

Topology Qualifying Exam Solutions

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Tuesday 2nd June, 2020

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1 Problems Suggest by Mike Usher

General Topology

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Fundamental Group

- 1

Covering Spaces

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2 Problems to Revisit

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- 6 (Without Heine-Borel)
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- 14

3 General Topology

3.1 2

- See definition section of review doc.
- Use Heine-Borel theorem: a set $U \subset \mathbb{R}^n$ is compact $\iff U$ is *closed* and *bounded*.
 - X is closed in \mathbb{R} , since we can write its complement as an arbitrary union of open intervals:

$$X^c = (-\infty, 0) \cup \left(\bigcup_{n \in \mathbb{Z}^+} \left(\frac{1}{n}, \frac{1}{n+1} \right) \right) \cup (1, \infty)$$

- X is *bounded*, since we can pick $r = 1$, then $x, y \in X \implies d(x, y) \leq r = 1$.
- Use Heine-Borel again: X is not closed because it does not contain all of its limit points, e.g. the sequence $\left\{ x_n := \frac{1}{n} \mid n \in \mathbb{Z}^{\geq 1} \right\} \subset X$ but $x_n \xrightarrow{n \rightarrow \infty} 0 \in X^c$. Thus X is **not** compact.

3.1.1 Alternate Proof of (ii)

See Munkres p.164

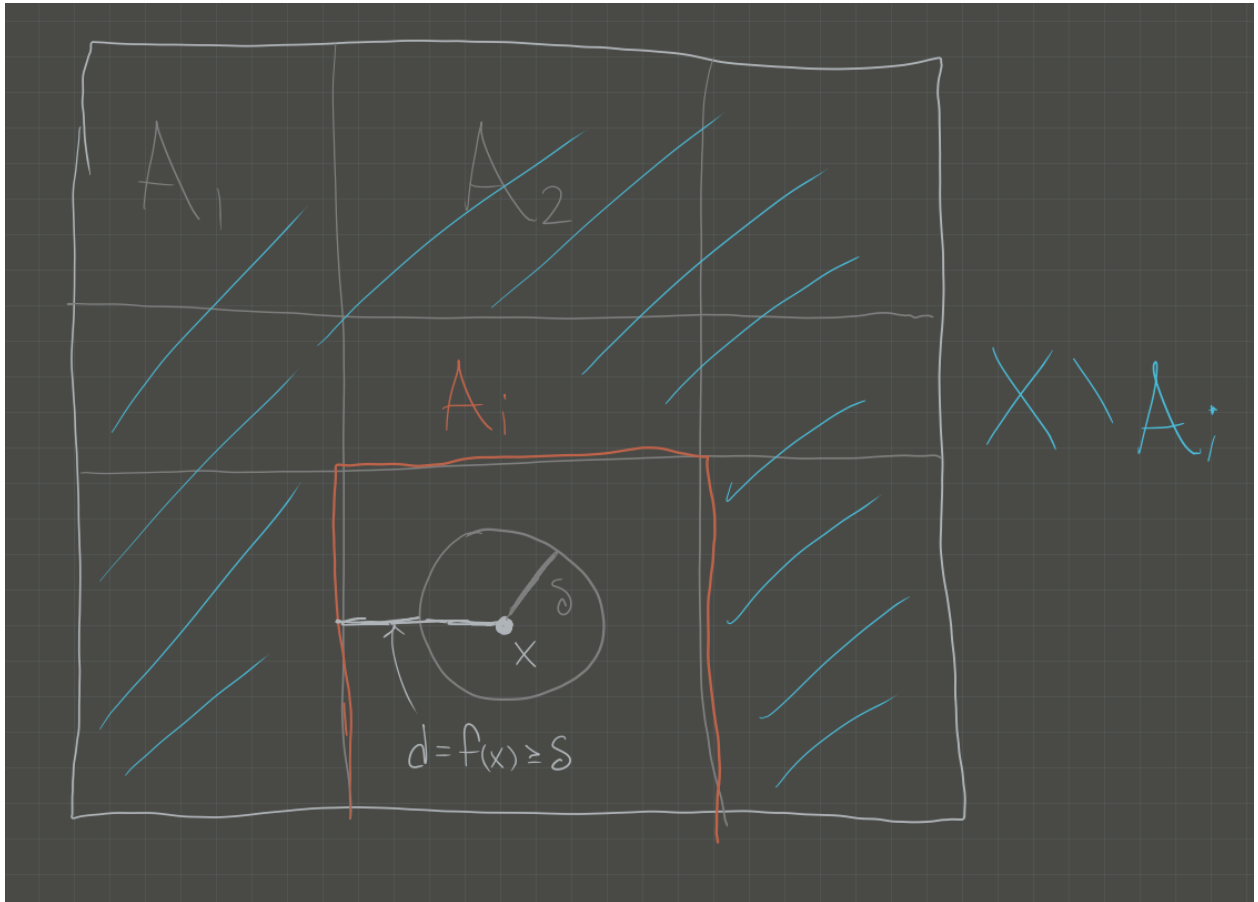
- Let $\{U_i \mid j \in J\} \Rightarrow X$; then $0 \in U_j$ for some $j \in J$.
- In the subspace topology, U_i is given by some $V \in \tau(\mathbb{R})$ such that $V \cap X = U_i$
 - A basis for the subspace topology on \mathbb{R} is open intervals, so write V as a union of open intervals $V = \bigcup_{k \in K} I_k$.
 - 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 . ■

3.2 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.

