

MATH 4431: Introduction to Topology

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Georgia Institute of Technology
Fall 2024

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Lecture 1

Aug. 20 — Review of Metric Spaces

1.1 Metric Spaces

Recall the definition of a *metric space*:

Definition 1.1. Given a set X , a function $d : X \times X \rightarrow \mathbb{R}$ is called a *metric* if

- (i) (strong positivity) $d(x, y) \geq 0$ for all $x, y \in X$, and $d(x, y) = 0$ if and only if $x = y$,
- (ii) (symmetry) $d(x, y) = d(y, x)$,
- (iii) and (triangle inequality) $d(x, z) \leq d(x, y) + d(y, z)$ for all $x, y, z \in X$.

Example 1.1.1. For any set X , we can define the *discrete metric* by

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

Verify as an exercise that this satisfies the triangle inequality.

Example 1.1.2. The Euclidean metric in \mathbb{R}^n is

$$d(\bar{x}, \bar{y}) = \sqrt{\sum_{i=1}^n (x_i - y_i)^2}$$

where $\bar{x} = (x_1, \dots, x_n)$ and $\bar{y} = (y_1, \dots, y_n)$.

1.2 Open Sets

Definition 1.2. The *open ball* of radius $R > 0$ around $x_0 \in X$ is

$$B_R(x_0) = \{y \in X \mid d(x_0, y) < R\}.$$

Given a set $S \subseteq X$, a point x_0 is called an interior point of S if there exists $r > 0$ such that $B_r(x_0) \subseteq S$. The set S is called *open* if all of its points are interior points.

Proposition 1.1. *The open ball $B_R(x)$ is open.*

Proof. Fix an arbitrary $y \in B_R(x)$, and observe that it suffices to show that y is an interior point. Take $r = R - d(x, y)$, and first note that $r > 0$ since $d(x, y) < R$. Now note that for all $z \in B_r(y)$, we have

$$d(x, z) \leq d(x, y) + d(y, z) < d(x, y) + (R - d(x, y)) = R,$$

so that $z \in B_R(x)$. Thus $B_r(y) \subseteq B_R(x)$, and so y is an interior point. \square

Corollary 1.0.1. $B_R(x) = \bigcup_{y \in B_R(x)} B_{r_y}(y)$, where $r_y = R - d(x, y)$.

Proof. We have $B_{r_y}(y) \subseteq B_R(x)$ for each $y \in B_R(x)$,¹ and so $\bigcup_{y \in B_R(x)} B_{r_y}(y) \subseteq B_R(x)$. For the reverse inclusion simply observe that $y \in B_{r_y}(y) \subseteq \bigcup_{y \in B_R(x)} B_{r_y}(y)$ for each $y \in B_R(x)$. \square

Proposition 1.2. *In a metric space (X, d) , the following are true:*

- (i) \emptyset, X are open,
- (ii) if $\{S_i\}_{i \in I}$ are open, then $\bigcup_{i \in I} S_i$ is open,
- (iii) and if $\{S_i\}_{i=1}^n$ are open, then $\bigcap_{i=1}^n S_i$ is open.

Proof. (i) The empty set is open vacuously. To see that X is open, simply take $R = 1$ for any $x \in X$.

(ii) Fix $x \in \bigcup_{i \in I} S_i$ arbitrary, so there exists $i_0 \in I$ with $x \in S_{i_0}$. Since S_{i_0} is open, x is an interior point and thus there exists $r > 0$ such that $B_r(x) \subseteq S_{i_0}$. But then $B_r(x) \subseteq S_{i_0} \subseteq \bigcup_{i \in I} S_i$, so x is an interior point of $\bigcup_{i \in I} S_i$ also and thus $\bigcup_{i \in I} S_i$ is open.

(iii) Now assume $x \in \bigcap_{i=1}^n S_i$. Then for each $1 \leq i \leq n$, there exists $r_i > 0$ such that $B_{r_i}(x) \subseteq S_i$. Then we can choose

$$r = \min\{r_1, \dots, r_n\} > 0,$$

so that $B_r(x) \subseteq B_{r_i}(x) \subseteq S_i$ for each $1 \leq i \leq n$. Thus $B_r(x) \subseteq \bigcap_{i=1}^n S_i$ and $\bigcap_{i=1}^n S_i$ is open. \square

Remark. The above argument for the finite intersection property requires that there are only finitely many r_i . Otherwise it may very well be that $r = \inf\{r_i\} = 0$ and the argument fails.

¹Using the argument from the previous proposition.

Lecture 2

Aug. 22 — Topology, Basis, Continuity

2.1 Topological Spaces

Definition 2.1. A *topology* $\mathcal{T} \subseteq \mathcal{P}(X)$ is a collection of sets such that

- (i) $\emptyset, X \in \mathcal{T}$,
- (ii) for any index set I , if $\{s_i\}_{i \in I} \subseteq \mathcal{T}$, then $\bigcup_{i \in I} s_i \in \mathcal{T}$ (closure under arbitrary union),
- (iii) and if $\{s_i\}_{i=1}^n \subseteq \mathcal{T}$, then $\bigcap_{i=1}^n s_i \in \mathcal{T}$ (closure under finite intersection).

A set with a topology, i.e. a pair (X, \mathcal{T}) , is called a *topological space*. Elements of \mathcal{T} are called *open sets*.

Example 2.1.1. The following are examples of topologies on a set X :

- The trivial topology: $\mathcal{T} = \{\emptyset, X\}$.
- The discrete topology: $\mathcal{T} = \mathcal{P}(X)$.¹
- If (X, d) is a metric space, then $\mathcal{T} = \{\text{collection of metrically open sets}\}$ is a topology on X .

Remark. Not every topology is induced by a metric. For instance consider the trivial topology on \mathbb{R} .

2.2 Basis for a Topology

Definition 2.2. A collection $\mathcal{B} \subseteq \mathcal{P}(X)$ is called a *basis* if

- (i) $\bigcup_{b \in \mathcal{B}} b = X$, i.e. \mathcal{B} is a covering of X ,
- (ii) and if $x \in b_1 \cap b_2$ for any $b_1, b_2 \in \mathcal{B}$, then there exists $b_3 \in \mathcal{B}$ such that $x \in b_3$ and $b_3 \subseteq b_1 \cap b_2$.

