

PSET 4 — 01/31/2024

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Credit Statement

I worked on these problems alone, with reference to class notes and the following books:

- (a) *Introduction to Analysis* by Maxwell Rosenlicht

Problem 1.

If a_1, a_2, a_3, \dots is a bounded sequence of real numbers, define

$$\limsup_{n \rightarrow \infty} a_n := \sup \{x \in \mathbb{R} \mid a_n > x \text{ for infinitely many } n \in \mathbb{N}\}$$

$$\liminf_{n \rightarrow \infty} a_n := \inf \{x \in \mathbb{R} \mid a_n < x \text{ for infinitely many } n \in \mathbb{N}\}$$

Prove that $\liminf_{n \rightarrow \infty} a_n \leq \limsup_{n \rightarrow \infty} a_n$ with the equality holding if and only if the sequence converges.

Let $A = a_1, a_2, a_3, \dots$ be a bounded sequence of real numbers as defined above.

Claim 1.1. $\liminf_{n \rightarrow \infty} a_n \leq \limsup_{n \rightarrow \infty} a_n$

Proof. Let $L = \liminf_{n \rightarrow \infty} a_n$ and $U = \limsup_{n \rightarrow \infty} a_n$. By the definitions of **lim inf** and **lim sup**, for any $\varepsilon > 0$, there exist $n_1, n_2 \in \mathbb{N}$ such that

$$a_n \geq L - \varepsilon \quad \text{for infinitely many } n > n_1$$

$$a_n \leq U + \varepsilon \quad \text{for infinitely many } n > n_2$$

Thus, we have

$$L - \varepsilon \leq a_n \leq U + \varepsilon$$

for infinitely many n . By making ε arbitrarily small, we have

$$L \leq a_n \leq U$$

Note: why can we make ε arbitrarily small? This argument stakes on the fact that L is the *infimum* of the set of all numbers such that r such that $a_n < r$ for infinitely many n , which means that for any other $L' < L$, the condition does not hold (or else L would not be the greatest such number), so $a_n \geq L'$ for infinitely many n . The same argument holds for U , in the opposite direction. □

Claim 1.2. *If the sequence converges, then $\liminf_{n \rightarrow \infty} a_n = \limsup_{n \rightarrow \infty} a_n$.*

Proof. Suppose the sequence $A = a_1, a_2, a_3, \dots$ converges to some point a .

Then, for any $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that $d(a_n, a) < \varepsilon$ for all $n \geq N$, so that $a - \varepsilon < a_n < a + \varepsilon$ for infinitely many $n \geq N$. Therefore, $\liminf_{n \rightarrow \infty} a_n > a - \varepsilon$ and $\limsup_{n \rightarrow \infty} a_n < a + \varepsilon$. So we have:

$$a - \varepsilon < \liminf_{n \rightarrow \infty} a_n \leq \limsup_{n \rightarrow \infty} a_n < a + \varepsilon$$

for any $\varepsilon > 0$.

Given that $\{a_n\}_1^\infty$ converges, we can make ε arbitrarily small, so that $\liminf_{n \rightarrow \infty} a_n = \limsup_{n \rightarrow \infty} a_n = a$. □

Problem 2.

Let $x_n = \left(1 + \frac{1}{n}\right)^n$ for all $n \in \mathbb{N}$.

Remark 2.1. The Euler number e can be defined as $\lim_{n \rightarrow \infty} \left(1 + \frac{1}{n}\right)^n$.

(i) Using induction, show that for all $x > -1$ and $n \in \mathbb{N}$, we have

$$(1+x)^n \geq 1+nx.$$

We shall prove the claim by induction on n .

Proof. Let $x > -1$ and $n \in \mathbb{N}$.

(a) Base case: $n = 1$.

$$\left[(1+x)^n\right]_{n=1} = (1+x)^1 = 1+x = 1+1 \cdot x = 1+nx$$

Since $1+nx \geq 1+nx$ (since any number is greater than or equal to itself), the inequality holds for $n = 1$.

(b) Inductive step: Assume $(1+x)^n \geq 1+nx$. We show that the invariant holds for $n+1$.

$$\begin{aligned} (1+x)^{n+1} &= (1+x)^n (1+x) \\ &\geq (1+nx) (1+x) = 1+x+nx+nx^2 \\ &\geq 1+x+nx = 1+(n+1)x \end{aligned}$$

Therefore, $(1+x)^n \geq 1+nx$ for all $n \in \mathbb{N}$. □

- (ii) Using the previous item, show that $\frac{x_{n+1}}{x_n} \geq 1$ so x_n is monotonically increasing.

