

Solutions to Mike's Compendium of Problems

D. Zack Garza

Thursday 11th June, 2020

Contents

| | | |
|----------|---|----------|
| 1 | Preface | 2 |
| 1.1 | Problems to Revisit | 2 |
| 2 | 1: Point-Set | 2 |
| 2.1 | 2 | 2 |
| 2.2 | 4 | 3 |
| 2.3 | 6 | 5 |
| 2.4 | 8 | 5 |
| | 2.4.1 Proof 1 | 5 |
| | 2.4.2 Proof 2 | 6 |
| | 2.4.3 Proof of Tube Lemma (Todo: Check) | 6 |
| 2.5 | 9 | 7 |
| 2.6 | 10 | 7 |
| | 2.6.1 Proof 1 | 7 |
| | 2.6.2 Proof 2? | 9 |
| 2.7 | 11 | 9 |
| 2.8 | 12 (Todo) | 9 |
| 2.9 | 14 | 9 |
| | 2.9.1 Proof 1 | 9 |
| | 2.9.2 Proof 2? | 10 |
| 2.10 | 16 | 10 |
| | 2.10.1 Proof 1 | 10 |
| | 2.10.2 Proof 2 | 11 |
| 2.11 | 18 | 12 |
| 2.12 | 19 | 12 |
| 2.13 | 20 | 13 |
| 2.14 | 23 | 14 |
| 2.15 | 27 | 14 |
| | 2.15.1 a | 14 |
| | 2.15.2 b | 15 |
| 2.16 | 30 | 15 |
| 2.17 | 31 | 15 |
| | 2.17.1 a | 15 |
| | 2.17.2 b | 16 |

| | | |
|----------|-----------------------------|-----------|
| 2.18 | 32 | 16 |
| 2.19 | 38 | 16 |
| 2.20 | 42 | 17 |
| 2.21 | 44 | 17 |
| 2.21.1 | a | 17 |
| 2.21.2 | b | 17 |
| 3 | Spring 2019 | 17 |
| 3.1 | Problem 1 | 17 |
| 3.2 | Problem 2 | 18 |
| 3.3 | 7 | 18 |
| 4 | 2: Fundamental Group | 19 |
| 4.1 | 1 | 19 |
| 5 | Covering Spaces | 19 |
| 5.1 | 1b | 19 |
| 5.2 | 1c | 19 |
| 5.3 | 6 | 19 |
| 5.4 | 7 | 20 |
| 5.5 | 8 | 20 |

1 Preface

Note: usually (1/3) of the qual problems relate to point set (around 8 problems).

1.1 Problems to Revisit

- 4
- 6 (Without Heine-Borel)
- 8
- 10
- 11
- 14

2 1: Point-Set

2.1 2

See Munkres p.164, especially for (ii).

i. See definition section of review doc.

ii. Direct proof:

- Let $\{U_i \mid i \in J\} \Rightarrow X$; then $0 \in U_j$ for some $j \in J$.
- In the subspace topology, U_i is given by some $V \in \tau(\mathbb{R})$ such that $V \cap X = U_i$

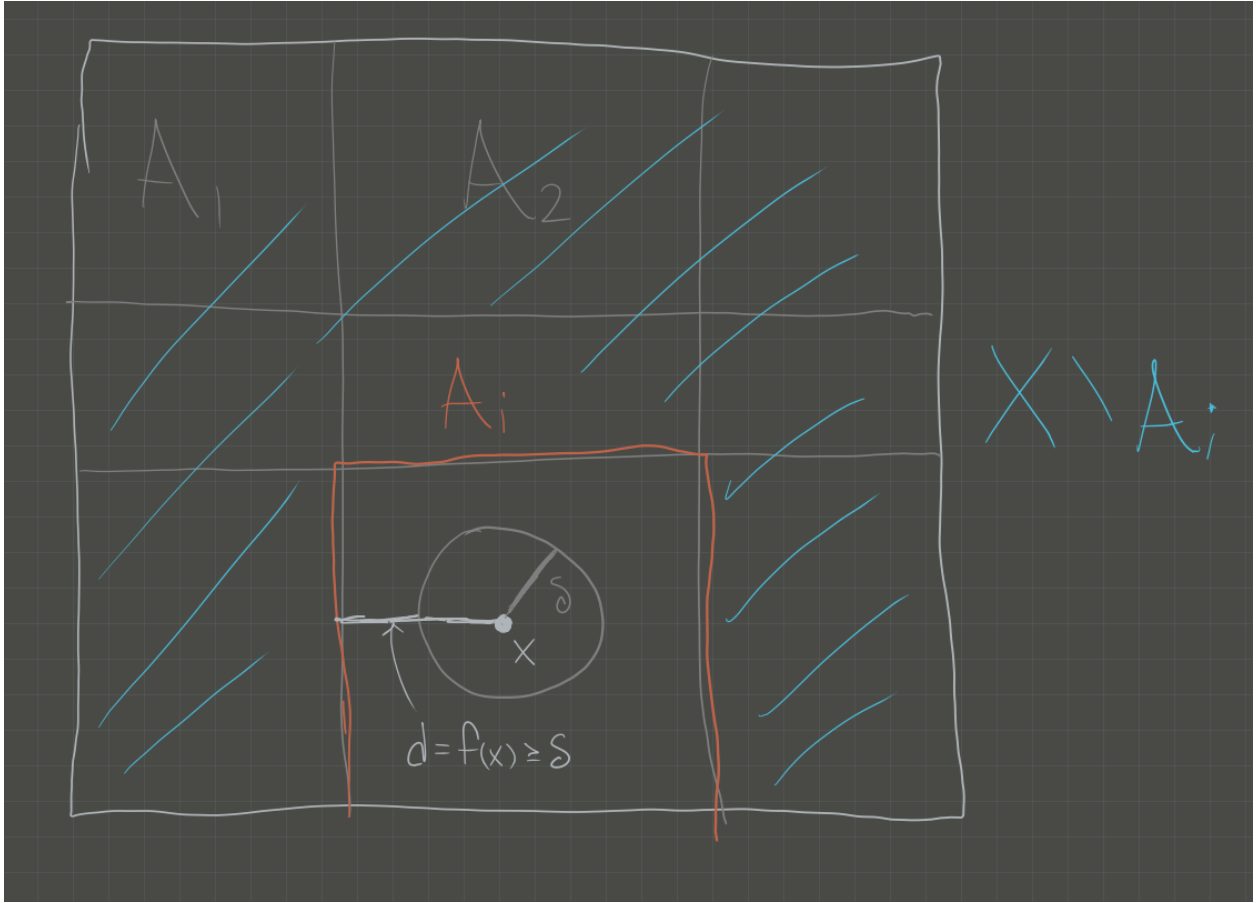
- A basis for the subspace topology on \mathbb{R} is open intervals, so write V as a union of open intervals $V = \bigcup_{k \in K} I_k$.
 - Since $0 \in U_j$, $0 \in I_k$ for some k .
 - Since I_k is an interval, it contains infinitely many points of the form $x_n = \frac{1}{n} \in X$
 - Then $I_k \cap X \subset U_j$ contains infinitely many such points.
 - So there are only *finitely* many points in $X \setminus U_j$, each of which is in $U_{j(n)}$ for some $j(n) \in J$ depending on n .
 - So U_j and the *finitely* many $U_{j(n)}$ form a finite subcover of X . ■
- iii. Todo: Need direct proof.