Theorem 2.1. Given a set X and a basis \mathcal{B} , define

$$\mathcal{T}_{\mathcal{B}} = \left\{ \bigcup_{i \in I} s_i \mid I \text{ is any index set and } \{s_i\}_{i \in I} \subseteq \mathcal{B} \right\}.$$

Then $\mathcal{T}_{\mathcal{B}}$ is a topology on X .

Proof. First observe that $\emptyset, X \in \mathcal{T}_{\mathcal{B}}$: Picking $I = \emptyset$ gives $\bigcup_{i \in I} s_i = \emptyset \in \mathcal{T}_{\mathcal{B}}$ and picking $I = \mathcal{B}$ gives $\bigcup_{b \in \mathcal{B}} b = X \in \mathcal{T}_{\mathcal{B}}$ by the covering property of a basis.

¹Note that the discrete topology is induced by the discrete metric.

Now assume $\{s_i\}_{i \in I} \subseteq \mathcal{T}_{\mathcal{B}}$. For each $i \in I$, we have $s_i \in \mathcal{T}_{\mathcal{B}}$ and so there exists an index set J_i such that $s_i = \bigcup_{j \in J_i} b_j$, where the $b_j \in \mathcal{B}$. Then

$$\bigcup_{i \in I} s_i = \bigcup_{i \in I} \bigcup_{j \in J_i} b_j,$$

which is a union of elements of \mathcal{B} and hence is in $\mathcal{T}_{\mathcal{B}}$.

Finally assume $\{s_i\}_{i=1}^n \subseteq \mathcal{T}_{\mathcal{B}}$. Now as each $s_i \in \mathcal{T}_{\mathcal{B}}$, there exists J_i such that $s_i = \bigcup_{j \in J_i} b_j$. Then

$$\bigcap_{i=1}^n s_i = \bigcap_{i=1}^n \bigcup_{j \in J_i} b_j.$$

Now assume $x \in \bigcap_{i=1}^n s_i = \bigcap_{i=1}^n \bigcup_{j \in J_i} b_j$. For each $1 \leq i \leq n$, there exists $j_i \in J_i$ such that $x \in b_{j_i}$. Hence $x \in \bigcap_{i=1}^n b_{j_i}$. Now by induction on the intersection property of a basis, we can find $b_x \in \mathcal{B}$ with

$$x \in b_x \subseteq \bigcap_{i=1}^n b_{j_i}$$

Also observe that

$$\bigcap_{i=1}^n b_{j_i} \subseteq \bigcap_{i=1}^n \bigcup_{j \in J_i} b_j = \bigcap_{i=1}^n s_i$$

by construction, so we may write

$$\bigcap_{i=1}^n s_i = \bigcup_{x \in \bigcap_{i=1}^n s_i} b_x \in \mathcal{T}_{\mathcal{B}}$$

as a union of elements of \mathcal{B} . □

Definition 2.3. A *subbasis* $\mathcal{B} \subseteq \mathcal{P}(X)$ is a collection of sets such that $\bigcup_{b \in \mathcal{B}} b = X$.

Remark. One may define a basis $\tilde{\mathcal{B}}$ from a subbasis \mathcal{B} by adding all finite intersections of elements of \mathcal{B} . We get the covering property for free and adding the finite intersections gives us the intersection property of a basis.

Example 2.3.1. For \mathbb{R} with the Euclidean metric, the following are bases for the standard topology:

- $\{B_R(x) \mid x \in \mathbb{R}, R > 0\}$.
- $\{B_R(x) \mid x \in \mathbb{R}, R > 0, R \in \mathbb{Q}\}$. For this use the fact that \mathbb{Q} is dense in \mathbb{R} .

In particular this shows that a basis for a topology is not unique in general.

2.3 Continuous Functions

Definition 2.4. Let (X, \mathcal{T}_X) and (Y, \mathcal{T}_Y) be two topological spaces. A function $f : X \rightarrow Y$ is called *continuous* if for any $O \in \mathcal{T}_Y$, we have $f^{-1}(O) \in \mathcal{T}_X$, i.e. the preimage of an open set is open.²

Example 2.4.1. Let X be equipped with the trivial topology $\{\emptyset, X\}$ and let \mathbb{R} be equipped with the standard topology. Then the only continuous functions $f : X \rightarrow \mathbb{R}$ are the constant functions $f : x \mapsto c$ for fixed $c \in \mathbb{R}$. To see this, observe that

²Recall that $f^{-1}(O) = \{x \in X \mid f(x) \in O\}$.

- $x \mapsto c$ is continuous since any open set in \mathbb{R} either contains c or does not, and so the preimage is either X or \emptyset .
- Suppose $f(x_1) = y_1$ and $f(x_2) = y_2$. Let $\epsilon = |y_1 - y_2|$ and observe that $x_1 \in f^{-1}(B_\epsilon(y_1))$ while $x_2 \notin f^{-1}(B_\epsilon(y_1))$, so $f^{-1}(B_\epsilon(y_1))$ is not open in X despite $B_\epsilon(y_1)$ being open in \mathbb{R} .

Example 2.4.2. Let X have the discrete topology $\mathcal{T} = \mathcal{P}(X)$ and let \mathbb{R} have the standard topology. Then all functions $X \rightarrow \mathbb{R}$ are continuous since any preimage is a subset of X and thus in $\mathcal{P}(X)$.

Remark. In a way, the trivial topology has too few open sets while the discrete topology has too many.

Definition 2.5. Two topological spaces (X, \mathcal{T}_X) and (Y, \mathcal{T}_Y) are *topologically equivalent* or *homeomorphic* if there exists a bijection $f : X \rightarrow Y$ such that f and f^{-1} are continuous.

Remark. A bijective function f being continuous does not necessarily imply that its inverse f^{-1} is.

Example 2.5.1. Consider $(-\pi/2, \pi/2)$ equipped with the Euclidean metric. This is homeomorphic to \mathbb{R} equipped with the Euclidean metric.³ One homeomorphism is given by $\tan : (-\pi/2, \pi/2) \rightarrow \mathbb{R}$.

³Note that $(-\pi/2, \pi/2)$ is bounded while \mathbb{R} is not.

Lecture 3

Aug. 27 — Closed Sets, Continuity, the Subspace Topology

3.1 Closed Sets

Definition 3.1. A set $S \subseteq X$ is called a *closed set* if $S^c = X \setminus S$ is open.

