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2 Results to Memorize

Proposition 2.1

- (a) The product space $X \times Y$ is compact if and only if both X and Y are compact.
- (b) The product space $X \times Y$ is connected if and only if both X and Y are connected.
- (c) The product space $X \times Y$ is path-connected if and only if both X and Y are path-connected.
- (d) The product space $X \times Y$ is Hausdorff if and only if both X and Y are Hausdorff.

Proposition 2.2

If X and Y are both regular, then $X \times Y$ is regular.

Proposition 2.3

- (a) The continuous image of a compact space is compact.
- (b) The continuous image of a connected space is connected.
- (c) The continuous image of a path-connected space is path-connected.

Proposition 2.4

For any topological spaces X and Y ,

$$\overline{X \times Y} = \overline{X} \times \overline{Y}$$

Proposition 2.5

A compact set in a Hausdorff space is closed.

Proposition 2.6

A closed subspace of a compact set is compact.

Proposition 2.7

A continuous bijection from a compact space to a Hausdorff space is a homeomorphism.

Proposition 2.8

Suppose that (X, d) is a metric space. Then X is compact if and only if X is sequentially compact.

Proposition 2.9: Contraction Mapping Theorem

Let X be a complete metric space and $f : X \rightarrow X$ a contraction map. Then f has a unique fixed point.

Proposition 2.10

Let $C([0, 1])$ be the collection of continuous functions from $[0, 1]$ to \mathbb{R} . Then $(C([0, 1]), \|\cdot\|_{\text{sup}})$ is connected and complete.

Proposition 2.11

The topologist's sine curve is connected but is not path-connected.

Proposition 2.12

A locally path-connected, connected space X is path-connected.

Proposition 2.13

A closed set is disconnected if and only if it is a union of disjoint, closed sets.

Proposition 2.14: Heine Borel Theorem

Let $X \subseteq \mathbb{R}^n$. Then, X is closed and bounded if and only if X is compact.

Proposition 2.15

Every compact Hausdorff space is normal.

Proposition 2.16

Every metrizable space is normal.

Proposition 2.17

Let X and Y be topological spaces and suppose that $U, V \subseteq X$ and $W \subseteq Y$. Then,

- (a) $\text{int}(U) \cap \text{int}(V) = \text{int}(U \cap V)$.
- (b) $\text{int}(U) \cup \text{int}(V) \subseteq \text{int}(U \cup V)$.
- (c) $\text{cl}(U) \cup \text{cl}(V) = \text{cl}(U \cup V)$.
- (d) $\text{cl}(U) \cap \text{cl}(V) \supseteq \text{cl}(U \cap V)$.
- (e) $X \setminus \text{int}(U) = \text{cl}(X \setminus U)$.
- (f) $X \setminus \text{cl}(U) = \text{int}(X \setminus U)$.
- (g) $\text{int}(U \times W) = \text{int}(U) \times \text{int}(W)$.
- (h) $\text{cl}(U \times W) = \text{cl}(U) \times \text{cl}(W)$.

3 Common True/False Questions

Problem 3.1

Prove or disprove: Suppose that $X = U \cup V$ where U and V are both open and simply connected. Then, X is simply connected.

Solution. This is false. Let $X = S^1$ and define $U = \{e^{i\theta} : 0 < \theta < 3\pi/2\}$ and $V = \{e^{i\theta} : \pi < \theta < 5\pi/2\}$. Each of U and V is an open arc of S^1 and thus each is simply connected. Also, $U \cup V = X$. However, $\pi_1(X) = \mathbb{Z}$ meaning that S^1 is not simply connected.

Problem 3.2

Prove or disprove: If $f : X \rightarrow Y$ is continuous and surjective, then the induced homeomorphism $f_* : \pi_1(X) \rightarrow \pi_1(Y)$ is surjective.

Problem 3.3

Prove or disprove: If $f : X \rightarrow Y$ is continuous and injective, then the induced homeomorphism $f_* : \pi_1(X) \rightarrow \pi_1(Y)$ is injective.

Problem 3.4

Prove or disprove: Let X be a compact topological space and $\{F_n\}$ a nested sequence of nonempty closed sets $F_1 \supseteq F_2 \supseteq \dots$. Then $\cap F_n \neq \emptyset$.

Proof. Seeking a contradiction, suppose that $\bigcap_{n=1}^{\infty} F_n = \emptyset$. Then,

$$X = X - \bigcap_{n=1}^{\infty} F_n = \emptyset = \bigcup_{n=1}^{\infty} X - F_n.$$

Since each F_n is closed, each $X - F_n$ is open and therefore the collection $\{X - F_n\}$ forms an open cover for X . As X is compact, we may extract a finite subcover, say $\{X - F_1, \dots, X - F_N\}$ (possibly relabeling, but still maintaining the nestedness of the F_k). Then,

$$X = \bigcup_{k=1}^N X - F_k = X - \bigcap_{k=1}^N F_k = X - F_N$$

implying that $F_N = \emptyset$, a contradiction. □

Problem 3.5

Prove or disprove: Let X be a compact topological space and $\{U_n\}$ a nested sequence of open sets $U_1 \supseteq U_2 \supseteq \dots$. Then $\cap U_n \neq \emptyset$.

Solution. Let $X = [0, 1]$ with the usual topology and define $U_n = (0, \frac{1}{n})$. Then $U_1 \supseteq U_2 \supseteq \dots$, but $\cap U_n = \emptyset$.

Problem 3.6

Prove or disprove: A closed and bounded subset of a topological space is compact.

Solution. Consider \mathbb{R} with the discrete topology induced by the metric

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

Then $\mathbb{R} = \overline{B_2(0)}$ where $\overline{B_2(0)}$ is the closed ball of radius 2 about 0. However, \mathbb{R} with this topology is not compact: consider the open cover $\{B_{1/2}(x)\}_{x \in \mathbb{R}}$. Each element of the open cover contains a single element of \mathbb{R} and therefore no finite subcover exists.

Problem 3.7

Prove or disprove: The continuous image of a closed set is closed.