2.2 4

Statement: show that the *Lebesgue number* is well-defined for compact metric spaces.

Note: this is a question about the *Lebesgue Number*. See Wikipedia for detailed proof.

- Write $U = \{U_i \mid i \in I\}$, then $X \subseteq \bigcup_{i \in I} U_i$. Need to construct a $\delta > 0$.
- By compactness of X , choose a finite subcover U_1, \dots, U_n .
- Define the distance between a point x and a set $Y \subset X$: $d(x, Y) = \inf_{y \in Y} d(x, y)$.
 - **Claim:** the function $d(\cdot, Y) : X \rightarrow \mathbb{R}$ is continuous for a fixed set.
 - Proof: Todo, not obvious.



- Define a function

$$f : X \longrightarrow \mathbb{R}$$

$$x \mapsto \frac{1}{n} \sum_{i=1}^n d(x, X \setminus U_i).$$

- Note this is a sum of continuous functions and thus continuous.

- **Claim:**

$$\delta := \inf_{x \in X} f(x) = \min_{x \in X} f(x) = f(x_{\min}) > 0$$

suffices.

- That the infimum is a minimum: f is a continuous function on a compact set, apply the extreme value theorem: it attains its minimum.
- That $\delta > 0$: otherwise, $\delta = 0 \implies \exists x_0$ such that $d(x_0, X \setminus U_i) = 0$ for all i .
 - * Forces $x_0 \in X \setminus U_i$ for all i , but $X \setminus \bigcup U_i = \emptyset$ since the U_i cover X .
- That it satisfies the Lebesgue condition:

$$\forall x \in X, \exists i \text{ such that } B_\delta(x) \subset U_i$$

- * Let $B_\delta(x) \ni x$; then by minimality $f(x) \geq \delta$.
- * Thus it can *not* be the case that $d(x, X \setminus U_i) < \delta$ for *every* i , otherwise

$$f(x) \leq \frac{1}{n}(\delta + \dots + \delta) = \frac{n\delta}{n} = \delta$$

- * So there is some particular i such that $d(x, X \setminus U_i) \geq \delta$.
- * But then $B_\delta \subseteq U_i$ as desired.

2.3 6

Facts used:

- Cantor's Intersection Theorem
- Bases for standard topology on \mathbb{R} .
- Definition of compactness

- Toward a contradiction, let $\{U_\alpha\} \rightrightarrows [0, 1]$ be an open cover with no finite subcover.
- Then either $[0, \frac{1}{2}]$ or $[\frac{1}{2}, 1]$ has no finite subcover; WLOG assume it is $[0, \frac{1}{2}]$.
- Then either $[0, \frac{1}{4}]$ or $[\frac{1}{4}, \frac{1}{2}]$ has no finite subcover
- Inductively defining $[a_n, b_n]$ this way yields a sequence of closed, bounded, nested intervals (each with no finite subcover) with $\text{diam}([a_n, b_n]) \leq \frac{1}{2^n} \rightarrow 0$, so Cantor's Nested Interval theorem applies and the intersection contains exactly one point $p \in [0, 1]$.
- Since $p \in [0, 1]$, $p \in U_\alpha$ for some α .
- Since a basis for $\tau(\mathbb{R})$ is given by open intervals, we can find an $\varepsilon > 0$ such that $(p - \varepsilon, p + \varepsilon) \subseteq U_\alpha$
- Then if $\frac{1}{2^N} < \varepsilon$, for $n \geq N$ we have

$$[a_n, b_n] \subseteq (p - \varepsilon, p + \varepsilon) \subseteq U_\alpha.$$

- But then $U_\alpha \rightrightarrows [a_n, b_n]$, yielding a finite subcover of $[a_n, b_n]$, a contradiction.

2.4 8

Topic: proof of the tube lemma.

Statement: show $X, Y \in \text{Top}_{\text{compact}} \iff X \times Y \in \text{Top}_{\text{compact}}$

2.4.1 Proof 1

\Leftarrow :

- By universal properties, the product $X \times Y$ is equipped with continuous projections
- The continuous image of a compact set is compact, and $\pi_1(X \times Y) = X, \pi_2(X \times Y) = Y$
- So X, Y are compact.

\Rightarrow :

- Let $\{U_j \mid j \in J\} \rightrightarrows X \times Y$.
- Fix $x_0 \in X$, the slice $\{x_0\} \times Y$ is compact and can be covered by finitely many elements $\{U_j \mid j \leq m\} \rightrightarrows \{x_0\} \times Y$.
 - Sum: write $N = \bigcup_{j=1}^m U_j$; then $\{x_0\} \times Y \subset N$.

- Apply the tube lemma to N : produce $\{x_0\} \times Y \in W \times Y \subset N$; then $\{U_j \mid j \leq m\} \Rightarrow W \times Y$.
- Now let $x \in X$ vary: for each $x \in X$, produce $W_x \times Y$ as above, then $\{W_x \times Y \mid x \in X\} \Rightarrow X$.
 - By above argument, every tube $W_x \times Y$ can be covered by *finitely* many U_j .
- Since $\{W_x \mid x \in X\} \Rightarrow X$ and X is compact, produce a finite subset $\{W_k \mid k \leq m'\} \Rightarrow X$.
- Then $\{W_k \times Y \mid k \leq m'\} \Rightarrow X \times Y$; the claim is that it is a finite cover.
 - Finitely many k
 - For each k , the tube $W_k \times Y$ is covered by finitely by U_j
 - And finite \times finite = finite. ■

Shorter mnemonic:

19.U It is sufficient to consider a cover consisting of elementary sets. Since Y is compact, each fiber $x \times Y$ has a finite subcovering $\{U_i^x \times V_i^x\}$. Put $W^x = \cap U_i^x$. Since X is compact, the cover $\{W^x\}_{x \in X}$ has a finite subcovering W^{x_j} . Then $\{U_i^{x_j} \times V_i^{x_j}\}$ is the required finite subcovering.