Example 3.1.1. In \mathbb{R} , observe that $[a, b]^c = (-\infty, a) \cup (b, \infty)$, which is a union of open sets and thus open. Thus the closed intervals $[a, b] \subseteq \mathbb{R}$ are closed.

Remark. This is not a dichotomy. Sets can be both open and closed (*clopen*), or even neither. Trivially, if X is any topological space, then \emptyset and X are both open and closed.

Example 3.1.2. Let $X = \{0, 1\}$ and $\mathcal{T} = \mathcal{P}(X)$. Then $\{0\}$ is both open and closed.

Example 3.1.3. Let $X = \{1, 2, 3\}$ and $\mathcal{T} = \{\emptyset, X, \{1\}, \{1, 2\}\}$. Then $\{2\}$ is neither open nor closed.

Recall the following De Morgan's laws from set theory:

Proposition 3.1 (De Morgan's laws). *Let I be an index set and $\{A_i\}_{i \in I}$ be sets. Then*

$$\left(\bigcup_{i \in I} A_i \right)^c = \bigcap_{i \in I} A_i^c \quad \text{and} \quad \left(\bigcap_{i \in I} A_i \right)^c = \bigcup_{i \in I} A_i^c.$$

Corollary 3.0.1. *In a topological space (X, \mathcal{T}) , we have:*

- (i) \emptyset, X are closed.
- (ii) if $\{A_i\}_{i \in I}$ are closed, then $\bigcap_{i \in I} A_i$ is closed,
- (iii) and if $\{A_i\}_{i=1}^n$ are closed, then so is $\bigcup_{i=1}^n A_i$.

This gives a dual characterization of a topology.

Proof. (i) We have $\emptyset^c = X \in \mathcal{T}$ and $X^c = \emptyset \in \mathcal{T}$.

(ii) Note that

$$\left(\bigcap_{i \in I} A_i \right)^c = \bigcup_{i \in I} A_i^c.$$

As each A_i is closed, we have $A_i^c \in \mathcal{T}$ is open, and hence $\bigcup_{i \in I} A_i^c \in \mathcal{T}$ is open. So $\bigcap_{i \in I} A_i$ is closed.

(iii) Observe that

$$\left(\bigcup_{i=1}^n A_i \right)^c = \bigcap_{i=1}^n A_i^c.$$

Each A_i is closed, so A_i^c is open. Thus $\bigcap_{i=1}^n A_i^c$ is open, and so $\bigcup_{i=1}^n A_i$ is closed. \square

3.2 Properties of Continuity

Recall that a function $f : (X, \mathcal{T}_X) \rightarrow (Y, \mathcal{T}_Y)$ is continuous if for every $O \in \mathcal{T}_Y$, we have $f^{-1}(O) \in \mathcal{T}_X$.

Theorem 3.1. *A function $f : X \rightarrow Y$ is continuous if and only if for every C closed in Y , $f^{-1}(C)$ is closed in X .*

Proof. (\Rightarrow) Let $C \subseteq Y$ be closed. Note that

$$f^{-1}(C) = \{x \in X \mid f(x) \in C\},$$

so we have

$$(f^{-1}(C))^c = \{x \in X \mid f(x) \notin C\} = \{x \in X \mid f(x) \in C^c\} = f^{-1}(C^c).$$

Since C is closed, C^c is open and so $f^{-1}(C^c) = (f^{-1}(C))^c$ is open. Thus $f^{-1}(C)$ is closed.

(\Leftarrow) Assume $S \subseteq Y$ is open. Note that

$$(f^{-1}(S))^c = \{x \in X \mid f(x) \in S\}^c = \{x \in X \mid f(x) \notin S\} = \{x \in X \mid f(x) \in S^c\} = f^{-1}(S^c).$$

Since S is open, S^c is closed and so $f^{-1}(S^c) = (f^{-1}(S))^c$ is closed by assumption. Thus $f^{-1}(S)$ is open, and so we see that f is continuous. \square

Theorem 3.2 (Composition theorem). *Let (X, \mathcal{T}_X) , (Y, \mathcal{T}_Y) , and (Z, \mathcal{T}_Z) be topological spaces. Let*

$$f : X \rightarrow Y \quad \text{and} \quad g : Y \rightarrow Z$$

be continuous functions. Then $g \circ f : X \rightarrow Z$ is continuous.

Proof. Let $S \subseteq Z$ be open. It suffices to show that $(g \circ f)^{-1}(S) \subseteq X$ is open. Note that

$$\begin{aligned} (g \circ f)^{-1}(S) &= \{x \in X \mid (g \circ f)(x) \in S\} = \{x \in X \mid f(x) \in g^{-1}(S)\} \\ &= \{x \in X \mid x \in f^{-1}(g^{-1}(S))\} = f^{-1}(g^{-1}(S)). \end{aligned}$$

Now as g is continuous, $g^{-1}(S)$ is open in Y . Finally as f is continuous, $f^{-1}(g^{-1}(S))$ is open in X . \square

Theorem 3.3. *Assume $X = \bigcup_{\alpha \in I} U_\alpha$ for open sets U_α and let $f : X \rightarrow Y$. Assume that $f|_{U_\alpha} : U_\alpha \rightarrow Y$ is continuous for each $\alpha \in I$. Then f is continuous.*

Proof. Let $S \subseteq Y$ be open, and it suffices to show that $f^{-1}(S)$ is open. Observe that

$$f^{-1}(S) = f^{-1}(S) \cap X = f^{-1}(S) \cap \left(\bigcup_{\alpha \in I} U_\alpha \right) = \bigcup_{\alpha \in I} (f^{-1}(S) \cap U_\alpha) = \bigcup_{\alpha \in I} f|_{U_\alpha}^{-1}(S).$$

The $f|_{U_\alpha}$ are continuous, so each $f|_{U_\alpha}^{-1}(S)$ is open. Thus $f^{-1}(S)$ is open as a union of open sets. \square

Theorem 3.4 (Pasting lemma). *Assume X, Y are topological spaces and $A, B \subseteq X$ are open. Suppose $f_1 : A \rightarrow Y$ and $f_2 : B \rightarrow Y$ are continuous, and that $f_1 \equiv f_2$ on $A \cap B$. Then $f : A \cup B \rightarrow Y$ defined by*

$$f(x) = \begin{cases} f_1(x) & \text{if } x \in A, \\ f_2(x) & \text{if } x \in B \end{cases}$$

is continuous.