Solution. Consider the identity map $f : X \rightarrow Y$ where $X = [0, 1]$ with the discrete metric and $Y = [0, 1]$ with the indiscrete metric. Since X is equipped with the discrete topology, every set is closed but the only closed sets in Y are $[0, 1]$ and \emptyset . Therefore, $f(\{0\}) = \{0\}$ is a continuous image of a closed set but is not closed.

Problem 3.8

Prove or disprove: If $f : X \rightarrow Y$ is a continuous surjective and Y is Hausdorff, then X is Hausdorff.

Solution. Let $X = \{0, 1\}$ with the topology $\{\emptyset, \{0\}, X\}$ and $Y = \{0\}$ with the topology $\{\emptyset, Y\}$. Let $f : X \rightarrow Y$ be the zero map. Then f is continuous and a surjection. Any space with a single point is trivially Hausdorff. However, X is not Hausdorff as 0 and 1 cannot be separated with open sets.

4 Basic Point Set Topology

Problem 4.1: F13

Prove or provide a counter example to the following:

- (a) The interior of a connected set is connected.
- (b) The closure of a path connected set is path connected.
- (c) The quotient of a connected set is connected (under the quotient topology).
- (d) If C is an infinite collection of connected sets where every pair of sets in C has a non-empty intersection then its union is connected.

Solution. The interior of a connected set need not be connected. Let $X \subseteq \mathbb{R}^2$ be the closed unit ball with center $(0,1)$ and $Y \subseteq \mathbb{R}^2$ the closed unit ball with center $(0,-1)$. Then $X \cup Y$ is connected as the set is path-connected. However, the interior of $X \cup Y$ is the union of the corresponding open balls. In this case, the open balls provide a separation meaning that the interior is not connected.

Solution. The closure of a path connected set need not be path connected. Consider the Topologist's Spiral. Let X denote the spiral and $Y = S^1$ so that the Topologist's Spiral can be written as $X \cup Y$. In this case, X is path-connected, but the closure of X in $X \cup Y$ is $X \cup Y$ which is not path-connected.

Proof. Let X be a connected set and \sim some equivalence relation on X . Let $Y = X/\sim$. The quotient map $q : X \rightarrow X/\sim$ is a surjective, continuous map. As the continuous image of a connected set is connected, it follows that X/\sim is connected. \square

Proof. **Help!** \square

Problem 4.2: F12

Suppose X, Y are topological spaces and $A \subseteq X$ and $B \subseteq Y$. Prove that

- (a) $\text{int}(A \times B) = \text{int}(A) \times \text{int}(B)$.
- (b) $\text{cl}(A \times B) = \text{cl}(A) \times \text{cl}(B)$.
- (c) $\partial(A \times B) = [\partial(A) \times \text{cl}(B)] \cup [\text{cl}(A) \times \partial(B)]$.

Proof. Let $(x, y) \in \text{int}(A \times B)$. There exists a basic open set $U \times V \subseteq A \times B$ such that $(x, y) \in U \times V$. Then $U \subseteq A$ is open in X and $x \in U$ meaning that $x \in \text{int}(A)$. Similarly, $V \subseteq B$ is open in Y and $y \in V$ and therefore $y \in \text{int}(B)$. This means that $(x, y) \in \text{int}(A) \times \text{int}(B)$.

Conversely, suppose that $(x, y) \in \text{int}(A) \times \text{int}(B)$. Choose open sets $U \subseteq A$ and $V \subseteq B$ that contain x and y , respectively. Then, $U \times V$ is a basic open set in $X \times Y$ that contains (x, y) and is contained in $A \times B$. Thus $(x, y) \in \text{int}(A \times B)$. \square

Proof. Suppose that $(x, y) \in \text{cl}(A \times B)$. If $(x, y) \in A \times B$ then $(x, y) \in \text{cl}(A) \times \text{cl}(B)$ as the closure of any set must contain the original set. Suppose now that (x, y) is a boundary point of $A \times B$. Let $U \times V$ be a basic open set about (x, y) . Since (x, y) is a boundary point of $A \times B$, $(A \times B) \cap (U \times V) \neq \emptyset$ and $(X - A \times Y - B) \cap (U \times V) \neq \emptyset$. In particular, $A \cap U$ and $X - A \cap U$ are both nonempty meaning that x is a boundary point of A . Similarly, y is a boundary point of B . Therefore, $(x, y) \in \text{cl}(A) \times \text{cl}(B)$.

Conversely, suppose that $(x, y) \in \text{cl}(A) \times \text{cl}(B)$. If $x \in A$ and $y \in B$, then $(x, y) \in A \times B$.

Suppose that x is a boundary point of A and $y \in B$. Let $U \times V$ be a basic open set in $X \times Y$ that contains (x, y) . Then U is an open set in X that contains x . Since x is a boundary point of A , both $(X - A) \cap U$ and $A \cap U$ are nonempty. By assumption, $B \cap V$ is nonempty as it contains y . Therefore,

$$(A \times B) \cap (U \times V) = (A \cap U) \times (B \cap V) \neq \emptyset.$$

Observe that

$$((X \times Y) - (A \times B)) \cap (U \times V) = ((X - A) \times Y) \cup (X \times (Y - B)) \cap (U \times V)$$

and since $((X - A) \times Y) \cap (U \times V) \neq \emptyset$, $((X \times Y) - (A \times B)) \cap (U \times V) \neq \emptyset$. That is, (x, y) is a boundary point of $A \times B$ and therefore $(x, y) \in \text{cl}(A \times B)$.

An identical proof shows that $(x, y) \in \text{cl}(A \times B)$ if $x \in A$ and y is a boundary point of B . If both x and y are boundary points of A and B respectively, then $(x, y) \in \text{cl}(A \times B)$ since it is a boundary point of $A \times B$. \square

The proof for (c) follows from my proof for (b). Is there a better way for me to have proved (b)?

Problem 4.3: F20

- (a) Give an example of two topological spaces X, Y and a continuous bijection $f : X \rightarrow Y$ that is not a homeomorphism.
- (b) Show that if X is compact and Y is Hausdorff, then every continuous bijection between the spaces is a homeomorphism.