2.4.2 Proof 2

Let π_X, π_Y denote the canonical projections, which we can note are continuous and preserve open sets.

\Rightarrow : Suppose $X \times Y$ is compact, and let $\{U_\alpha\}, \{V_\beta\}$ be open covers of X and Y respectively.

Let $T_{\alpha\beta} = U_\alpha \times V_\beta$; then $\{T_{\alpha\beta}\}$ is an open cover of $X \times Y$. So there is a finite subcover $\{T_{ij}\}$, $\{\pi_X(T_{ij})\}$ is an open cover of X , and similarly for Y . So both X, Y are compact.

\Leftarrow : Suppose X and Y are compact, and let $U_\alpha \Rightarrow X \times Y$ be an open cover. Let $\pi_Y : X \times Y \rightarrow Y$ be the canonical projection; then $\{\pi_Y(U_\alpha)\} \Rightarrow Y$ and by compactness of Y there is a finite subcover of the form $\{\pi_Y(U_i) \mid 1 \leq i \leq n\}$. Then $\{V_{x,i} := \{x\} \times U_i\}$ is an open cover of $\{x\} \times Y$ for any fixed x .

So if we fix an $x \in X$, we can let $V_{x,i} \Rightarrow \{x\} \times Y$ be any finite subcollection covering this slice. By the Tube Lemma, there is an open set W_x such that $\{x\} \times Y \subset W_x \times Y \subset \bigcup V_{x,i} = \{x\} \times Y$.

Then $\{W_x\} \Rightarrow X$ as x varies is an open cover of X , and by compactness of X , there are finitely many $x_j \in X$ such that $W_{x_j} \Rightarrow X$. But then $X \times Y = \bigcup_j W_{x_j} \times Y = \bigcup_j \bigcup_i W_{x_j} \times V_{x_j,i} \subset \bigcup_\alpha U_\alpha$ is a finite cover.

2.4.3 Proof of Tube Lemma (Todo: Check)

Proof of Tube Lemma:

- Let $\{U_j \times V_j \mid j \in J\} \Rightarrow X \times Y$.
- Fix a point $x_0 \in X$, then $\{x_0\} \times Y \subset N$ for some open set N .
- By the tube lemma, there is a $U^x \subset X$ such that the tube $U^x \times Y \subset N$.

- Since $\{x_0\} \times Y \cong Y$ which is compact, there is a finite subcover $\{U_j \times V_j \mid j \leq n\} \Rightarrow \{x_0\} \times Y$.
- “Integrate the X ”: write

$$W = \bigcap_{j=1}^n U_j,$$

then $x_0 \in W$ and W is a finite intersection of open sets and thus open.

- Claim: $\{U_j \times V_j \mid j \leq n\} \Rightarrow W \times Y$
 - Let $(x, y) \in W \times Y$; want to show $(x, y) \in U_j \times V_j$ for some $j \leq n$.
 - Then $(x_0, y) \in \{x_0\} \times Y$ is on the same horizontal line
 - $(x_0, y) \in U_j \times V_j$ for some j by construction
 - So $y \in V_j$ for this j
 - Since $x \in W$, $x \in U_j$ for *every* j , thus $x \in U_j$.
 - So $(x, y) \in U_j \times V_j$

2.5 9

2.6 10

2.6.1 Proof 1

X is connected:

- Write $X = L \coprod G$ where $L = \{0\} \times [-1, 1]$ and $G = \{\Gamma(\sin(x)) \mid x \in (0, 1]\}$ is the graph of $\sin(x)$.
- $L \cong [0, 1]$ which is connected
 - Claim: Every interval is connected (todo)
- Claim: G is connected (i.e. as the graph of a continuous function on a connected set)
 - The function

$$\begin{aligned} f : (0, 1] &\longrightarrow [-1, 1] \\ x &\mapsto \sin(x) \end{aligned}$$

is continuous (how to prove?)

- Products of continuous functions are continuous iff all of the components are continuous.
- Claim: The diagonal map $\Delta : Y \longrightarrow Y \times Y$ where $\Delta(t) = (t, t)$ is continuous for any Y since $\Delta = (\text{id}, \text{id})$
 - * Product of identity functions, which are continuous.
- The composition of continuous function is continuous, therefore

$$\begin{aligned} F : (0, 1] &\xrightarrow{\Delta} (0, 1]^2 \xrightarrow{(\text{id}, f)} (0, 1] \times [-1, 1] \\ t &\mapsto (t, t) \mapsto (t, f(t)) \end{aligned}$$

- Then $G = F((0, 1])$ is the continuous image of a connected set and thus connected.
- Claim: X is connected
 - Suppose there is a disconnecting cover $X = A \coprod B$ such that $\bar{A} \cap B = A \cap \bar{B} = \emptyset$ and $A, B \neq \emptyset$.
 - WLOG let $(x, \sin(x)) \in B$ for $x > 0$ (otherwise just relabeling A, B)
 - Claim: $B = G$

* It can't be the case that A intersects G : otherwise

$$X = A \amalg B \implies G = (A \cap G) \amalg (B \cap V)$$

disconnects G . So $A \cap G = \emptyset$, forcing $A \subseteq L$

* Similarly L can not be disconnected, so $B \cap L = \emptyset$ forcing $B \subset G$

* So $A \subset L$ and $B \subset G$, and since $X = A \amalg B$, this forces $A = L$ and $B = G$.

– But any open set U in the subspace topology $L \subset \mathbb{R}^2$ (generated by open balls) containing $(0,0) \in L$ is the restriction of a ball $V \subset \mathbb{R}^2$ of radius $r > 0$, i.e. $U = V \cap X$.

* But any such ball contains points of G :

$$n \gg 0 \implies \frac{1}{n\pi} < r \implies \exists g \in G \text{ s.t. } g \in U.$$

* So $U \cap L \cap G \neq \emptyset$, contradicting $L \cap G = \emptyset$.

