |x_n - y_n|$

Following shows the ball of radius 1, centered at the origin for each of these three metrics when $n = 2$.



To see that d_1 and d_2 give rise to the same topology, we note that inside any disc we can find a square, and conversely inside a square we can find a disc.

Given two distinct points in a metric space, we can always find disjoint open sets containing them. For if $d(x, y) = \delta > 0$, set $U = \{z \in X \mid d(x, z) < \delta/2\}$ and $V = \{z \in X \mid d(y, z) \leq \delta/2\}$. Then both U and V are open sets. The set U is usually called the **open ball** with center x and radius $\delta/2$. A topological space with the property that two distinct points can always be surrounded by disjoint open sets is called a **Hausdorff space**.

If d is a metric on X and if A is a subset of X , the distance $d(x, A)$ of the point x from A is defined to be the infimum of the numbers $d(x, a)$ where $a \in A$.

Lemma 2.13. *The real-valued function on X defined by $x \mapsto d(x, A)$ is continuous*

Proof. Let $x \in X$ and let N be a neighbourhood of $d(x, A)$ on the real line. Choose $\epsilon > 0$ small enough so that the interval $(d(x, A) - \epsilon, d(x, A) + \epsilon)$ lies inside N . Let U denote the open ball centered x , radius $\epsilon/2$, $z \in U$, and choose a point $a \in A$ s.t. $d(x, a) < d(x, A) + \epsilon/2$. If $z \in U$ we have

$$d(z, A) \leq d(z, a) \leq d(z, x) + d(x, a) < d(x, A) + \epsilon$$

By reversing the roles of x and z , we also have $d(x, A) < d(z, A) + \epsilon$. Therefore U is mapped inside $(d(x, A) - \epsilon, d(x, A) + \epsilon)$ and hence inside N , by our function, showing that the inverse image of N is a neighbourhood of x in X as required. \square

Lemma 2.14. *If A, B are disjoint closed subsets of a metric space X , there is a continuous real-valued function on X which takes the value 1 on points of A , -1 on points of B , and values strictly between ± 1 on points of $X - (A \cup B)$*

Proof. Since A and B \square

2.4.1 Exercise

Exercise 2.4.1. Show $d(x, A) = 0$ iff x is a point of \bar{A}

Proof. Suppose that $d(x, A) = 0 = \inf_{a \in A} d(x, a)$. Then for every $\epsilon > 0$, there exists $a \in A$ s.t.

$$|d(x, a) - 0| = d(x, a) < \epsilon$$

Now let \mathcal{O} be an open subset of X , $x \in \mathcal{O}$. Choose $a \in A$ s.t. $d(x, a) < \epsilon$. Then $a \in \mathcal{O}$ and $\mathcal{O} \cap A \neq \emptyset$. Thus $x \in \bar{A}$

Suppose that $x \in \bar{A}$. Then we do the canonical ball construction and pick a sequence $\{a_n\}_n$ of elements of A , s.t. $d(x, a_n) \rightarrow 0, n \rightarrow \infty$ \square