To show this, we need to show that $x_{n+1} \geq x_n$ for all $n \in \mathbb{N}$.

$$\begin{aligned}
\frac{x_{n+1}}{x_n} &= \frac{\left(1 + \frac{1}{n+1}\right)^{n+1}}{\left(1 + \frac{1}{n}\right)^n} \\
&= \frac{\left(1 + \frac{1}{n+1}\right)^n}{\left(1 + \frac{1}{n}\right)^n} \cdot \left(1 + \frac{1}{n+1}\right) \\
&= \left(\frac{1 + \frac{1}{n+1}}{1 + \frac{1}{n}}\right)^n \cdot \left(1 + \frac{1}{n+1}\right) \\
&= \left(\frac{1 + \frac{1}{n+1}}{\frac{n+1}{n}}\right)^n \cdot \left(1 + \frac{1}{n+1}\right) \\
&= \left(\frac{n + \frac{n}{n+1}}{n+1}\right)^n \cdot \left(1 + \frac{1}{n+1}\right) \\
&= \left(\frac{n}{n+1} + \frac{n}{(n+1)^2}\right)^n \cdot \left(1 + \frac{1}{n+1}\right) \\
&= \left(1 - \frac{1}{n+1} + \frac{n}{(n+1)^2}\right)^n \cdot \left(1 + \frac{1}{n+1}\right) \\
&= \left(1 - \frac{-(n+1)+n}{(n+1)^2}\right)^n \cdot \left(1 + \frac{1}{n+1}\right) \\
&= \left(1 - \frac{1}{(n+1)^2}\right)^n \cdot \left(1 + \frac{1}{n+1}\right) \\
&\geq \left(1 - \frac{n}{(n+1)^2}\right) \cdot \left(1 + \frac{n}{n+1}\right) \quad (\text{by the previous proof}) \\
&> \left(1 - \frac{n+1}{(n+1)^2}\right) \cdot \left(1 + \frac{n}{n+1}\right) \quad (\text{subtracting a bigger term}) \\
&= \left(1 - \frac{1}{n+1}\right) \cdot \left(1 + \frac{n}{n+1}\right) \\
&= 1 - \frac{1}{n+1} + \frac{1}{n} - \frac{1}{n(n+1)} \\
&= \frac{n(n+1) - n + (n+1) - 1}{n(n+1)} \\
&= \frac{n(n+1)}{n(n+1)} \\
&= 1
\end{aligned}$$

(iii) Show that x_n is bounded using the binomial formula

$$(a + b)^n = \frac{n!}{k!(n-k)!} a^{n-k} b^k = \sum_{k=0}^n \binom{n}{k} a^{n-k} b^k.$$

Fix a and b to arbitrary real numbers. We shall prove this by induction on n .

(a) Base case: $n = 1$

$$\begin{aligned} (a + b)^n &= a + b \\ &= \binom{1}{0} a^1 \cdot b^0 + \binom{1}{1} a^0 b^1 \\ &= \binom{1}{0} a^{1-0} b^0 + \binom{1}{1} a^{1-1} b^1 = \sum_{k=0}^1 \binom{n}{k} a^{n-k} b^k \end{aligned}$$

(b) Inductive step: Assume the invariant holds for $(a + b)^n$. We shall show that it holds for $(a + b)^{(n+1)}$.

$$\begin{aligned} (a + b)^{n+1} &= (a + b)^n (a + b) \\ &= \left(\sum_{k=0}^n \binom{n}{k} a^{n-k} b^k \right) (a + b) \\ &= \sum_{k=0}^n \binom{n}{k} a^{n-k} b^k \cdot a + \sum_{k=0}^n \binom{n}{k} a^{n-k} b^k \cdot b \\ &= \sum_{k=0}^n \binom{n}{k} a^{n+1-k} b^k + \sum_{k=0}^n \binom{n}{k} a^{n-k} b^{k+1} \\ &= \sum_{k=0}^n \binom{n}{k} a^{n+1-k} b^k + a^{n-k} b^{k+1} \\ &= \sum_{k=0}^n \binom{n}{k} a^{n+1-k} b^k + \binom{n}{k-1} a^{n+1-k} b^k \quad (\text{Grouping together equal powers}) \\ &= \sum_{k=0}^n \left(\frac{n!}{k!(n-k)!} + \frac{n!}{(k-1)!(n-k+1)!} \right) a^{n+1-k} b^k \\ &= \sum_{k=0}^n \left(\frac{(n+1-k) n! + k n!}{k! (n+1-k)!} \right) a^{n+1-k} b^k \\ &= \sum_{k=0}^n \left(\frac{(n+1) n!}{k! (n+1-k)!} \right) a^{n+1-k} b^k \\ &= \sum_{k=0}^n \left(\frac{(n+1)!}{k! (n+1-k)!} \right) a^{n+1-k} b^k \\ &= \sum_{k=0}^n \binom{n+1}{k} a^{n+1-k} b^k \\ &= \sum_{k=0}^{n+1} \binom{n+1}{k} a^{n+1-k} b^k \end{aligned}$$

Since a and b were arbitrary, this holds for all a and b , including $a = 1$ and $b = \frac{1}{n}$, thus x_n is bounded by the binomial formula since equality satisfies both *less than or equal to* and *greater than or equal to*.