Solution. Let $X = [0, 1]$ with the standard topology and $Y = [0, 1]$ with the trivial topology. Let $f : X \rightarrow Y$ be the identity map. Clearly f is bijective. The only open sets in Y are \emptyset and $[0, 1]$. Since both $f^{-1}(\emptyset) = \emptyset$ and $f^{-1}([0, 1]) = [0, 1]$ are open in X , f is continuous. However, f is not a homeomorphism since $(0, 1)$ is open in X but $f(0, 1) = (0, 1)$ is not open in Y .

Proof. Let $f : X \rightarrow Y$ be a continuous bijection from a compact space to a Hausdorff space. To show that f is a homeomorphism, it remains to check that f is an open mapping. This is equivalent to proving that f maps closed sets to closed sets. Let $A \subseteq X$ be a closed set. Since X is compact, A is compact in X . Then, $f(A) \subseteq Y$ must be compact since f is continuous. In a Hausdorff space, any compact set is closed and thus $f(A)$ is closed in Y , as desired. \square

Problem 4.4: S12

Prove the following:

- (a) A closed subspace of a compact space is compact.
- (b) A compact subspace of a Hausdorff space is closed.
- (c) If $f : X \rightarrow Y$ is a continuous bijection, X is compact and Y is Hausdorff, then f is a homeomorphism.

Proof. Suppose that $A \subseteq X$ is a closed subspace of a compact space. Let $\{U_i\}_{i \in I}$ be an open cover of A . Extend this collection to an open cover of X by appending the open set $X - A$. Because X is compact, there exists a finite subcover of X , say $\{U_1, \dots, U_n\}$. If some $U_j = X - A$, remove this U_j from the list to obtain a finite subcover for A , from the original collection of open sets. As any open cover of A has a finite subcover, A is compact. \square

Proof. Assume that $A \subseteq X$ is a compact subspace of a Hausdorff space. To prove that A is closed, we prove that $X - A$ is open. Let $x \in X - A$. Because X is Hausdorff, for each $a \in A$ there exist open neighborhoods U_a of x and V_a of a where $U_a \cap V_a = \emptyset$. Then, the collection $\{V_a\}_{a \in A}$ forms an open cover of A . Since A is compact, there exists a finite subcover, say $\{V_{a_1}, \dots, V_{a_n}\}$. Then, $U = \bigcap_{i=1}^n U_{a_i}$ is an open set containing x that is disjoint from A and thus is contained in $X - A$. Therefore, $X - A$ is open and so A is closed. \square

Proof. See 4.3. □

Problem 4.5: S12

Let X, Y, T be topological spaces.

- (a) Define the product topology on $X \times Y$.
- (b) Show that the projection functions $p_X : X \times Y \rightarrow X$ and $p_Y : X \times Y \rightarrow Y$ are continuous.
- (c) Show that a function $f : T \rightarrow X \times Y$ is continuous if and only if both $p_X \circ f$ and $p_Y \circ f$ are continuous.
- (d) Show that the product topology on $X \times Y$ is the unique topology that for all spaces T and functions f , (c) is satisfied.

Let X, Y be topological spaces. The product topology on $X \times Y$ has a basis given by $U \times V$ where $U \subseteq X$ is open and $V \subseteq Y$ is open. That is, any open set in $X \times Y$ with respect to the product topology is the union of sets of the form $U \times V$.

Proof. Let $p_X : X \times Y \rightarrow X$ be the projection function onto X . Let $U \subseteq X$ be an open set. Then,

$$p_X^{-1}(U) = U \times Y.$$

Because U is open in X and Y is open in Y , $U \times Y$ is open in $X \times Y$. Therefore p_X is continuous. Similarly, for any open subset V of Y ,

$$p_Y^{-1}(V) = X \times V$$

which is open in $X \times Y$. Whence both projection functions are continuous. □

Proof. Assume that $f : T \rightarrow X \times Y$ is continuous. Let $U \subseteq X$ and $V \subseteq Y$ be arbitrary open subsets. Because p_X is continuous, $p_X^{-1}(U)$ is open in $X \times Y$. Since f is continuous, $f^{-1}(p_X^{-1}(U))$ is open in T . Therefore, $(p_X \circ f)^{-1}(U)$ is open in T implying that $p_X \circ f$ is continuous. Similarly, $p_Y^{-1}(V)$ is open in $X \times Y$ and therefore $f^{-1}(p_Y^{-1}(V))$ is open in T . This implies that $p_Y \circ f$ is continuous.

Now assume that both $p_X \circ f$ and $p_Y \circ f$ are continuous. Let $U \times V$ be an arbitrary basic open set in $X \times Y$. Then $U \subseteq X$ and $V \subseteq Y$ are both open. Because the projections are continuous, both $p_X^{-1}(U)$ and $p_Y^{-1}(V)$ are open in $X \times Y$. Let $t \in f^{-1}(U \times V)$. If $f(t) = (x, y)$ then $x \in U$ and $y \in V$. This means that $p_X(f(t)) = x \in U$ and $p_Y(f(t)) = y \in V$. That is, $t \in f^{-1}(p_X^{-1}(U)) \cap f^{-1}(p_Y^{-1}(V))$. Note that the reverse of each of these implications holds and therefore $f^{-1}(U \times V) = f^{-1}(p_X^{-1}(U)) \cap f^{-1}(p_Y^{-1}(V))$. As U and V are open and the compositions are assumed to be continuous, $f^{-1}(U \times V)$ is the intersection of two open sets and thus must also be open. Since $U \times V$ was an arbitrary basic open set, f is continuous. □

Proof. Let $T = X \times Y$ under an arbitrary topology. The identity map $\mathbb{1} : T \rightarrow T$ is continuous and therefore both $p_X \circ \mathbb{1} : T \rightarrow X$ and $p_Y \circ \mathbb{1} : T \rightarrow Y$ are continuous. That is, for any open sets $U \subseteq X$ and $V \subseteq Y$,

$$(p_X \circ \mathbb{1})^{-1}(U) = U \times Y$$

and

$$(p_Y \circ \mathbb{1})^{-1}(V) = X \times V$$

are both open in T . As a finite intersection of open sets is open, $(U \times Y) \cap (X \times V) = U \times V$ is open in T whenever U is open in X and V is open in Y . That is, every basis element for the product topology is open in T as well.