Proof. Let $S \subseteq Y$ be open, it suffices to show that $f^{-1}(S)$ is open. Observe that

$$f^{-1}(S) = f_1^{-1}(S) \cup f_2^{-1}(S).$$

Both $f_1^{-1}(S)$ and $f_2^{-1}(S)$ are open since f_1 and f_2 are continuous, so $f^{-1}(S)$ is open as their union. \square

3.3 Subspace Topology

Definition 3.2. Let (X, \mathcal{T}_X) be a topological space and $S \subseteq X$ a set. The *subspace topology* on S is defined as follows: $O \subseteq S$ is open if there exists $U \subseteq X$ open in X such that $U = O \cap S$.

Example 3.2.1. Let \mathbb{R} be given the metric topology and $S = [0, 1]$.

- The set $[0, 1]$ is not open in \mathbb{R} , but it is open in the subspace topology on S since $[0, 1] = S \cap (-1, 2)$.
- The set $[0, 1/2)$ is neither open nor closed in \mathbb{R} , but $[0, 1/2) = S \cap (-1/2, 1/2)$, so it is open in S .

Theorem 3.5. *The subspace topology is indeed a topology.*

Proof. Let (X, \mathcal{T}_X) be a topological space and $S \subseteq X$ be given the subspace topology.

(i) We have $S = S \cap X$ and $\emptyset = \emptyset \cap X$, so S, \emptyset are open in S .

(ii) Let $\{U_\alpha\}_{\alpha \in I}$ be open in the subspace topology. Then for every $\alpha \in I$, there exists $O_\alpha \in \mathcal{T}$ such that $U_\alpha = S \cap O_\alpha$. Then

$$\bigcup_{\alpha \in I} U_\alpha = \bigcup_{\alpha \in I} (S \cap O_\alpha) = S \cap \left(\bigcup_{\alpha \in I} O_\alpha \right).$$

The $\{O_\alpha\}_{\alpha \in I}$ are open in X , so their union is open in X . Thus $\bigcup_{\alpha \in I} U_\alpha$ is open in the subspace topology.

(iii) Let $\{U_i\}_{i=1}^n$ be open in the subspace topology. Then there are O_i for $1 \leq i \leq n$ with $U_i = S \cap O_i$. Then we have

$$\bigcap_{i=1}^n U_i = \bigcap_{i=1}^n (S \cap O_i) = S \cap \left(\bigcap_{i=1}^n O_i \right).$$

As the $O_i \in \mathcal{T}$ are open, $\bigcap_{i=1}^n O_i$ is open in X . Thus $\bigcap_{i=1}^n U_i$ is open in the subspace topology. \square

Theorem 3.6. *Assume $f : X \rightarrow Y$ is a continuous function and $S \subseteq X$ a subspace. Then $f|_S : S \rightarrow Y$ is continuous, where S is equipped with the subspace topology.*

Proof. Let $O \subseteq Y$ be an open set, it suffices to show that $f|_S^{-1}(O)$ is open in the subspace topology. But observing that $f|_S^{-1}(O) = f^{-1}(O) \cap S$ immediately shows that $f|_S^{-1}(O)$ is open in S since $f^{-1}(O)$ is open in X due to the continuity of f . \square

Remark. The subspace topology is the smallest topology on S such that the inclusion map $i : S \rightarrow X$ given by $i(s) = s$ is a continuous function.

Remark. Let X be a topological space with subspaces $Y \subseteq X$ and $Z \subseteq Y$. Then the subspace topology on Z induced by the subspace Y is the same as the subspace topology on Z induced directly by X .

Remark. A topological space can have a subspace homeomorphic to itself. For instance, consider \mathbb{R} and $(-\pi/2, \pi/2)$ with a homeomorphism given by the tangent function.

Lecture 4

Aug. 29 — Connectedness

4.1 Connected Spaces

Definition 4.1. A *separation* of a topological space X is two open, nonempty sets $U, V \subseteq X$ such that $X = U \cup V$ and $U \cap V = \emptyset$. A space is called *connected* if there is no separation of the space.

Proposition 4.1. If X is separated, i.e. $X = U \cup V$ with U, V open and disjoint, then U and V are both open and closed.

Proof. Observe that U is open by assumption, and we have

$$U^c = X \setminus U = V,$$

which is also open by assumption. Hence U is closed. The case for V is identical. \square

Example 4.1.1. Consider the following:

- The singleton space $\{x\}$ is connected. There are no two nonempty, disjoint open sets.
- Consider the space $X = \{0, 1\}$. This case depends on the choice of topology:
 1. With the trivial topology $\mathcal{T} = \{\emptyset, X\}$, the space is connected.
 2. With the discrete topology $\mathcal{T} = \{\emptyset, X, \{1\}, \{0\}\}$, X is disconnected since $X = \{0\} \cup \{1\}$.
 3. With the topology $\mathcal{T} = \{\emptyset, X, \{1\}\}$, the space is connected. The only nonempty sets $\{1\}, X$ are not disjoint and thus there can be no separation.

Theorem 4.1. A space X is disconnected if and only if there exists a surjective map $f : X \rightarrow \{0, 1\}$ with the discrete topology.

Proof. (\Rightarrow) If X is disconnected, then we may write $X = U \cup V$ with U, V open, disjoint, and nonempty. Then define

$$f(x) = \begin{cases} 0 & x \in U, \\ 1 & x \in V, \end{cases}$$

which is surjective as U, V are nonempty. To see that f is continuous, observe that

$$f^{-1}(\emptyset) = \emptyset, \quad f^{-1}(\{0, 1\}) = X, \quad f^{-1}(\{0\}) = U, \quad f^{-1}(\{1\}) = V,$$

each of which are open. These are all of the open sets in the discrete topology, so f is continuous.

(\Leftarrow) Assume there exists a surjective and continuous map $f : X \rightarrow \{0, 1\}$. Define

$$U = f^{-1}(\{0\}) \quad \text{and} \quad V = f^{-1}(\{1\}),$$

which are open since f is continuous. Observe that $U, V \neq \emptyset$ since f is surjective. Also $U \cap V = \emptyset$ since if there is any $x \in U \cap V$, then $f(x) = 0$ as $x \in U$ and $f(x) = 1$ as $x \in V$, a contradiction. Finally, $X = U \cup V$ since $f(x) = 0$ or $f(x) = 1$ for every $x \in X$, i.e. $x \in U$ or $x \in V$. So X is disconnected. \square

4.2 Connected Sets

Definition 4.2. Let X be a topological space and $S \subseteq X$. Then S is called *connected* if it is connected in the subspace topology.