• Claim: X is *not* path-connected.

– Todo: “can't get from L to G in finite time”.

– Toward a contradiction, choose a continuous function $f : I \longrightarrow X$ with $f(0) \in G$ and $f(1) \in L$.

* Since $L \cong [0, 1]$, use path-connectedness to create a path $f(1) \longrightarrow (0, 1)$

* Concatenate paths and reparameterize to obtain $f(1) = (0, 1) \in L \subset \mathbb{R}^2$.

– Let $\varepsilon = \frac{1}{2}$; by continuity there exists a $\delta \in I$ such that

$$t \in B_\delta(1) \subset I \implies f(t) \in B_\varepsilon(\mathbf{0}) \in X$$

– Using the fact that $[1 - \delta, 1]$ is connected, $f([1 - \delta, 1]) \subset X$ is connected.

– Let $f(1 - \delta) = \mathbf{x}_0 = (x_0, y_0) \in X \subset \mathbb{R}^2$.

– Define a composite map

$$F : [0, 1] \longrightarrow \mathbb{R}F \qquad \qquad \qquad := \mathbf{p}_{x\text{-axis}} \circ f.$$

* F is continuous as a composition of continuous functions.

– Then $F([1 - \delta, 1]) \subset \mathbb{R}$ is connected and thus must be an interval (a, b)

– Since $f(1) = \mathbf{0}$ which has x -component zero, $[0, b] \subset (a, b)$.

– Since $f(1 - \delta) = \mathbf{x}$, $F(\mathbf{x}) = x_0$ and this $[0, x_0] \subset (a, b)$.

– Thus for all $x \in (0, x_0]$ there exists a $t \in [1 - \delta, 1]$ such that $f(t) = (x, \sin\left(\frac{1}{x}\right))$.

– Now toward the contradiction, choose $x = \frac{1}{2n\pi - \pi/2} \in \mathbb{R}$ with n large enough such that $x \in (0, x_0)$.

* Note that $\sin\left(\frac{1}{x}\right) = -1$ by construction.

* Apply the previous statement: there exists a t such that $f(t) = (x, \sin\left(\frac{1}{x}\right)) = (x, -1)$.

* But then

$$\|f(t) - f(x)\| = \|(x, -1) - (0, 1)\| = \|(x, 2)\| > \frac{1}{2},$$

contradicting continuity of f .

2.6.2 Proof 2?

Let $X = A \cup B$ with $A = \{(0, y) \mid y \in [-1, 1]\}$ and $B = \{(x, \sin(1/x)) \mid x \in (0, 1]\}$. Since B is the graph of a continuous function, which is always connected. Moreover, $X = \bar{A}$, and the closure of a connected set is still connected.

Alternative direct argument: the subspace $X' = B \cup \{0\}$ is not connected. If it were, write $X' = U \amalg V$, where wlog $0 \in U$. Then there is an open such that $0 \in N_r(0) \subset U$. But any neighborhood about zero intersects B , so we must have $V \subset B$ as a strict inclusion. But then $U \cap B$ and V disconnects B , a connected set, which is a contradiction.

To see that X is not path-connected, suppose toward a contradiction that there is a continuous function $f : I \rightarrow X \subset \mathbb{R}^2$. In particular, f is continuous at 0 , and so

$$\forall \varepsilon \quad \exists \delta \quad \left\| \mathbf{x} \right\| < \delta \implies \|f(\mathbf{x})\| < \varepsilon.$$

where the norm is the standard Euclidean norm.

However, we can pick $\varepsilon < 1$, say, and consider points of the form $\mathbf{x}_n = (\frac{1}{2n\pi}, 0)$. In particular, we can pick n large enough such that $\|\mathbf{x}_n\|$ is as small as we like, whereas $\|f(\mathbf{x}_n)\| = 1 > \varepsilon$ for all n , a contradiction.

2.7 11

Consider the (continuous) projection $\pi : \mathbb{R}^2 \rightarrow \mathbb{RP}^1$ given by $(x, y) \mapsto [y/x, 1]$ in homogeneous coordinates. (I.e. this sends points to lines through the origin with rational slope).

Note that the image of π is $\mathbb{RP}^1 \setminus \{\infty\}$, which is homeomorphic to \mathbb{R} .

If we now define $f = \pi|_X$, we have $f(X) \rightarrow \mathbb{Q} \subset \mathbb{R}$. If X were connected, then $f(X)$ would also be connected, but $\mathbb{Q} \subset \mathbb{R}$ is disconnected, a contradiction.

2.8 12 (Todo)

- Using the fact that $[0, \infty) \subset \mathbb{R}$ is Hausdorff, any retract must be closed, so any closed interval $[\varepsilon, N]$ for $0 \leq \varepsilon \leq N \leq \infty$.
 - Note that $\varepsilon = N$ yields all one point sets $\{x_0\}$ for $x_0 \geq 0$.
- No finite discrete sets occur, since the retract of a connected set is connected.
- ?

2.9 14

2.9.1 Proof 1

- Take two connected sets X, Y ; then there exists $p \in X \cap Y$.
- Toward a contradiction: write $X \cup Y = A \amalg B$ with both $A, B \subset A \amalg B$ open.
- Since $p \in X \cup Y = A \amalg B$, WLOG $p \in A$. We will show B must be empty.

- Claim: $A \cap X$ is clopen in X .
 - $A \cap X$ is open in X : ?
 - $A \cap X$ is closed in X : ?
- The only clopen sets of a connected set are empty or the entire thing, and since $p \in A$, we must have $A \cap X = X$.
- By the same argument, $A \cap Y = Y$.
- So $A \cap (X \cup Y) = (A \cap X) \cup (A \cap Y) = X \cup Y$
- Since $A \subset X \cup Y$, $A \cap (X \cup Y) = A$
- Thus $A = X \cup Y$, forcing $B = \emptyset$.

2.9.2 Proof 2?

Let $X := \bigcup_{\alpha} X_{\alpha}$, and let $p \in \bigcap X_{\alpha}$. Suppose toward a contradiction that $X = A \coprod B$ with A, B nonempty, disjoint, and relatively open as subspaces of X . Wlog, suppose $p \in A$, so let $q \in B$ be arbitrary.