Worried about reverse direction here.

Now consider the identity map $\mathbb{1} : T \rightarrow X \times Y$. Let $U \times V \subseteq X \times Y$ be a basic open set for the product topology. Then,

$$(p_X \circ \mathbb{1})^{-1}(U \times V) = \mathbb{1}^{-1}(U \times V) = U \times V$$

and

$$(p_Y \circ \mathbb{1})^{-1}(U \times V) = \mathbb{1}^{-1}(X \times V) = X \times V.$$

Since both $U \times Y$ and $X \times V$ are open in $X \times Y$,

□

5 Compactness

Problem 5.1: F13

Prove that a finite union of compact subsets of a topological space is compact. Give a counterexample to show that countable unions of compact sets need not be compact.

Proof. Suppose that A_1, \dots, A_n are each compact. Define $A = \bigcup_{k=1}^n A_k$ and suppose that $\{U_\alpha\}$ is an open cover of A . Note that each $A_k \subseteq A$ and thus $\{U_\alpha\}$ is an open cover for each A_k . For each A_k , let $\mathcal{A}_k \subseteq \{U_\alpha\}$ be a finite subcover for A_k . That is, \mathcal{A}_k is a finite collection of the U_α that covers A_k . Then, $\mathcal{A} = \bigcup_{k=1}^n \mathcal{A}_k$ is a finite collection of U_α that covers each A_k . That is, \mathcal{A} is a finite subcover of $\{U_\alpha\}$ for A . \square

6 Homeomorphic Spaces

Problem 6.1: F13

Let $f : X \rightarrow Y$ be a continuous, surjective map between compact, Hausdorff spaces. Define an equivalence relation \sim on X so that f factors as

$$X \xrightarrow{q} X' \xrightarrow{f'} Y$$

where $X' = X/\sim$, q is the quotient map, and f' is any bijection. Prove that f' is a homeomorphism.

Proof. Observe that the quotient of a compact space is compact. Therefore, $f' : X/\sim \rightarrow Y$ is a map from a compact space to a Hausdorff space. Because f' is a bijection, proving that f' is continuous will imply that f' is a homeomorphism. By definition of the quotient topology, a set in X/\sim is open if and only if its preimage under q is open in X . If $U \subseteq Y$ is any open set,

$$f^{-1}(U) = (f' \circ q)^{-1}(U) = q^{-1}((f')^{-1}(U)).$$

Since f is continuous, $f^{-1}(U)$ is open and therefore $(f')^{-1}(U)$ is open. That is, f' is continuous. \square

Problem 6.2: S20

Prove that S^2 is homeomorphic to a quotient space of $S^1 \times [0, 1]$.

Proof. Define an equivalence relation \sim on $S^1 \times [0, 1]$ such that

$$(\theta, 0) \sim (\theta', 0)$$

and

$$(\theta, 1) \sim (\theta', 1)$$

for any $\theta, \theta' \in S^1$. Then $S^1 \times [0, 1]/\sim$ is an annulus with each of the boundary disks crushed to a point. Note that

$$S^2 = \{(\theta, \phi) : 0 \leq \theta \leq 2\pi, 0 \leq \phi \leq \pi\}.$$

where all points of the form $(\theta, 0)$ correspond to the north pole of S^2 and all points of the form (θ, π) correspond to the south pole of S^2 . Every other point in S^2 has a unique description in this coordinate system.

Define $f : S^1 \times [0, 1]/\sim \rightarrow S^2$ by $f(\theta, t) = (\theta, \pi t)$. Observe that f is well-defined as all points in $S^1 \times \{0\}$ are mapped to the north pole and all points in $S^1 \times \{1\}$ are mapped to the south pole. As both component functions of f are continuous, f is continuous. Given any $(\theta, \varphi) \in S^2$, $f(\theta, \varphi/\pi) = (\theta, \varphi)$, proving that f is surjective. To see that f is injective, suppose that $f(\theta, t) = f(\theta', t')$. Then, $(\theta, \pi t) = (\theta', \pi t')$. This means that $t = t'$. If $t = 0$, then $(\theta, 0) \sim (\theta', 0)$. If $t = 1$, $(\theta, 1) \sim (\theta', 1)$. If $t, t' \notin \{0, \pi\}$ then $\theta = \theta'$. In any case, $(\theta, t) = (\theta', t') \in S^1 \times [0, 1]/\sim$. As f is a continuous bijection from a compact space to a Hausdorff space, f is a homeomorphism. \square

7 Metric Spaces

Problem 7.1: F13

Let X be a complete metric space and $\{C_n\}_{n \in \mathbb{N}}$ a collection of non-empty closed sets such that $C_1 \supseteq C_2 \supseteq \dots$. Assume that the sequence of diameters of the C_n goes to zero. Prove that the intersection $\bigcap C_n$ of this collection is nonempty.

Proof. Construct a sequence $\{x_n\}$ by choosing any $x_i \in C_i$ for each $i = 1, 2, \dots$. Because the sets are nested, $x_n \in C_k$ whenever $k \leq n$ for each $n \in \mathbb{N}$.

Let $\{r_n\}$ be the sequence of diameters of the C_n . By assumption, $r_n \rightarrow 0$. Let $\epsilon > 0$ be arbitrary and choose $N \in \mathbb{N}$ where $n \geq N$ implies that $|r_n| < \epsilon$. Assume that $m, n \geq N$ and that $m \geq n$. Then,

$$\|x_n - x_m\| \leq r_n < \epsilon$$

since $x_n, x_m \in C_n$. This means that $\{x_n\}$ is a Cauchy sequence in a complete space – let $x \in X$ be the limit of $\{x_n\}$.

To see that $x \in C_N$ for each N , notice that $\{x_n\}_{n \geq N}$ is a subsequence of $\{x_n\}$ that is contained in C_N . Since $x_n \rightarrow x$, this subsequence also converges to x meaning that x is a limit point of C_N . But, C_N is closed and therefore contains all its limit points. Since $x \in \bigcap_{n=1}^{\infty} C_n$, the intersection is nonempty. \square

Problem 7.2: S12

Suppose that (X, d) is a metric space and $A \subseteq X$.