Theorem 4.2. If A, B are connected sets and $A \cap B \neq \emptyset$, then $A \cup B$ is connected.

Proof. Assume not. Then there exists a continuous, surjective map $f : A \cup B \rightarrow \{0, 1\}$ with the discrete topology. Consider $f|_A : A \rightarrow \{0, 1\}$, which is continuous in the subspace topology. Notice that $f(A)$ cannot be $\{0, 1\}$ since otherwise A is disconnected. Without loss of generality, assume $f(A) = \{0\}$ since A is nonempty. Now consider $f|_B : B \rightarrow \{0, 1\}$, which is also continuous. Similarly, notice that $f(B)$ cannot be $\{0, 1\}$. But there exists $p \in A \cap B$, and $f(p) = 0$ as $p \in A$. Then since $p \in B$, we must have $f(B) = \{0\}$. But then we get that $f(A \cup B) = \{0\} \neq \{0, 1\}$, a contradiction to surjectivity. \square

Corollary 4.2.1. A union of connected sets with “common points” is connected.

Proof. Run induction (transfinite if the union is infinite) using the previous theorem. \square

Theorem 4.3. Closed intervals in $[a, b] \subseteq \mathbb{R}$ with the metric topology are connected.

Proof. Assume otherwise that $[a, b] = U \cup V$ with U, V disjoint, open, and nonempty. Assume without loss of generality that $a \in U$. Since V is nonempty, there exists $c > a$ such that $c \in V$. Now consider $[a, c] \subseteq [a, b]$ with $U_1 = U \cap [a, c]$ and $V_1 = V \cap [a, c]$. By the least upper bound property of \mathbb{R} , since U_1 is nonempty and bounded from above, there exists $s = \sup U_1$ with $s \leq c$. Now either $s \in U_1$ or $s \notin U_1$.

If $s \in U_1$ (note this implies $s \neq c$), then s is an interior point of U_1 since U_1 is open. So one may find a point t such that $t > s$ and $t \in U_1$. But then s is no longer an upper bound of U_1 , a contradiction.

Otherwise $s \notin U_1$. Since U_1, V_1 cover $[a, c]$, we must then have $s \in V_1$ (note this implies $s \neq a$). Since V_1 is open, s is an interior point of V_1 , and thus there exists $t < s$ such that $t \in V_1$ and t is an upper bound for U_1 . This contradicts s being the least upper bound of U_1 .

Since both cases lead to contradictions, we conclude that $[a, b]$ must be connected. \square

Corollary 4.3.1. Open intervals in \mathbb{R} are connected, and \mathbb{R} itself is connected.

Proof. For some $N_0 \geq 1$ (for instance choose $N_0 \geq 2/(b-a)$) we can write

$$(a, b) = \bigcup_{n=N_0}^{\infty} \left[a + \frac{1}{n}, b - \frac{1}{n} \right],$$

Each of these closed intervals is connected by the previous theorem, and thus the union is connected by Corollary 4.2.1 since they overlap. Similarly writing $\mathbb{R} = \bigcup_{n=1}^{\infty} [-n, n]$ shows that \mathbb{R} is connected. \square

Corollary 4.3.2 (Intermediate value theorem). *Let $f : [a, b] \rightarrow \mathbb{R}$ be a continuous function. Then for any $f(a) < t < f(b)$, there exists $c \in [a, b]$ such that $f(c) = t$.*

Proof. Assume not. We can consider the open sets $(-\infty, t)$ and (t, ∞) in \mathbb{R} . Then $f^{-1}((-\infty, t))$ and $f^{-1}((t, \infty))$ are open sets since f is continuous. They are clearly disjoint (since f must be well-defined), and also nonempty since $a \in f^{-1}((-\infty, t))$ and $b \in f^{-1}((t, \infty))$. Also since $f^{-1}(\{t\}) = \emptyset$ by assumption,

$$[a, b] = f^{-1}((-\infty, t)) \cup f^{-1}((t, \infty)).$$

But this is a separation of $[a, b]$, a contradiction since $[a, b]$ is connected. □

Proposition 4.2. *The open interval $(0, 1)$ is not homeomorphic to the closed interval $[0, 1]$.*

Proof. Removing any point from $(0, 1)$ disconnects it, but $[0, 1] = [0, 1] \setminus \{1\}$ remains connected.¹ □

Proposition 4.3. *The real line \mathbb{R} is not homeomorphic to the plane \mathbb{R}^n for any $n \geq 2$.*

Proof. Removing a point from \mathbb{R} disconnects it but the same is not true for \mathbb{R}^n when $n \geq 2$. □

¹To see that $[0, 1]$ is connected, we can write $[0, 1] = \bigcup_{n=2}^{\infty} [0, 1 - 1/n]$.

Lecture 5

Sept. 3 — Path-Connectedness

5.1 More on Connectedness

Remark. The intervals $[a, b] \subseteq \mathbb{R}$ are homeomorphic to $[0, 1]$ for any $a < b$. We can take $f : [a, b] \rightarrow [0, 1]$ defined by

$$f(x) = \frac{1}{b-a}(x-a)$$

for instance as a homeomorphism.

Lemma 5.1. *If X is connected and $f : X \rightarrow Y$ is continuous, then $f(X)$ is connected.*

Proof. This is part of Homework 2. □

Corollary 5.0.1. *The plane \mathbb{R}^2 is connected.*

Proof. Express \mathbb{R}^2 as the union of horizontal and vertical lines. Each line is the image of \mathbb{R} and is thus connected by Lemma 5.1. Also any pair of horizontal and vertical lines must intersect, so we can use Corollary 4.2.1 to conclude that the union \mathbb{R}^2 is connected. □

Remark. We can extend this to \mathbb{R}^3 by embedding planes (copies of \mathbb{R}^2), and similarly for \mathbb{R}^n .