Then $q \in X_{\alpha}$ for some α , so $q \in B \cap X_{\alpha}$. We also have $p \in A \cap X_{\alpha}$.

But then these two sets disconnect X_{α} , which was assumed to be connected – a contradiction.

2.10 16

2.10.1 Proof 1

Topic: closure and connectedness in the subspace topology. See Munkres p.148

- $S \subset X$ is **not** connected if S with the subspace topology is not connected.
 - I.e. there exist $A, B \subset S$ such that
 - * $A, B \neq \emptyset$,
 - * $A \cap B = \emptyset$,
 - * $A \coprod B = S$.
- Or equivalently, there exists a nontrivial $A \subset S$ that is clopen in S .

Show stronger statement: this is an iff.

\implies :

- Suppose S is not connected; we then have sets $A \cup B = S$ from above and it suffices to show $\text{cl}_Y(A) \cap B = A \cap \text{cl}_X(B) = \emptyset$.
- A is open by assumption and $Y \setminus A = B$ is closed in Y , so A is clopen.
- Write $\text{cl}_Y(A) := \text{cl}_X(A) \cap Y$.
- Since A is closed in Y , $A = \text{cl}_Y(A)$ by definition, so $A = \text{cl}_Y(A) = \text{cl}_X(A) \cap Y$.
- Since $A \cap B = \emptyset$, we then have $\text{cl}_Y(A) \cap B = \emptyset$.
- The same argument applies to B , so $\text{cl}_Y(B) \cap A = \emptyset$.

\impliedby :

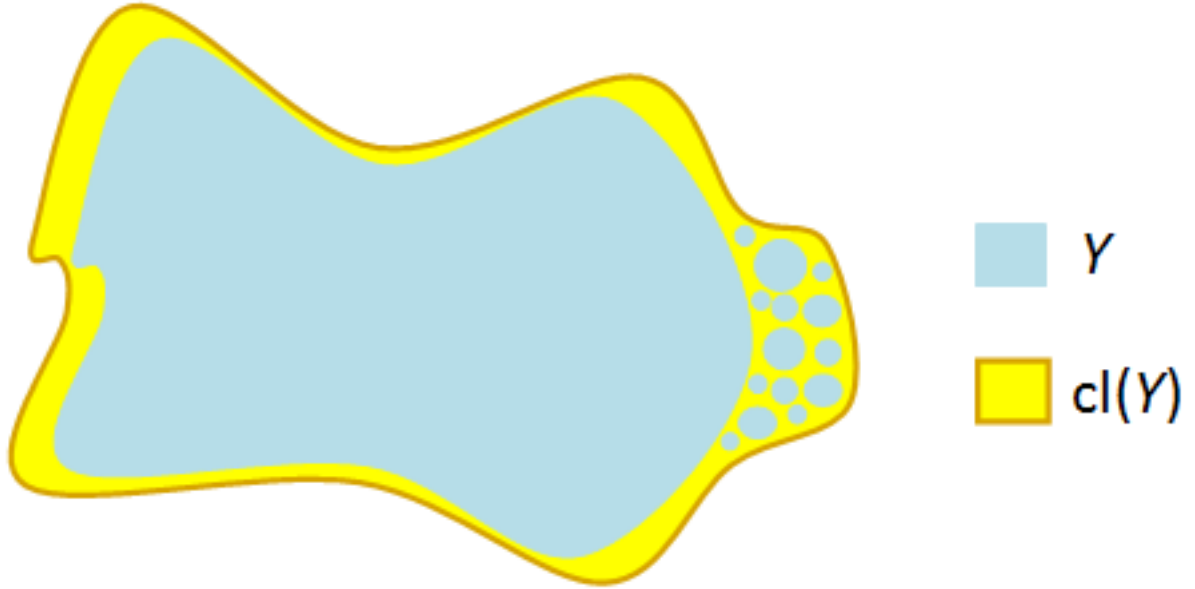
- Suppose displayed condition holds; given such A, B we will show they are clopen in Y .

- Since $\text{cl}_Y(A) \cap B = \emptyset$, (claim) we have $\text{cl}_Y(A) = A$ and thus A is closed in Y .
– Why?

$$\begin{aligned}
 \text{cl}_Y(A) &:= \text{cl}_X(A) \cap Y \\
 &= \text{cl}_X(A) \cap (A \amalg B) \\
 &= (\text{cl}_X(A) \cap A) \amalg (\text{cl}_X(A) \cap B) \\
 &= A \amalg (\text{cl}_X(A) \cap B) \quad \text{since } A \subset \text{cl}_Y(A) \\
 &= A \amalg (\text{cl}_Y(A) \cap B) \quad \text{since } B \subset Y \\
 &= A \amalg \emptyset \quad \text{using the assumption} \\
 &= A.
 \end{aligned}$$

- But $A = Y \setminus B$ where B is closed, so A is open and thus a nontrivial clopen subset.

■



2.10.2 Proof 2

Lemma: X is connected iff the only subsets of X that are closed and open are \emptyset, X .

If $S \subset X$ is not connected, then there exists a subset $A \subset S$ that is both open and closed in the subspace topology, where $A \neq \emptyset, S$.

Suppose S is not connected, then choose A as above. Then $B = S \setminus A$ yields a pair A, B that disconnects S . Since A is closed in S , $\bar{A} = A$ and thus $\bar{A} \cap B = A \cap B = \emptyset$. Similarly, since A is open, B is closed, and $\bar{B} = B \implies \bar{B} \cap A = B \cap A = \emptyset$.

2.11 18

- Define a new function

$$g : X \longrightarrow \mathbb{R}$$

$$x \mapsto d_X(x, f(x)).$$

- Attempt to minimize. Claim: g is a continuous function.
- Given claim, a continuous function on a compact space attains its infimum, so set

$$m := \inf_{x \in X} g(x)$$

and produce $x_0 \in X$ such that $g(x_0) = m$.

- Then

$$m > 0 \iff d(x_0, f(x_0)) > 0 \iff x_0 \neq f(x_0).$$

- Now apply f and use the assumption that f is a contraction to contradict minimality of m :

$$\begin{aligned} d(f(f(x_0)), f(x_0)) &\leq C \cdot d(f(x_0), x_0) \\ &< d(f(x_0), x_0) \quad \text{since } C < 1 \\ &\leq m \end{aligned}$$

- Proof that g is continuous: use the definition of g , the triangle inequality, and that f is a contraction:

$$\begin{aligned} d(x, f(x)) &\leq d(x, y) + d(y, f(y)) + d(f(x), f(y)) \\ \implies d(x, f(x)) - d(y, f(y)) &\leq d(x, y) + d(f(x), f(y)) \\ \implies g(x) - g(y) &\leq d(x, y) + C \cdot d(x, y) = (C + 1) \cdot d(x, y) \end{aligned}$$

- This shows that g is Lipschitz continuous with constant $C + 1$ (implies uniformly continuous, but not used).