3.3 6

Todo! Did the wrong question here.

3.4 8

Topic: proof of the tube lemma.

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

3.4.1 Proof 1 (DZG)

\Leftarrow :

- By universal properties, the product $X \times Y$ is equipped with continuous projections
- The continuous image of a compact set is compact, and $\pi_1(X \times Y) = X, p_2(X \times Y) = Y$
- So X, Y are compact.

\Rightarrow :

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 $(x, y) \in U_j \times V_j$

Actual Proof:

- Let $\{U_j \mid j \in J\} \Rightarrow X \times Y$.
- Fix $x_0 \in X$, the slice $\{x_0\} \times Y$ is compact and can be covered by finitely many elements $\{U_j \mid j \leq m\} \Rightarrow \{x_0\} \times Y$.
 - 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.

3.5 10

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

$$f : (0, 1] \longrightarrow [-1, 1]$$

$$x \mapsto \sin(x)$$

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

$$F : (0, 1] \xrightarrow{\Delta} (0, 1]^2 \xrightarrow{(\text{id}, f)} (0, 1] \times [-1, 1]$$

$$t \mapsto (t, t) \mapsto (t, f(t))$$

- 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

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

* 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 .

■

3.6 12

- 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.
- ?

3.7 14

- 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 $B = \emptyset$.

3.8 16

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
 - * $A, B \neq \emptyset$,
 - * $A \cap B = \emptyset$,
 - * $A \amalg B = S$.
- 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 $\text{cl}_Y(B) \cap A = \emptyset$.

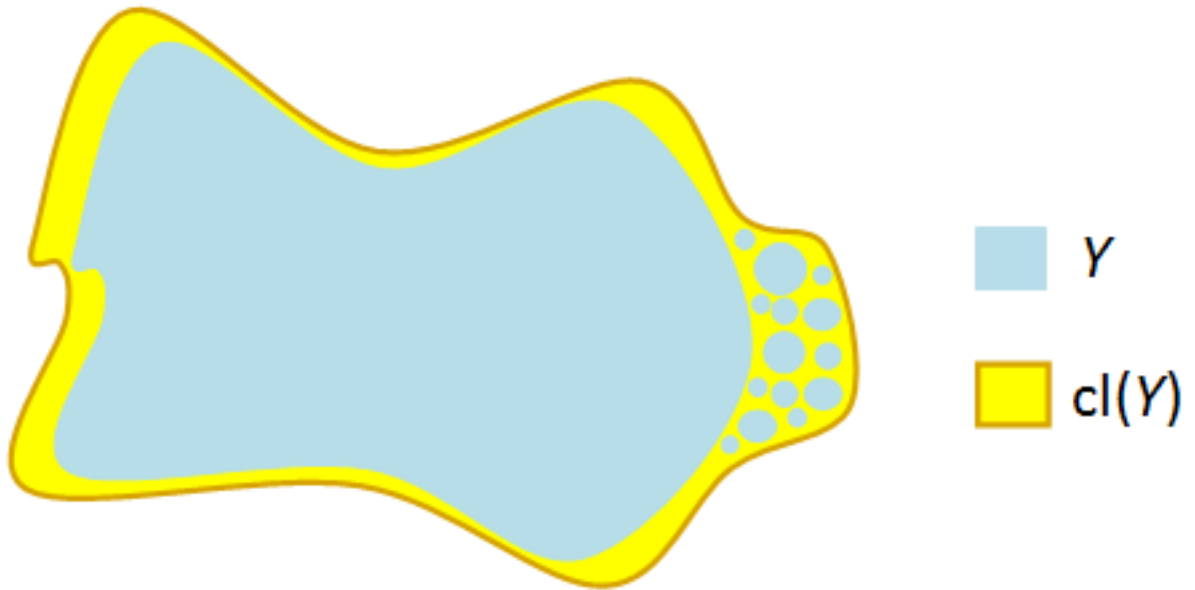
$\Leftarrow :$

- 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.

■



3.9 18

- Define a new function

$$\begin{aligned}
 g : X &\longrightarrow \mathbb{R} \\
 x &\mapsto d_X(x, f(x)).
 \end{aligned}$$

- 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 $g(x) = m$.

- 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).

3.10 20

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

- See definitions in intro.
- 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?