Proposition 5.1. *The unit circle $\mathbb{S}^1 \subseteq \mathbb{R}^2$ is connected.*

Proof. Define $\gamma : [0, 2\pi] \rightarrow \mathbb{R}^2$ by $\gamma(t) = (\cos t, \sin t)$. The image of γ is precisely \mathbb{S}^1 . □

Proposition 5.2. *Define a relation \sim on X by $x \sim y$ if there exists a connected subset $S \subseteq X$ such that $x, y \in S$. Then \sim is an equivalence relation.*

Proof. For reflexivity, fix $x \in X$ and let S be the largest connected set containing x (this exists since we know at least $\{x\}$ must be connected). Then $x \in S$, so $x \sim x$.

For symmetry, fix $x, y \in X$. If $x \sim y$, then there exists a connected set S such that $x, y \in S$. But then $y, x \in S$, so we see that $y \sim x$.

For transitivity, assume that $x \sim y$ and $y \sim z$. Then there exists S_1 connected such that $x, y \in S_1$ and S_2 connected such that $y, z \in S_2$. Notice that $S_1 \cap S_2 \neq \emptyset$ since $y \in S_1 \cap S_2$. Then $S_1 \cup S_2$ is connected by Theorem 4.2 and $x, y, z \in S_1 \cup S_2$. In particular, $x, z \in S_1 \cup S_2$ and thus $x \sim z$.

So we see that \sim is an equivalence relation. □

Definition 5.1. Let the equivalence relation \sim be defined on X as in Proposition 5.2. Then we can write X as the disjoint union of the equivalence classes of \sim . These equivalence classes are called the *connected components* of X .

Remark. The connected components of a space are defined solely via topologies, so they must be invariant under homeomorphism.

Example 5.1.1. The letter S , sitting in \mathbb{R}^2 , is not homeomorphic to the letter T . There is a point we can remove from T to give three connected components, but removing any point from S gives at most two such connected components.

5.2 Path-Connectedness

Remark. Connectedness is usually a very difficult property to verify. This motivates *path-connectedness*.

Definition 5.2. A set S is *path-connected* if for all $x, y \in S$, there exists a continuous map $\gamma : [0, 1] \rightarrow S$ such that $\gamma(0) = x$ and $\gamma(1) = y$. Here $[0, 1]$ is given the usual metric topology.

Lemma 5.2. *If S is path-connected, then S is connected.*

Proof. This is part of Homework 2. □

Remark. Unlike connectedness, it is immediately obvious that \mathbb{R}^n is path-connected. Simply take the line segment between any two points. Then we can conclude connectedness by the previous lemma.

Example 5.2.1. There are spaces which are connected but not path-connected.

- Consider the *topologist's sine curve*, given by the union of the vertical segment $\{(0, y) \mid -1 \leq y \leq 1\}$ and the image of $(0, \infty)$ under $x \mapsto (x, \sin(1/x))$, is an example of such a space. See Homework 2 for more details.
- Consider the *cone* C in \mathbb{R}^2 defined by ($(0, 1)$ denotes an open interval unless otherwise specified)

$$C = ([0, 1] \times \{0\}) \cup (K \times [0, 1]) \cup (\{0\} \times [0, 1]),$$

where $K = \{1/n : n \in \mathbb{N}\}$. Note that C is clearly path-connected and hence also connected. Then define the space

$$D = C \setminus (\{0\} \times (0, 1)),$$

which is now not path-connected (consider the point $(0, 1) \in D$) but still connected.

Remark. Observe the following:

- One can define *path-connected components* in a similar manner as connected components.
- A continuous image of a path-connected space is path-connected. Simply compose the curve with the continuous map, which is now a path in the image.
- The union of path-connected spaces sharing a point is path-connected. Take two curves to the common point and concatenate them using the pasting lemma.
- In \mathbb{R}^n , connectedness is equivalent to path-connectedness. In general, this holds if you can get a basis of only connected sets.

Remark. Recall from homework that if $f : [0, 1] \rightarrow [0, 1]$ is continuous, then f has a fixed point, i.e. there exists $c \in [0, 1]$ with $f(c) = c$. This follows from a clever use of the intermediate value theorem. Now consider a more topological perspective. Consider the diagonal $\{(x, x) \mid x \in [0, 1]\}$ and look at the graph of f , which is contained in the closed unit square. This graph is path-connected as the image of a path-connected set and so there is a path between the points $(0, f(0))$ and $(1, f(1))$. But then this path must intersect the diagonal at some point, which gives a fixed point.

Theorem 5.1. (*Brouwer fixed point theorem*) *Let K be a closed, bounded, and convex set in \mathbb{R} . Then any continuous map $f : K \rightarrow K$ has a fixed point, i.e. there exists $c \in K$ such that $f(c) = c$.*

Remark. One can see the existence of the Nash equilibrium as a consequence of this theorem.

Remark. In \mathbb{R}^2 , this theorem follows from the following claim. Let $X = \text{maps}(\mathbb{S}^1, \mathbb{S}^1)$ be the set of all continuous maps from \mathbb{S}^1 to itself. Then Brouwer's fixed point theorem in \mathbb{R}^2 follows from the following:

Theorem 5.2. *The space $\text{maps}(\mathbb{S}^1, \mathbb{S}^1)$ is not path connected.*

Lecture 6

Sept. 5 — Compactness

6.1 Note on the Subspace Topology

Remark. Let X be a topological space with topology \mathcal{T}_X , and let $Y \subseteq X$ be a subset endowed with a topology τ . Suppose that for any continuous $f : X \rightarrow Z$, there exists a continuous $\tilde{f} : Y \rightarrow Z$ such that the following diagram commutes,

$$\begin{array}{ccc} X & \xrightarrow{f} & Z \\ i \uparrow & \nearrow \tilde{f} & \\ Y & & \end{array}$$

where $i : Y \rightarrow X$ is the inclusion map.¹ Then in Homework 2 we showed that $\mathcal{T}_Y \subseteq \tau$. We can see this as a *universal property* for the subspace topology.

6.2 Compactness

Definition 6.1. A set $C \subseteq X$ is called *compact* if for any *open cover*

$$C \subseteq \bigcup_{\alpha \in I} U_{\alpha}, \quad \text{each } U_{\alpha} \text{ is open,}$$

there exists a finite subcover $C \subseteq \bigcup_{i=1}^n U_{\alpha_i}$.