- (a) For a fixed $x \in X$, define what is meant by $d(x, A)$.
- (b) Show that for all $x, y \in X$, $d(x, A) \leq d(x, y) + d(y, A)$.
- (c) Show that the function $f : X \rightarrow \mathbb{R}$ given by $f(x) = d(x, A)$ is a continuous function.

Fix $x \in X$. Then $d(x, A) = \inf_{a \in A} d(x, a)$ describes the distance from x to the set A .

Proof. Let $x, y \in X$ be arbitrary. Because d is a metric, for each $a \in A$, $d(x, a) \leq d(x, y) + d(y, a)$. Therefore,

$$d(x, A) \leq d(x, a) \leq d(x, y) + d(y, a).$$

This means that for each $a \in A$, $d(x, A) - d(x, y) \leq d(y, a)$. Because $d(y, A)$ is the infimum over all $d(y, a)$ with $a \in A$, it is the greatest lower bound. It then follows that $d(x, A) - d(x, y) \leq d(y, A)$, as desired. \square

Problem 7.3: S20

Let (X, d) be a metric space and fix a point $x_0 \in X$. Let ρ be a new metric given by $\rho(x, y) = d(x, x_0) + d(y, x_0)$ whenever $x \neq y$ and $\rho(x, y) = 0$ if $x = y$. Verify that ρ is a metric and (X, ρ) is complete.

Proof. By construction, $\rho(x, y) \geq 0$ for each $x, y \in X$. Suppose $\rho(x, y) = 0$ but $x \neq y$. Then, $0 = \rho(x, y) = d(x, x_0) + d(y, x_0)$. Since at most one of x and y can be x_0 , $d(x, x_0) + d(y, x_0) > 0$. Therefore $\rho(x, y) = 0$ if and only if $x = y$. Suppose now that $x, y, z \in X$. Then,

$$\rho(x, y) + \rho(y, z) = d(x, x_0) + d(y, x_0) + d(y, x_0) + d(z, x_0) = \rho(x, z) + 2d(y, x_0) \geq \rho(x, z)$$

proving that ρ is a metric.

To see that (X, ρ) is a complete metric space, let (x_n) be a Cauchy sequence in (X, ρ) . Let $\epsilon > 0$ and choose $N \in \mathbb{N}$ sufficiently large such that $\rho(x_N, x_n) < \epsilon$ whenever $n \geq N$. This means that whenever $n \geq N$,

$$d(x_n, x_0) \leq d(x_N, x_0) + d(x_n, x_N) = \rho(x_N, x_n) < \epsilon.$$

Therefore, $x_n \rightarrow x_0$ in (X, d) . Equivalently, as $n \rightarrow \infty$, $d(x_n, x_0) \rightarrow 0$. Then,

$$\rho(x_n, x_0) = d(x_n, x_0) + d(x_0, x_0) = d(x_n, x_0)$$

meaning that as $n \rightarrow \infty$, $\rho(x_n, x_0) \rightarrow 0$. That is, $x_n \rightarrow x_0$ in (X, ρ) . □

8 Fundamental Group

Problem 8.1: F20

Prove that no pair of the following spaces are homeomorphic to one another:

$$S^0, S^1 \times \mathbb{R}, S^1 \times S^2, \mathbb{R} \times S^2, S^2$$

Proof. First note that S^0 is a discrete space while the remaining spaces are not. Therefore, S^0 cannot be homeomorphic to any of the other spaces. Because $S^1 \times \mathbb{R}$ and $\mathbb{R} \times S^2$ are unbounded and therefore not compact, neither of these spaces is homeomorphic to either of compact spaces, $S^1 \times S^2$ or S^2 . As $S^1 \times \mathbb{R}$ is the product of path-connected spaces, $\pi_1(S^1 \times \mathbb{R}) \cong \pi_1(S^1) \times \pi_1(\mathbb{R}) \cong \mathbb{Z}$. Similarly, $\pi_1(\mathbb{R} \times S^2) \cong \pi_1(\mathbb{R}) \times \pi_1(S^2) \cong 0$. As the fundamental group is preserved under homeomorphisms, $S^1 \times \mathbb{R}$ and $\mathbb{R} \times S^2$ are not homeomorphic. Similarly, $S^1 \times S^2$ and S^2 are not homeomorphic since $\pi_1(S^1 \times S^2) \cong \mathbb{Z}$ and $\pi_1(S^2) = 0$. \square

9 Homotopy

Problem 9.1: F12

Define *homotopy equivalence*. Show that a homotopy equivalence $f : X \rightarrow Y$ gives a bijection between the path components of X and those of Y .

Proof. If $f : X \rightarrow Y$ is a homotopy equivalence, then there exists a homotopy inverse $g : Y \rightarrow X$ such that $g \circ f \simeq \mathbb{1}_X$ and $f \circ g \simeq \mathbb{1}_Y$.

Let D_X and D_Y be the sets of connected components of X and Y , respectively. Define a function $\varphi : D_X \rightarrow D_Y$ by

$$\varphi([x]) = [f(x)]$$

where $[x]$ denotes the connected component of X containing x and $[f(x)]$ denotes the connected component of Y containing $f(x)$. We first show that φ is well-defined. Suppose that a and b are in the same connected component of X . That is $a \in [b]$. Because connectedness is preserved under continuous maps, $f([b]) = \{f(x) : x \in [b]\}$ is a connected set. Furthermore, both $f(a)$ and $f(b)$ are contained in $f([b])$. As the connected component of an element is defined to be the union of all connected sets containing that element, $f(a)$ and $f(b)$ are in the same connected component. That is, $\varphi([a]) = [f(a)] = [f(b)] = \varphi([b])$ and so φ is well-defined. Define a second function $\psi : D_Y \rightarrow D_X$ by

$$\psi([y]) = [g(y)]$$

ψ is also well defined, closely following the proof given for φ .