(iv) Show that $\{x_n\}$ is convergent.

As seen in (ii) and (iii), $\{x_n\}$ is monotonically increasing and is bounded above.

Claim 2.2. $\{x_n\}$ is convergent.

Proof. Suppose $\{x_n\}$ is not convergent. Since $\{x_n\}$ is monotonically increasing, this implies that it must not be bounded above and $\lim_{n \rightarrow \infty} x_n = \infty$, which contradicts the known fact (by remark 2.1) that $\lim_{n \rightarrow \infty} x_n = e \neq \infty$. Therefore, the sequence must be convergent. \square

Problem 3.

Show that a complete subspace of a metric space is a closed subset.

Definition 3.1. A metric space X is complete if every Cauchy sequence in X has a limit point in X .

Definition 3.2. A subset S of a metric space X is closed if S contains all its limit points.

Claim 3.3. *Every convergent sequence is Cauchy.*

Proof. Let X be a metric space and $P := \{p_n\}_1^\infty \subseteq X$ be a convergent sequence in X . Let $p \in X$ be the limit of P . For any $\varepsilon > 0$, since P converges to p , there exists $N \in \mathbb{N}$ such that $d(p_n, p) < \frac{\varepsilon}{2}$ for all $n \geq N$. Therefore,

$$d(p_n, p_m) \leq d(p_n, p) + d(p, p_m) < \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon$$

Therefore, P is Cauchy. □

Claim 3.4. *A complete subspace of a metric space is a closed subset.*

Proof. Let X be a metric space and $Y \subseteq X$ be a complete subspace of X .

Let $P := \{p_n\}_1^\infty \subseteq Y$ be an arbitrary convergent sequence in Y (i.e. a sequence that has a limit). To show that Y is closed, we need to show that any such P has a limit point in Y .

By claim 3.3, the convergence of P implies that P is Cauchy. Since Y is complete by definition, and P is Cauchy, P has a limit point $p \in Y$.

Since P was arbitrary, Y contains all its limit points, whenever limit points exist, so Y is closed. □

Problem 4.

Definition 4.1. A set S is compact if every open cover of S has a finite subcover.

Definition 4.2. An open cover of a set S is a collection of open sets $\{U_a\}_{a \in A}$ such that $S \subseteq \bigcup_{a \in A} U_a$.

Let $A := \left\{ \frac{1}{n} \mid n \in \mathbb{N} \right\} \subset \mathbb{R}$.

(i) Show that A is not compact directly using the definition.

Claim 4.3. A has no finite subcover.

Proof. For each $n \in \mathbb{N}$, $a_n = \frac{1}{n} \in A$, set

$$r_n = \frac{1}{2} \cdot \min \left\{ \frac{1}{n-1} - \frac{1}{n}, \frac{1}{n} - \frac{1}{n+1} \right\}$$

such that $r_n \leq \frac{1}{2}d(a_{n-1}, a_n)$ and $r_n \leq \frac{1}{2}d(a_n, a_{n+1})$. Define the open ball

$$B_n := B_{r_n}(a_n) = (a_n - r_n, a_n + r_n).$$

Then each B_n is a non-empty open set containing *only* the single element a_n . Furthermore, any two distinct B_n and B_m are disjoint. Therefore, $\{B_n\}_{n \in \mathbb{N}}$ is an infinite open cover of A , (since there are infinitely many B_n), and each a_n is contained in exactly one B_n , so there is no finite subcover. \square

(ii) Show that $A \cup \{0\}$ is compact directly using the definition.

Claim 4.4. $A \cup \{0\}$ has a finite subcover.

Proof. Let $S := A \cup \{0\}$. First, note that A is bounded below by 0 and bounded above by 1. Let $\{U_a\}_{a \in A}$ be an open cover of S . Since $0 \in S$, there exists $a_0 \in A$ such that $0 \in U_{a_0}$. U_{a_0} is an open set, so there exists some $\varepsilon > 0$ such that $B_\varepsilon(0) \subseteq U_{a_0}$. However, we know that for all $\varepsilon > 0$, there exists some $N \in \mathbb{N}$ such that $\frac{1}{N} < \varepsilon$, and by the order properties of \mathbb{R} , $0 < \frac{1}{N} < \varepsilon \implies 0 < \frac{1}{n} \geq \frac{1}{N} < \varepsilon$ for all $n \geq N$.