Example 6.1.1. Consider the following:

- In a finite topology, any set is compact. This is because any open cover is already finite.
- In a discrete space, i.e. $\mathcal{T} = \mathcal{P}(X)$, compact sets are precisely the finite sets. It is clear that finite sets are compact, for each x choose a single open set in the cover containing x . Conversely, if a set is compact, we can pick our open cover to contain only singletons, and the existence of a finite subcover means that the set has only finitely many elements.

Theorem 6.1 (Heine-Borel). *Let $C \subseteq \mathbb{R}^n$ be a subset, where \mathbb{R}^n is given the metric topology. Then C is compact if and only if C is closed and bounded.*

Proof. We postpone this proof until later. □

Lemma 6.1. *Let X be compact. If $Y \subseteq X$ is closed, then Y is compact.*

¹Note that at least set-theoretically, this immediately defines $\tilde{f} = f|_Y$. But a priori we do not know that \tilde{f} is continuous.

Proof. Let $Y \subseteq X$ closed be given, and assume that $Y \subseteq \bigcup_{\alpha \in I} U_\alpha$ an open cover. Since Y is closed, its complement Y^c is open. Then

$$Y^c \cup \bigcup_{\alpha \in I} U_\alpha$$

is an open cover of X since $X = Y \cup Y^c$. Since X is compact, there exists a finite subcover

$$X \subseteq Y^c \cup \bigcup_{i=1}^n U_{\alpha_i}.$$

Now observe that $Y \subseteq X$ and $Y \cap Y^c = \emptyset$, so actually $Y \subseteq \bigcup_{i=1}^n U_{\alpha_i}$, which is a finite subcover. \square

Theorem 6.2. *Let X be compact and $f : X \rightarrow Y$ continuous. Then $f(X)$ is compact.*

Proof. Consider $f(X) \subseteq Y$ and let $f(X) \subseteq \bigcup_{\alpha \in I} V_\alpha$, an open cover in Y . Notice that

$$X = f^{-1}(f(X)) \subseteq f^{-1}\left(\bigcup_{\alpha \in I} V_\alpha\right) = \bigcup_{\alpha \in I} f^{-1}(V_\alpha).$$

Note that each $f^{-1}(V_\alpha)$ is open in X since f is continuous and V_α is open in Y , so this is in fact an open cover of X . Thus since X is compact, we may extract a finite subcover

$$X \subseteq \bigcup_{i=1}^n f^{-1}(V_{\alpha_i}).$$

Then we see that

$$f(X) \subseteq f\left(\bigcup_{i=1}^n f^{-1}(V_{\alpha_i})\right) \subseteq \bigcup_{i=1}^n V_{\alpha_i},$$

which is a finite subcover of $f(X)$. Therefore $f(X)$ is compact. \square

Theorem 6.3. *Assume $\{C_j\}_{j=1}^m$ are compact subsets of X . Then $\bigcup_{j=1}^m C_j$ is compact.*

Proof. Assume $\bigcup_{j=1}^m C_j \subseteq \bigcup_{\alpha \in I} U_\alpha$, an open cover. Observe this is also an open cover of C_j for each $1 \leq j \leq m$, so we can extract a finite subcover, i.e. we can find $\alpha_{j,1}, \dots, \alpha_{j,n_j}$ with

$$C_j \subseteq \bigcup_{i=1}^{n_j} U_{\alpha_{j,i}}.$$

Then we see that

$$\bigcup_{j=1}^m C_j \subseteq \bigcup_{j=1}^m \bigcup_{i=1}^{n_j} U_{\alpha_{j,i}},$$

which is still a finite union. This is then a finite subcover of $\bigcup_{j=1}^m C_j$, so $\bigcup_{j=1}^m C_j$ is compact. \square

Theorem 6.4 (Weierstrass). *Let $f : [a, b] \rightarrow \mathbb{R}$ be continuous. Then $f([a, b])$ is bounded, and moreover there exist $x_{\max}, x_{\min} \in [a, b]$ such that $f(x_{\max}) \geq f(x) \geq f(x_{\min})$ for all $x \in [a, b]$.*

Proof. Since f is continuous and $[a, b]$ is compact (by Heine-Borel), $f([a, b]) \subseteq \mathbb{R}$ is compact. Thus by Heine-Borel, $f([a, b])$ is bounded. In particular, we can find M, m such that

$$m \leq f(x) \leq M \quad \text{for all } x \in [a, b].$$

For the second part, observe that $f([a, b])$ is bounded and nonempty, so $s = \sup f([a, b])$. Since this is the supremum, there must exist $y_i \in f([a, b])$ such that $y_i \rightarrow s$ as $i \rightarrow \infty$. Now observe that $f([a, b])$ is closed by Heine-Borel, and in particular it contains its limit points. Thus we obtain $s \in f([a, b])$. Then pick $x_{\max} \in f^{-1}(\{s\}) \subseteq [a, b]$, which will satisfy $f(x_{\max}) = s \geq f(x)$ for all $x \in [a, b]$. by construction.

The argument for finding $x_{\min} \in [a, b]$ is similar. □

Theorem 6.5. *Let X be a topological space, $K \subseteq X$ compact, and $f : K \rightarrow \mathbb{R}$ a continuous function. Then f is bounded over K and attains its minimum and maximum on K .*

Proof. The same argument goes through, replacing $[a, b]$ by the compact set K . □

Lecture 7

Sept. 10 — More Compactness

7.1 The Cantor Set

Define $I_0 = [0, 1]$ and remove the open middle-thirds interval to get

$$I_1 = [0, 1] \setminus (1/3, 2/3) = [0, 1/3] \cup [2/3, 1].$$

Continue by removing the middle thirds of each interval to get I_2, I_3, \dots . Then the *Cantor set* is defined to be $K = \bigcap_{I \geq 0} I_n$. The Cantor set is compact and uncountable. See more on Homework 3.

7.2 The Heine-Borel Theorem

Theorem 7.1 (Heine-Borel). *If $C \subseteq \mathbb{R}$, then C is compact if and only if C is closed and bounded.*

Proof. (\Rightarrow) This direction is easy, see Homework 3 for details.