Fix $x \in X$ and let h_t be a homotopy from $g \circ f$ to $\mathbb{1}_X$. Since $\psi \circ \varphi([x]) = [g \circ f(x)]$ and $\alpha : t \mapsto h_t(x)$ is a path from $g \circ f(x)$ to x , we see that $g \circ f(x)$ and x are in the same path-component of X . But, path-connected sets are connected, and thus $g \circ f(x)$ and x are in the same connected component of X . This means that $\psi \varphi = \mathbb{1}$ and similarly, $\varphi \psi = \mathbb{1}$. □

Note that a similar result holds when connected components are replaced instead with path components. The proof is nearly identical.

10 Worksheet Problems

Worksheet 10.1

Let X and Y be non-empty topological spaces. Prove or disprove the following:

- (a) $f : X \rightarrow Y$ is continuous if and only if $f(\text{cl}(H)) \subseteq \text{cl}(f(H))$ for all $H \subseteq X$.
- (b) If $f : X \rightarrow Y$ is continuous and $H \subseteq X$, then $f(\text{cl}(H)) = \text{cl}(f(H))$.
- (c) If $f : X \rightarrow Y$ is continuous and $H \subseteq Y$ then $f^{-1}(\text{cl}(H)) = \text{cl}(f^{-1}(H))$.

Worksheet 10.2

Prove or disprove the following:

- (a) Any quotient of a Hausdorff space is Hausdorff.
- (b) Any metric space is normal.
- (c) If X is a topological space and $A \subseteq B \subseteq X$, then $\text{cl}(A) \cap B$ is the closure of A with respect to the subspace topology on B . Here $\text{cl}(A)$ is the closure of A in X .

Solution. Let $X = \mathbb{R} \times \{0, 1\}$. Then X is clearly Hausdorff. Let \sim be the equivalence relation on X where $(x, 0) \sim (x, 1)$ if and only if $x \neq 0$. Then, X/\sim is not Hausdorff as there is no way to separate $(0, 0)$ and $(0, 1)$.

Alternatively, let $Y = [0, 2]$ and let $A = (1, 2]$. Then Y is Hausdorff, but Y/A is not Hausdorff as there is no way to separate 1 from 2 with open sets in the quotient space.

Proof. Let (X, d) be a metric space. Let $A, B \subseteq X$ be disjoint, closed sets. Fix $a \in A$. □

Worksheet 10.3

Let X be a topological space. Prove or provide a counterexample:

- (a) $\text{int}(X - A) = X - \text{cl}(A)$.
- (b) $\text{int}(\text{cl}(A)) = \text{int}(\text{cl}(\text{int}(A)))$.
- (c) $\text{int}(\text{int}(A)) = \text{int}(A)$.

Worksheet 10.4

Suppose that X is compact, Y is Hausdorff, and $f : X \rightarrow Y$ is a continuous bijection.

- (a) Prove that f is a homeomorphism.
- (b) Give counterexamples to show that both hypotheses are necessary.

Proof. See 4.3 for a full solution. The lemmas necessary in this proof are the following:

- A closed subset of a compact space is compact.
- A compact subset of a Hausdorff space is closed.

□

Solution. Let $X = [0, 2\pi)$, $Y = S^1$, and $f : X \rightarrow Y$ the map given by $f(\theta) = e^{i\theta}$. Then X is not compact, Y is a Hausdorff space, and f is a continuous bijection. However, f is not a homeomorphism because X is not compact and S^1 is compact.

Let $X = [0, 1]$ under the usual topology and $Y = [0, 1]$ under the trivial topology. Let $f : X \rightarrow Y$ be the identity map. Then X is compact, Y is not Hausdorff, and f is a continuous bijection. However, f is not a homeomorphism because $(0, 1/2)$ is open in X but its image is not open in Y .

Worksheet 10.5

A nonempty subset U of \mathbb{R} is open in the Zriski topology on \mathbb{R} if $\mathbb{R} - U$ is a finite set. Prove that \mathbb{R} is compact with respect to this topology.

11 Unfinished

11.1 Fall 2013

Problem 11.1: F13

Show that the fundamental group of the torus $T^2 = S^1 \times S^1$ is $\mathbb{Z} \oplus \mathbb{Z}$ in two distinct ways:

- (a) Describe a cell structure for T^2 and use related results to compute its fundamental group.
- (b) Describe the universal covering space of T^2 and use this description to compute the fundamental group.

Problem 11.2: F13

Let S^1 be the unit complex numbers under multiplication and U an open subset of $S^1 \times S^1$ containing the diagonal

$$\Delta = \{(x, x) : x \in S^1\}.$$

Show that there is an open set $W \subseteq S^1$ containing $1 \in S^1$ such that

$$V = \{(x, xw) : x \in S^1, w \in W\}$$

is an open set with $\Delta \subseteq V \subseteq U$.

Problem 11.3: F13

Prove or provide a counter example to the following:

- (a) The interior of a connected set is connected.
- (b) The closure of a path connected set is path connected.
- (c) The quotient of a connected set is connected (under the quotient topology).
- (d) If C is an infinite collection of connected sets where every pair of sets in C has a non-empty intersection then its union is connected.

Solution. The interior of a connected set need not be connected. Let $X \subseteq \mathbb{R}^2$ be the closed unit ball with center $(0, 1)$ and $Y \subseteq \mathbb{R}^2$ the closed unit ball with center $(0, -1)$. Then $X \cup Y$ is connected as the set is path-connected. However, the interior of $X \cup Y$ is the union of the corresponding open balls. In this case, the open balls provide a separation meaning that the interior is not connected.

Solution. The closure of a path connected set need not be path connected. Consider the Topologist's Spiral. Let X denote the spiral and $Y = S^1$ so that the Topologist's Spiral can be written as $X \cup Y$. In this case, X is path-connected, but the closure of X in $X \cup Y$ is $X \cup Y$ which is not path-connected.

Proof. Let X be a connected set and \sim some equivalence relation on X . Let $Y = X/\sim$. The quotient map $q : X \rightarrow X/\sim$ is a surjective, continuous map. As the continuous image of a connected set is connected, it follows that X/\sim is connected. □

Proof. **Help!** □

Problem 11.4: F13

Let $\{Y_\alpha\}$ be a collection of topological spaces, $Y = \prod_\alpha Y_\alpha$ their product under the product topology, and $\pi_\beta : Y \rightarrow Y_\beta$ the projection map to the β th factor of the product. Prove that a function $f : X \rightarrow Y$ is continuous if and only if for all β the composition $\pi_\beta \circ f : X \rightarrow Y_\beta$ is continuous.

