MATH 4431: Introduction to Topology

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Contents

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

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

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

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

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

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) $\varnothing, X$ *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 $1 \le i \le n$, 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 $1 \le i \le n$. 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.

[1] Using 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) $\varnothing, X \in \mathcal{T}$,

(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: $\mathcal{T} = \{\varnothing, X\}$.
- 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 $b_1, b_2 \in B$, 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*

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

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

Proof. First observe that $\varnothing, X \in \mathcal{T}_\mathcal{B}$: Picking $I = \varnothing$ gives $\bigcup_{i\in I} s_i = \varnothing \in \mathcal{T}_\mathcal{B}$ 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.

[1] Note 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 $1 \le i \le n$, 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 $\mathcal{B}$. $\square$

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 $\widetilde{\mathcal{B}}$ 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 $f : X \to Y$ 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 $\{\varnothing, X\}$ and let $\mathbb{R}$ be equipped with the standard topology. Then the only continuous functions $f : X \to \mathbb{R}$ are the constant functions $f : x \mapsto c$ for fixed $c \in \mathbb{R}$. To see this, observe that

[2] Recall 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 $\varnothing$.
- 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 $X \to \mathbb{R}$ 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 $f : X \to Y$ 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 $\tan : (-\pi/2, \pi/2) \to \mathbb{R}$.

[3] Note 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 $\varnothing$ 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 $\mathcal{T} = \{\varnothing, X, \{1\}, \{1,2\}\}$. 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*

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

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

(i) $\varnothing, X$ 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 $\varnothing^c = X \in \mathcal{T}$ and $X^c = \varnothing \in \mathcal{T}$.

(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. □

3.2 Properties of Continuity

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

Theorem 3.1. *A function $f : X \to Y$ 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. □

Theorem 3.2 (Composition theorem)**.** *Let $(X, \mathcal{T}_X)$, $(Y, \mathcal{T}_Y)$, and $(Z, \mathcal{T}_Z)$ be topological spaces. Let*
$$f : X \to Y \quad \text{and} \quad g : Y \to Z$$
be continuous functions. Then $g \circ f : X \to Z$ 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. □

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

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

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 $\varnothing = \varnothing \cap X$, so $S, \varnothing$ 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. □

Theorem 3.6. *Assume $f : X \to Y$ is a continuous function and $S \subseteq X$ a subspace. Then $f|_S : S \to Y$ 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. □

Remark. The subspace topology is the smallest topology on S such that the inclusion map $i : S \to X$ 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 homemorphism 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 $U \cap V = \varnothing$. 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. □

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 $\mathcal{T} = \{\varnothing, X\}$, the space is connected.
  2. With the discrete topology $\mathcal{T} = \{\varnothing, X, \{1\}, \{0\}\}$, X is disconnected since $X = \{0\} \cup \{1\}$.
  3. With the topology $\mathcal{T} = \{\varnothing, X, \{1\}\}$, 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 $f : X \to \{0, 1\}$ 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

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

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 $f : X \to \{0, 1\}$. Define

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

which are open since f is continuous. Observe that $U, V \neq \varnothing$ since f is surjective. Also $U \cap V = \varnothing$ 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. □

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 $A \cap B \neq \varnothing$, then $A \cup B$ is connected.*

Proof. Assume not. Then there exists a continuous, surjective map $f : A \cup B \to \{0, 1\}$ with the discrete topology. Consider $f|_A : A \to \{0, 1\}$, 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 $f|_B : B \to \{0, 1\}$, 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. □

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. □

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 conclue that $[a, b]$ must be connected. □

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. □

Corollary 4.3.2 (Intermediate value theorem)**.** *Let $f : [a, b] \to \mathbb{R}$ 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 $f^{-1}(\{t\}) = \varnothing$ 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 $n \geq 2$. □

[1] To 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 $f : [a, b] \to [0, 1]$ defined by

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

for instance as a homemorphism.

Lemma 5.1. *If X is connected and $f : X \to Y$ 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 $\gamma : [0, 2\pi] \to \mathbb{R}^2$ 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 $S_1 \cap S_2 \neq \varnothing$ since $y \in S_1 \cap S_2$. Then $S_1 \cup S_2$ is connected by Theorem 4.2 and $x, y, z \in S_1 \cap S_2$. In particular, $x, z \in S_1 \cap S_2$ 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 $\gamma : [0,1] \to S$ 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. $\square$

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 $\{(0,y) \mid -1 \le y \le 1\}$ 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 $f : [0,1] \to [0,1]$ 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 $f : K \to K$ 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 $X = \mathrm{maps}(\mathbb{S}^1, \mathbb{S}^1)$ 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* $\mathrm{maps}(\mathbb{S}^1, \mathbb{S}^1)$ *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 $f : X \to Z$, there exists a continuous $\widetilde{f} : Y \to Z$ such that the following diagram commutes,

$$\begin{tikzcd} X \arrow[r, "f"] & Z \\ Y \arrow[u, "i"] \arrow[ur, dashed, "\widetilde{f}"'] & \end{tikzcd}$$

where $i : Y \to X$ 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.*

[1] Note that at least set-theoretically, this immediately defines $\widetilde{f} = f|_Y$. But a priori we do not know that $\widetilde{f}$ 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 $Y \cap Y^c = \varnothing$, 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 $f : X \to Y$ 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 $\alpha_{j,1}, \ldots, \alpha_{j,n_j}$ 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 $f : [a,b] \to \mathbb{R}$ 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 $y_i \to s$ as $i \to \infty$. 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 $f : K \to \mathbb{R}$ 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. □