2.12 19

Statement: prove that the product of two connected spaces is connected.

Solution:

Use the fact that a union of spaces containing a common point is still connected. Fix a point $(a, b) \in X \times Y$. Since the horizontal slice $X_b := X \times \{b\}$ is homeomorphic to X which is connected, as are all of the vertical slices $Y_x := \{x\} \times Y \cong Y$ (for any x), the “T-shaped” space $T_x := X_b \bigcup Y_x$ is connected for each x .

Note that $(a, b) \in T_x$ for every x , so $\bigcup_{x \in X} T_x = X \times Y$ is connected.

Image

| Space | Connected | Locally Connected |
|----------------------|-----------|-------------------|
| \mathbb{R} | ✓ | ✓ |
| $[0, 1] \cup [2, 3]$ | | ✓ |
| Sine Curve | ✓ | |
| \mathbb{Q} | | |

- a. See definitions in intro.
- b. Claim: the Topologist's sine curve X suffices.

Proof:

- Claim 1: X is connected.
 - Intervals and graphs of cts functions are connected, so the only problem point is 0.
- Claim 2: X is **not** locally path connected.
 - Take any $B_\varepsilon(0) \in \mathbb{R}^2$; then $\pi_X B_\varepsilon(0)$ yields infinitely many arcs, each intersecting the graph at two points on $\partial B_\varepsilon(0)$.
 - These are homeomorphic to a collection of disjoint embedded open intervals, and any disjoint union of intervals is clearly not connected. ■

Todo: what's the picture?

2.14 23

Note: this is precisely the cofinite topology.

1. $\mathbb{R} \in \tau$ since $\mathbb{R} \setminus \mathbb{R} = \emptyset$ is trivially a finite set, and $\emptyset \in \tau$ by definition.
2. If $U_i \in \tau$ then $(\bigcup_i U_i)^c = \bigcap_i U_i^c$ is an intersection of finite sets and thus finite, so $\bigcup_i U_i \in \tau$.
3. If $U_i \in \tau$, then $(\bigcap_{i=1}^n U_i)^c = \bigcup_{i=1}^n U_i^c$ is a finite union of finite sets and thus finite, so $\bigcap_{i=1}^n U_i \in \tau$.

So τ forms a topology.

To see that (\mathbb{R}, τ) is compact, let $\{U_i\} \rightrightarrows \mathbb{R}$ be an open cover by elements in τ .

Fix any U_α , then $U_\alpha^c = \{p_1, \dots, p_n\}$ is finite, say of size n . So pick $U_1 \ni p_1, \dots, U_n \ni p_n$; then $\mathbb{R} \subset U_\alpha \cup \bigcup_{i=1}^n U_i$ is a finite cover.

2.15 27

Notes: use diagonal trick to construct the Cauchy sequence.

2.15.1 a

\implies :

If X is totally bounded, let $\varepsilon = \frac{1}{n}$ for each n , and let $\{x_i\}$ be an arbitrary sequence. For $n = 1$, pick a finite open cover $\{U_i\}_n$ such that $\text{diam} U_i < \frac{1}{n}$ for every i .

Choose V_1 such that there are infinitely many $x_i \in V_1$. (Why?) Note that $\text{diam} V_1 < 1$. Now choose $x_i \in V_1$ arbitrarily and define it to be y_1 .

Then since V_1 is totally bounded, repeat this process to obtain $V_2 \subseteq V_1$ with $\text{diam}(V_2) < \frac{1}{2}$, and choose $x_i \in V_2$ arbitrarily and define it to be y_2 .

This yields a nested family of sets $V_1 \supseteq V_2 \supseteq \cdots$ and a sequence $\{y_i\}$ such that $d(y_i, y_j) < \max(\frac{1}{i}, \frac{1}{j}) \rightarrow 0$, so $\{y_i\}$ is a Cauchy subsequence.

$\Leftarrow :$

Then fix $\varepsilon > 0$ and pick x_1 arbitrarily and define $S_1 = B(\varepsilon, x_1)$. Then pick $x_2 \in S_1^c$ and define $S_2 = S_1 \cup B(\varepsilon, x_2)$, and so on. Continue by picking $x_{n+1} \in S_n^c$ (Since X is not totally bounded, this can always be done) and defining $S_{n+1} = S_n \cup B(\varepsilon, x_{n+1})$.

Then $\{x_n\}$ is not Cauchy, because $d(x_i, x_j) > \varepsilon$ for every $i \neq j$.

2.15.2 b

Take $X = C^0([0, 1])$ with the sup-norm, then $f_n(x) = x^n$ are all bounded by 1, but $\|f_i - f_j\| = 1$ for every i, j , so no subsequence can be Cauchy, so X can not be totally bounded.

Moreover, $\{f_n\}$ is closed. (Why?)

2.16 30

Let $A \subset X$ be compact, and pick a fixed $x \in X \setminus A$. Since X is Hausdorff, for arbitrary $a \in A$, there exists opens $U_a \ni a$ and $U_{x,a} \ni x$ such that $U_a \cap U_{x,a} = \emptyset$. Then $\{U_a \mid a \in A\} \Rightarrow A$, so by compactness there is a finite subcover $\{U_{a_i}\} \Rightarrow A$.

Now take $U = \bigcup_i U_{a_i}$ and $V_x = \bigcap_i U_{x,a_i}$, so $U \cap V_x = \emptyset$. Note that both U and V_x are open.

But then defining $V := \bigcup_{x \in X \setminus A} V_x$, we have $X \setminus A \subset V$ and $V \cap A = \emptyset$, so $V = X \setminus A$, which is open and thus A is closed.

2.17 31

2.17.1 a

Theorems used:

- Continuous bijection + open map (or closed map) \implies homeomorphism.
- **Closed** subsets of compact sets are compact.
- The continuous image of a compact set is compact.
- Closed subsets of Hausdorff spaces are compact.