11.2 Fall 2012**Problem 11.5: F12**

Let X be a nonempty set and let $\mathcal{B} = \mathcal{B}(X, \mathbb{R})$ denote the set of bounded real valued functions on X . Metrize \mathcal{B} by setting

$$d(f, g) = \sup_{x \in X} |f(x) - g(x)|.$$

Prove that (\mathcal{B}, d) is a complete metric space.

Problem 11.6: F12

- (a) Let X be a nonempty set and B a subset of the power set of X . Give necessary and sufficient conditions on B such that it is a basis for some topology on X .
- (b) Let $\{F_i : i \in \mathbb{N}\}$ be a countable collection of finite sets. Show that both of the following form a basis for some topology on the infinite product $\prod F_i$.
 - (i) All the sets of the form $\prod U_i$ where each $U_i \subseteq F_i$.
 - (ii) All the sets of the form $\prod U_i$ where $U_i \subseteq F_i$ and $U_i = F_i$ except for possibly finitely many i .
- (c) Show that the set $\prod F_i$ equipped with the topology from (i) need not be homeomorphic to the set $\prod F_i$ equipped with the topology from (ii).

Problem 11.7: F12

Let X, Y be non-empty topological spaces.

- (a) Define the product topology on $X \times Y$.
- (b) Define path connected.
- (c) Show that X and Y are path connected if and only if $X \times Y$ is path connected.

See 4.5 for the definition.

A topological space X is path connected if for any two points $x, y \in X$, there exists a continuous function $\gamma : [0, 1] \rightarrow X$ where $\gamma(0) = x$ and $\gamma(1) = y$. Here, γ is a path.

Proof. Assume that X and Y are both path connected. Let $(x_1, y_1), (x_2, y_2) \in X \times Y$ be arbitrary. Since $x_1, x_2 \in X$, there exists a path $\alpha : [0, 1] \rightarrow X$ with $\alpha(0) = x_1$ and $\alpha(1) = x_2$. Similarly, since $y_1, y_2 \in Y$ there exists a path $\beta : [0, 1] \rightarrow Y$ where $\beta(0) = y_1$ and $\beta(1) = y_2$. Define $\gamma : [0, 1] \rightarrow X \times Y$ by $\gamma(t) = (\alpha(t), \beta(t))$. Observe that $\gamma(0) = (x_1, y_1)$ and $\gamma(1) = (x_2, y_2)$. Furthermore, γ is continuous as each of its component functions is continuous. Thus, γ is a path in $X \times Y$ between (x_1, y_1) and (x_2, y_2) . As these points were arbitrary, $X \times Y$ is path connected. \square

Problem 11.8: F12

Give a careful definition of a connected topological space.

- (a) Prove that the closed interval $[0,1]$ is connected.
- (b) Show that a connected metric space with at least two points is uncountable.

Problem 11.9: F12

Let X be a connected Hausdorff space and $Y = X \cup \{p\}$ with $p \notin X$. Define a topology \mathcal{T} on Y which has a basis consisting of open sets in X together with all sets of the form $V \cup \{p\}$ where V is the complement of a compact subset of X . Prove that (Y, \mathcal{T}) is

- (a) compact
- (b) Hausdorff if and only if X is locally compact.
- (c) connected if and only if X is not compact.

Problem 11.10: F12

Let $\mathbb{R}^2 - \{(0,0)\}$ be the plane punctured at the origin, equipped with the usual topology. Define an equivalence relation on X by $(x,y) \sim (tx,ty)$ for any $t > 0$. Let $Y = X/\sim$ under the quotient topology. Prove that Y is homeomorphic to S^1 .

Proof. Let $f : Y \rightarrow S^1$ be given by $f([v]) = \frac{v}{\|v\|}$. Let $g : S^1 \rightarrow Y$ be given by $g(v) = [v]$. To see that f is well-defined, suppose that $v = tv$ for some $t > 0$. Then, $\|tv\| = t\|v\|$ and therefore

$$f([v]) = \frac{v}{\|v\|} = \frac{tv}{t\|v\|} = f([tv]).$$

Also, $f \circ g(v) = f([v]) = \frac{v}{\|v\|} = v$ since $\|v\| = 1$ whenever $v \in S^1$. Similarly, $g \circ f([v]) = g\left(\frac{v}{\|v\|}\right) = \left[\frac{v}{\|v\|}\right] = [v]$. Therefore f is a bijection. \square

11.3 Spring 2012**Problem 11.11: S12.1**

- (a) Define what it means for a topological space to be connected.
- (b) Suppose that H is a connected subspace of a topological space X and that $H \subseteq K \subseteq \text{cl}(H)$. Show that K is connected.
- (c) Suppose that U is a connected open subset of $C[0,1]$ with the sup metric. Prove that U is path-connected.

A topological space X is disconnected if there exist open sets A, B with $A \cap B = \emptyset$ and $X = A \sqcup B$. A space X is connected if it is not disconnected.

Proof. \square

Problem 11.12: S12.5

Let X be a metric space.

- (a) Suppose that there exists $\epsilon > 0$ such that every $B(x, \epsilon)$ has compact closure. Prove that X is complete.
- (b) Suppose that for each $x \in X$ there exists $\epsilon_x > 0$ so that $B(x, \epsilon_x)$ has compact closure. Give an example to show that X need not be complete.

Problem 11.13: S12

Covering space problem!

Problem 11.14: S12.7

Define a metric d on $N = \mathbb{N} \cup \{0\}$ by

$$d(x, y) = 0$$

whenever $x = y$ and otherwise

$$d(x, y) = 5^{-k}$$

where 5^k is the largest power of 5 that divides $|x - y|$.

- (a) Verify that d is a metric.
- (b) Give an example of a sequence that converges to 0.
- (c) Prove or disprove: The space (N, d) is compact.
- (d) Prove or disprove: The set of prime numbers greater than 103 is open in (N, d) .