(\Leftarrow) First we show that $[a, b] \subseteq \mathbb{R}$ is compact. Let $\{U_\alpha\}_{\alpha \in I}$ be an open cover for $[a, b]$, i.e. $[a, b] \subseteq \bigcup_{\alpha \in I} U_\alpha$. Now define

$$R = \{x \in [a, b] \mid [a, x] \text{ has a finite subcover}\}$$

Clearly $a \in R$ since $a \in [a, b] \subseteq \bigcup_{\alpha \in I} U_\alpha$, so picking any single U_α with $a \in U_\alpha$ gives a finite subcover for $[a, a] = \{a\}$. The goal is now to show that $b \in R$. Observe that $a \in R$ implies $R \neq \emptyset$, and $R \subseteq [a, b]$, so

$$s = \sup R$$

exists by the completeness of \mathbb{R} . We proceed to show that $s \in R$ and then $s = b$, which will show that $b \in R$. As $s \in [a, b] \subseteq \bigcup_{\alpha \in I} U_\alpha$, we can find α_s such that $s \in U_{\alpha_s}$. Since U_{α_s} is open, we can find $\delta > 0$ such that $(s - \delta, s + \delta) \subseteq U_{\alpha_s}$. Then since s is a least upper bound of R , we can find $r \in R$ such that $s - \delta < r \leq s$. Now since $r \in R$, $[a, r]$ admits a finite subcover $\{U_{\alpha_i}\}_{i=1}^n$. Then

$$[a, s] = [a, r] \cup (s - \delta, s] \subseteq \left(\bigcup_{i=1}^n U_{\alpha_i} \right) \cup U_{\alpha_s}$$

is a finite subcover for $[a, s]$, so $s \in R$. Now observe that we actually covered

$$\left[a, s + \frac{\delta}{2} \right] = [a, r] \cup (s - \delta, s + \delta) \subseteq \left(\bigcup_{i=1}^n U_{\alpha_i} \right) \cup U_{\alpha_s}$$

in the previous construction. Then $s + \delta/2 \in R$, which contradicts the minimality of s unless $s = b$. Thus $b \in R$, so $[a, b]$ admits a finite subcover and thus $[a, b]$ is compact.

Now let $C \subseteq \mathbb{R}$ be an arbitrary closed and bounded set. Since C is bounded, there exists $I = (a, b)$ such that $C \subseteq I$. But then $C \subseteq I \subseteq \bar{I} = [a, b]$, so C is a closed subset of a compact set, hence compact. \square

Remark. The Heine-Borel theorem also holds more generally in \mathbb{R}^n . A later theorem will say that the product of compact sets is compact in the product topology, and thus we can run the same argument as above but with boxes in \mathbb{R}^n instead of intervals.

7.3 The Bolzano-Weierstrass Theorem

Definition 7.1. A point x is an *accumulation point* for a set S if for all open sets U containing x , we have $(U \setminus \{x\}) \cap S \neq \emptyset$.

Remark. We disallow constant sequences when talking about accumulation points.

Proposition 7.1. Let $\text{Acc}(A)$ be the set of accumulation points of a set A . Then $\bar{A} = A \cup \text{Acc}(A)$.

Proof. We show that $A \cup \text{Acc}(A)$ is closed, which will imply $\bar{A} \subseteq A \cup \text{Acc}(A)$ by the minimality of the closure. Write

$$(A \cup \text{Acc}(A))^c = A^c \cap \text{Acc}(A)^c.$$

Now assume $x \in A^c \cap \text{Acc}(A)^c$. Since $x \notin \text{Acc}(A)$, there exists U_x open such that $x \in U_x$ and

$$(A \setminus \{x\}) \cap U_x = \emptyset.$$

But also $x \notin A$, so $A \setminus \{x\} = A$ and $A \cap U_x = \emptyset$. Then we can write

$$(A \cup \text{Acc}(A))^c = A^c \cap \text{Acc}(A)^c = \bigcup_{x \in A^c \cap \text{Acc}(A)^c} U_x.$$

This is a union of open sets, hence open, and so $A \cup \text{Acc}(A)$ is closed.

For the other direction, assume $x \in A \cup \text{Acc}(A)$. If $x \in A$, we are done, so assume $x \in \text{Acc}(A) \setminus A$. Now assume otherwise that $x \notin \bar{A}$. Then $x \in (\bar{A})^c$, which is open. Set $U = (\bar{A})^c$, so that

$$U \cap (A \setminus \{x\}) = U \cap A = \emptyset.$$

But then this says that x is not an accumulation point, in contradiction. \square

Definition 7.2. We say that a topological space X is *sequentially compact* if every bounded sequence has a convergent subsequence.

Theorem 7.2 (Bolzano-Weierstrass). Any bounded infinite set $S \subseteq \mathbb{R}^n$ has an accumulation point.

Proof. Since S is bounded, find a compact set containing S . Then apply the later Theorem 7.4. \square

Remark. In general, compactness is *not* equivalent to sequential compactness, but both imply the Bolzano-Weierstrass theorem. However, in many spaces (including metric spaces, in particular), the two notions coincide (and are also equivalent to the Bolzano-Weierstrass theorem).

Theorem 7.3. *A sequentially compact space has the Bolzano-Weierstrass property, namely that any bounded infinite set has an accumulation point.*

Proof. This is easy, pick a countable subset (i.e. a sequence) and apply sequential compactness. \square

Theorem 7.4. *A compact space has the Bolzano-Weierstrass property, namely that any infinite set has an accumulation point.*

Proof. Let A be an infinite set in X , where X is compact. Assume otherwise that A has no accumulation points in X . Then there is no accumulation point for A outside of A , so $\text{Acc}(A) \subseteq A$. This gives

$$\overline{A} = A \cup \text{Acc}(A) = A,$$

so A is closed. Thus A is a closed subset of a compact space, hence compact. Now for any $a \in A$, pick an open set U_a such that $a \in U_a$ and $U_a \cap (A \setminus \{a\}) = \emptyset$. Write $A \subseteq \bigcup_{a \in A} U_a$, and by compactness we can find a finite subcover $A \subseteq \bigcup_{i=1}^n U_{a_i}$. Then observe that

$$A = A \cap \bigcup_{i=1}^n U_{a_i} = \bigcup_{i=1}^n (A \cap U_{a_i}) = \bigcup_{i=1}^n \{a_i\} = \{a_1, \dots, a_n\},$$

This is in contradiction with A being infinite. \square

Remark. Usually, this proof goes by showing that compactness implies sequential compactness, which then implies the Bolzano-Weierstrass property. But this proof avoids going through convergent sequences.