So we'll show that f is a closed map.

Let $U \in X$ be closed.

- Since X is compact, U is compact
- Since f is continuous, $f(U)$ is compact
- Since Y is Hausdorff, $f(U)$ is closed.

2.17.2 b

Note that any finite space is clearly compact.

Take $f : ([2], \tau_1) \longrightarrow ([2], \tau_2)$ to be the identity map, where τ_1 is the discrete topology and τ_2 is the indiscrete topology. Any map into an indiscrete topology is continuous, and f is clearly a bijection.

Let g be the inverse map; then note that $1 \in \tau_1$ but $g^{-1}(1) = 1$ is not in τ_2 , so g is not continuous. ■

2.18 32

$\implies :$

- Let $p \in \Delta^c$.
- Then p is of the form (x, y) where $x \neq y$ and $x, y \in X$.
- Since X is Hausdorff, pick N_x, N_y in X such that $N_x \cap N_y = \emptyset$.
- Then $N_p := N_x \times N_y$ is an open set in X^2 containing p .
- Claim: $N_p \cap \Delta = \emptyset$.
 - If $q \in N_p \cap \Delta$, then $q = (z, z)$ where $z \in X$, and $q \in N_p \implies q \in N_x \cap N_y = \emptyset$.
- Then $\Delta^c = \bigcup_p N_p$ is open.

$\impliedby :$

- Let $x \neq y \in X$.
- Consider $(x, y) \in \Delta^c \subset X^2$, which is open.
- Thus $(x, y) \in B$ for some box in the product topology.
- $B = U \times V$ where U, V are open in X , and $B \subset \Delta^c$.
- So $x \in U, y \in V$.
- Claim: $U \cap V = \emptyset$.
 - Otherwise, $z \in U \cap V \implies (z, z) \in B$, but $B \cap \Delta^c = \emptyset$.

2.19 38

\mathbb{R} is clearly Hausdorff, and \mathbb{R}/\mathbb{Q} has the indiscrete topology, and is thus non-Hausdorff. So take the quotient map $\pi : \mathbb{R} \longrightarrow \mathbb{R}/\mathbb{Q}$.

Direct proof that \mathbb{R}/\mathbb{Q} isn't Hausdorff:

- Pick $[x] \subset U \neq [y] \subset V \in \mathbb{R}/\mathbb{Q}$ and suppose $U \cap V = \emptyset$.
- Pull back $U \longrightarrow A, V \longrightarrow B$ open disjoint sets in \mathbb{R}
- Both A, B contain intervals, so they contain rationals $p \in A, q \in B$

- Then $[p] = [q] \in U \cap V$.

2.20 42

Proof that \mathbb{R}/\mathbb{Q} has the indiscrete topology:

- Let $U \subset \mathbb{R}/\mathbb{Q}$ be open and nonempty, show $U = \mathbb{R}/\mathbb{Q}$.
- Let $[x] \in U$, then $x \in \pi^{-1}(U) := V \subset \mathbb{R}$ is open.
- Then V contains an interval (a, b)
- Every $y \in V$ satisfies $y + q \in V$ for all $q \in \mathbb{Q}$, since $y + q - y \in \mathbb{Q} \implies [y + q] = [y]$.
- So $(a - q, b + q) \in V$ for all $q \in \mathbb{Q}$.
- So $\bigcup_{q \in \mathbb{Q}} (a - q, b + q) \in V \implies \mathbb{R} \subset V$.
- So $\pi(V) = \mathbb{R}/\mathbb{Q} = U$, and thus the only open sets are the entire space and the empty set.

2.21 44

2.21.1 a

- Suppose X has a countable basis $B = \{B_i\}$.
- Choose an arbitrary $x_i \in B_i$ for each i . Define $Q = \{x_i\}$.
- Let $y \in N_y \subset X$.
- By definition of a basis, there exists some B_i such that $y \in B_i \subset N_y$.
- Since $x_i \in B_i$, $Q \cap N_y \neq \emptyset$.
- Thus Q is dense in X .

2.21.2 b

- Let $\{q_i\}$ be a countable dense subset.
- Define $B_{i,j} = B_{\frac{1}{i}}(q_j)$, which is still countable.
- Property 1: Every $x \in B_{i,j}$
 - Take $x \in N_{\frac{1}{2}}(x) \ni q_j$ by density.
 - Then $x \in B_{\frac{1}{2},j}$.
- Property 2: $x \in B_{i_1,j_1} \cap B_{i_2,j_2} \implies x \in B_{i_3,j_3} \subset B_{i_1,j_1} \cap B_{i_2,j_2}$:
 - Take $i < \min(i_1, i_2)$, then $N_i(x) \ni q_j$ for some j .
 - Thus $x \in B_{i,j}$.

3 Spring 2019

3.1 Problem 1

Complete and **totally** bounded \implies compact. - Definition: A space X is *totally bounded* if for every $\varepsilon > 0$, there is a finite cover $X \subseteq \bigcup_{\alpha} B_{\alpha}(\varepsilon)$ such that the radius of each ball is less than ε .

- Definition: A subset of a space $S \subset X$ is *bounded* if there exists a $B(r)$ such that $r < \infty$ and $S \subseteq B(r)$ - Totally bounded \implies bounded - Counterexample to converse: \mathbb{N} with the discrete metric. - Equivalent for Euclidean metric - Compact \implies totally bounded.

Counterexample for problem: the unit ball in any Hilbert (or Banach) space of infinite dimension is closed, bounded, and not compact.

Proof: Inductively, let $\mathbf{x}_1 \in B(1, \mathbf{0})$ and $A_1 = \text{span}(\mathbf{x}_1)$, then choose $s = \mathbf{x} + A_1 \in B(1, \mathbf{0})/A_1$ such that $\|s\| = \frac{1}{2}$ and then a representative \mathbf{x}_2 such that $\|\mathbf{x}_2\| \leq 1$. Then $\|\mathbf{x}_2 - \mathbf{x}_1\| \geq \frac{1}{2}$. Then, let $A_2 = \text{span}(\mathbf{x}_1, \mathbf{x}_2)$, (which is closed) and repeat this for $s = \mathbf{x} + A_2 \in B(1, \mathbf{0})/A_2$ to get an \mathbf{x}_3 such that $\|\mathbf{x}_3 - \mathbf{x}_{\leq 2}\| \geq \frac{1}{2}$. This produces a non-convergent sequence in the closed ball, so it can not be compact.