11.4 Fall 2020**Problem 11.15: F20.3**

Let (X, d) be a metric space and let $f : X \rightarrow X$ be a continuous function without any fixed points.

- (i) If X is compact, show that there exists $\epsilon > 0$ so that $d(x, f(x)) > \epsilon$ for all $x \in X$.
- (ii) Show that this fails if X is not compact.

Problem 11.16: F20

A subset E of a topological space X is called a G_δ if there is a sequence U_1, U_2, \dots of open subsets of X such that $E = \bigcap_j U_j$.

- (i) Show that if $f : X \rightarrow \mathbb{R}$ is a continuous function from X to the real line, then $\{x : f(x) = 0\}$ is closed and is a G_δ .
- (ii) Show that in a metric space, every closed set is a G_δ .
- (iii) Prove that (ii) fails in an arbitrary topological space.

11.5 Spring 2020

Problem 11.17: S20

Prove that the product of two regular spaces is regular.

Problem 11.18: S20

A topological space is called *totally disconnected* if every pair of points is contained in a pair of disjoint open sets whose union is the whole space. Prove that every countable metric space is totally disconnected.

Problem 11.19: S20

Let X be a compact metric space. Prove that there exists a finite set of points x_1, \dots, x_n such that every point in X is distance less than 3 from some x_i and $d(x_i, x_j) \geq 1$ for any $i \neq j$.

Problem 11.20: S20

Suppose that X is a metric space such that every sequence in X has a Cauchy subsequence. Prove that X can be covered by finitely many balls of radius 1.

11.6 Fall 2016

Problem 11.21: F16

Give a proof or counter example for the following:

- (a) Every closed subset of a compact space is compact.
- (b) The product of any two connected spaces is connected.

Problem 11.22: F16

A topological space X is *regular* if for every closed subset C of X and point $p \in X \setminus C$, there are disjoint open sets $U, V \subseteq X$ with $C \subseteq U$ and $p \in V$. Prove that every compact Hausdorff space is regular.

Problem 11.23: F16

Give an example of a space that is connected but not path-connected. Prove the example works.

Problem 11.24: F16

Prove that a metric space is compact if and only if it is sequentially compact.

Problem 11.25: F16

For each of the following either give a proof or provide a justified counterexample.

- (a) Suppose that A and B are non-empty topological spaces and $A \times B$ is equipped with the product topology. Let \sim be the equivalence relation on $A \times B$ defined by $(a, b) \sim (a', b')$ if and only if $b = b'$. Is $A \times B / \sim$ homeomorphic to A ?
- (b) Suppose that B and C are subspaces of a topological space A . If B is homeomorphic to C , does it follow that A/B is homeomorphic to A/C ?

Problem 11.26: F16

State the contraction mapping theorem. Prove there is a unique continuous function $f : [0, 1] \rightarrow [0, 1]$ that satisfies

$$f(x) = \frac{f(\sin x) + \cos x}{2}$$

for all $x \in [0, 1]$.

Problem 11.27: S20

A topological space is *separable* if it has a countable dense subset. Prove that the product of countable collection of separable topological spaces is separable.

Problem 11.28: F20

Let X be a topological space. Show that the intersection of any two dense open sets in X is also dense. Give an example that shows that this may fail if the two sets are not required to be open.

Problem 11.29: F20

- (i) Suppose that X is a topological space with the property that every two point space lies in a connected subspace of X . Prove that X is connected.
- (ii) Suppose that the word **TOPOLOGY** is written in purple ink on a square of white paper. Let V denote the subspace consisting of the white paper that remains. How many path-connected components does V have? For each such component X , compute $\pi_1(X)$.

Problem 11.30: F20

Suppose that X is a metric space. Define what it means for $C \subseteq X$ to be *complete*.

- (i) Show that if C and D are complete subsets of X then $C \cup D$ is complete.
- (ii) Suppose that $\{C_\lambda\}$ is a family of complete subspaces of X . Prove that $\bigcap_\lambda C_\lambda$ is either empty or complete.

Problem 11.31: F19

Give careful definitions of *continuity* and *uniform continuity* for maps between metric spaces.

- (i) Show that if $f : X \rightarrow Y$ is a continuous map between metric spaces and X is compact, then f is uniformly continuous.
- (ii) Prove or disprove: If $f : X \rightarrow Y$ is a uniformly continuous map between metric spaces and X is complete, then Y is complete.

Problem 11.32: F19

Let X be the set of subsets of \mathbb{N} . If A is a finite subset of \mathbb{N} and B is a subset of \mathbb{N} whose complement is finite, define a subset $[A, B]$ of X by

$$[A, B] = \{E \subseteq \mathbb{N} : A \subseteq E \subseteq B\}$$

Show that the sets $[A, B]$ form a base for a topology on X . Prove that with this topology, X is Hausdorff and disconnected. Prove that the function $f : X \times X \rightarrow Y$ given by

$$f(E_1, E_2) = E_1 \cap E_2$$

is continuous.

Problem 11.33: F19

Are the following true or false? Give a proof or counter-example.

- (a) If $X = U \cup V$ where U and V are both open and simply connected, then X is simply connected.
- (b) If $f : X \rightarrow Y$ is a continuous map which is onto, then $f_* : \pi_1(X) \rightarrow \pi_1(Y)$ is onto.
- (c) If $f : X \rightarrow Y$ is a continuous map which is injective, then $f_* : \pi_1(X) \rightarrow \pi_1(Y)$ is injective.

Problem 11.34: F19

Given $\epsilon > 0$, two points a, b of a metric space M are said to be *connected by an ϵ -chain*, if there exist points $x_0, \dots, x_n \in M$ such that $x_0 = a$, $x_n = b$ and $d(x_i, x_{i+1}) < \epsilon$ for each $i = 0, \dots, n-1$.

- (a) Show that if M is connected, then for every $\epsilon > 0$ any two points are connected by an ϵ -chain. Provide an example to show that the converse does not hold.
- (b) Show that if M is a compact metric space and for every $\epsilon > 0$ any two points of M are connected by an ϵ -chain, then M is connected.