Second counterexample: $(\mathbb{R}, (x, y) \mapsto \frac{|x - y|}{1 + |x - y|})$.

Best counterexample: $X = \left(\mathbb{Z}, \rho(x, y) = \begin{cases} 1 & \text{if } x \neq y \\ 0 & \text{if } x = y \end{cases}\right)$. This metric makes X complete for any X , then take $\mathbb{N} \subset X$. All sets are closed, and bounded, so we have a complete, closed, bounded set that is not compact – take that cover $U_i = B(1, i)$.

Useful tool: $(X, d) \cong_{\text{Top}} (X, \min(d(x, y), 1))$ where the RHS is now a bounded space. This preserves all topological properties (e.g. compactness).

3.2 Problem 2

Definition: (X, τ) where $\tau \subseteq \mathcal{P}(X)$ is a *topological space* iff

- $\emptyset, X \in \tau$
- $\{U_i\}_{i \in I} \subseteq \tau \implies \bigcup_{i \in I} U_i \in \tau$
- $\{U_i\}_{i \in \mathbb{N}} \subseteq \tau \implies \bigcap_{i \in \mathbb{N}} U_i \in \tau$

We can write $\overline{(X, \tau)} = (X \amalg \{\text{pt}\}, \tau \cup \tau')$ where $\tau' = \{U \amalg \{\text{pt}\} \mid X - U \text{ is compact}\}$. We need to show that $T := \tau \cup \tau'$ forms a topology.

- We have $\emptyset, X \in \tau \implies \emptyset, X \in \tau \cup \tau'$.
- We just need to check that τ' is closed under arbitrary unions. Let $\{U_i\} \subset \tau'$, so $X - U_i = K_i$ a compact set for each i . Then $\bigcup_i U_i = \bigcup_i X - (X - U_i) = \bigcup_i X - K_i = X - \bigcap_i K_i$

3.3 7

Let $f : S^1 \xrightarrow{\times k} S^1$.

Claim: The inclusion $S^1 \longrightarrow C_\varphi$ induces an isomorphism $\pi_1(C_\varphi) \cong \pi_1(S^1)/H$ where $H = N_{\pi_1(S^1)}(\langle f^* \rangle)$ is the normal subgroup generated by the induced map $f^* \pi_1(S^1) \longrightarrow \pi_1(S^1)$.

Since f is a k -fold cover, the induced map is multiplication by k on the generator $\alpha \in \pi_1(S^1)$, i.e. $\alpha \mapsto \alpha^k$. But then $\pi_1(S^1) \cong \mathbb{Z}$ and $H \cong k\mathbb{Z}$, so $\pi_1(C_\varphi) \cong \mathbb{Z}/m\mathbb{Z}$. ■

4 2: Fundamental Group

4.1 1

Proposition: $\gamma_1 \simeq \gamma_2 \iff \gamma_1, \gamma_2$ are conjugate in $\pi_1(X, x_0)$, i.e. $\exists[\alpha] \in \pi_1$ such that $[\gamma_1] = [\alpha][\gamma_2][\alpha]^{-1}$.

Proof:

\implies : Clear, since $\gamma_1 \sim \gamma_2 \implies [\gamma_1] = [\gamma_2] \in \pi_1(X)$, so take $\alpha(t) = x_0$ the constant loop for all t .

\impliedby : ? Forgot how these arguments go.

Image

■

Counterexample where homotopic loops are not equal in π_1 , but just conjugate:

Image

5 Covering Spaces

5.1 1b

Homotopy lifting property:

$$\begin{array}{ccc}
 & & \tilde{X} \\
 & \nearrow \exists \tilde{H} & \downarrow \pi \\
 Y \times I & \xrightarrow{H} & X
 \end{array}$$

π clearly induces a map p_* on π_1 by functoriality, so we'll show that $\ker p_*$ is trivial. Let $\gamma : S^1 \rightarrow \tilde{X} \in \pi_1(\tilde{X})$ and suppose $\alpha := p_*(\gamma) = [e] \in \pi_1(X)$. We'll show $\gamma \simeq [e]$ in $\pi_1(\tilde{X})$.

Since $\alpha = [e]$, $\alpha \simeq \text{const.}$ and thus there is a homotopy $H : I \times S^1 \rightarrow X$ such that $H_0 = \text{const.}(x_0)$ and $H_1 = \gamma$. By the HLP, this lifts to $\tilde{H} : I \times S^1 \rightarrow \tilde{X}$. Noting that $\pi^{-1}(\text{const.}(x_0))$ is still a constant loop, this says that γ is homotopic to a constant loop and thus nullhomotopic.

5.2 1c

Since both spaces are path-connected, the degree of the covering map π is precisely the index of the included fundamental group. This forces π to be a degree 1 covering and hence a homeomorphism.

5.3 6

Note $\pi_1 \mathbb{RP}^2 = \mathbb{Z}/2\mathbb{Z}$, so $\pi_1 X = (\mathbb{Z}/2\mathbb{Z})^2$.

The pullback of any neighborhood of the basepoint needs to be locally homeomorphic to one of

- $S^2 \vee S^2$
- $\mathbb{RP}^2 \vee S^2$

And so *all* possibilities for regular covering spaces are given by

- $\bigvee^{2k} S^2$ “beads” wrapped into a necklace for any $k \geq 1$
- $\mathbb{RP}^2 \vee (\bigvee^k S^2) \vee \mathbb{RP}^2$
- $\vee^\infty S^2$, the universal cover

To get a threefold cover, we want the basepoint to lift to three preimages, so we can take

- $S^2 \vee S^2 \vee S^2$ wrapped
- $\mathbb{RP}^2 \vee S^2 \vee \mathbb{RP}^2$.

5.4 7

- $\mathbb{RP}_3 \vee S^2 \vee \mathbb{RP}^3$, which has $\pi_2 = 0 * \mathbb{Z} * 0 = \mathbb{Z}$ since $\pi_{i \geq 1} X = \pi_{i \geq 1} \tilde{X}$ and $\tilde{\mathbb{RP}}^3 = S^3$.
- $\mathbb{RP}^2 \vee S^3 \vee \mathbb{RP}^2$, which has $\pi_2 = \mathbb{Z} * 0 * \mathbb{Z} = \mathbb{Z} * \mathbb{Z} \neq \mathbb{Z}$

5.5 8

Yes,

Image