Therefore, $B_\varepsilon(0)$ contains infinitely many points, and only the points $\frac{1}{k}$ for $k < N$ are not contained in $B_\varepsilon(0)$. Therefore, $\{B_\varepsilon(0)\} \cup \{U_k \mid k < N\}$ is a finite subcover of S . \square

Problem 5.

Let (X, d) be a metric space and $S \subset X$. Show directly that if S is sequentially compact then S is limit-point compact without using the theorem we proved in class.

Definition 5.1. A metric space X is sequentially compact if every sequence in X has a convergent subsequence converging to a point in X .

Definition 5.2. A subset S of a metric space X is limit-point compact if every infinite subset of S has a limit point in S .

Claim 5.3. *If a subsequence of a sequence converges to a point in S , then the sequence also converges to that point.*

Proof. Let X be a metric space and $S \subseteq X$. Let $P := \{p_n\}_1^\infty \subseteq S$ be a sequence in S , and let $Q := \{p_{n_k}\}_1^\infty \subseteq P$ be a subsequence of P . Suppose Q converges to $q \in S$. Then, for every $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that $d(q_n, q) < \varepsilon$ for all $n \geq N$. Since $Q \subseteq P$, this implies that $d(p_k, q) < \varepsilon$ for infinitely many distinct $k \in \mathbb{N}$, hence $d(p_k, q) > \varepsilon$ for finite $k \in \mathbb{N}$. Pick $K = \max \{k \in \mathbb{N} \mid d(p_k, q) > \varepsilon\}$. Then, for all $n \geq K$, $d(p_n, q) < \varepsilon$, so P also converges to q . \square

Claim 5.4. *If S is sequentially compact then S is limit-point compact.*

Proof. For any infinite subset of S , we can construct a sequence P in S by picking any arbitrary element p_1 in the subset, then picking any arbitrary element p_2 in the subset that is not p_1 , and so on. Since the subset is infinite, we can always pick an element that is not in the sequence so far.

Suppose S is sequentially compact. Then, by definition of sequential compactness, every such sequence P in S has a convergent subsequence Q converging to some point $q \in S$. By claim 5.3, P also converges to q , so P itself has a limit point in S .

Therefore, S is limit-point compact. \square

Problem 6.

Prove that every bounded sequence of real numbers has a convergent subsequence (This statement is known as the *Bolzano-Weierstrass Theorem*).

[Hint]: Construct a Cauchy subsequence from the given sequence by constructing a sequence of nested intervals whose length converges to 0 and each interval has infinitely many elements from the original sequence.

Let $P := \{p_n\}_1^\infty \subseteq \mathbb{R}$ be a bounded sequence of real numbers. Then P is contained in some interval $[a, b]$. For an interval S , let $\mathcal{L}(S)$ denote the length of the interval. We shall construct a sequence of nested intervals as follows:

1. Let $I_0 := [a, b]$. Note that $\mathcal{L}(I_0) = |a - b|$.
2. Let I_1 be whichever of $\left[a, \frac{a+b}{2}\right]$ and $\left[\frac{a+b}{2}, b\right]$ contains infinitely many elements of P at least one of them must contain infinitely many elements of P , since their union is I_0 , which contains infinitely many elements of P . If both contain infinitely many elements of P , pick either one. Note that $\mathcal{L}(I_1) = \frac{|a-b|}{2}$ and $I_1 \subseteq I_0$.
3. Construct I_2 to be whichever half of I_1 contains infinitely many elements of P such that $\mathcal{L}(I_2) = \frac{|a-b|}{2^2}$ and $I_2 \subseteq I_1$.
4. For each $n \in \mathbb{N}$, recursively construct I_n to be whichever half of I_{n-1} contains infinitely many elements of P so that $\mathcal{L}(I_n) = \frac{|a-b|}{2^n}$ and $I_n \subseteq I_{n-1} \subseteq \dots \subseteq I_0$.

Next, for each $n \in \mathbb{N}$, pick any element q_n from the sequence P such that $q_n \in I_n$.

Claim 6.1. $\{q_n\}$ is Cauchy.

Proof. For any $\varepsilon > 0$. Since $\lim_{n \rightarrow \infty} \mathcal{L}(I_n) = 0$, there exists $N \in \mathbb{N}$ such that $\mathcal{L}(I_N) < \varepsilon$. Note that for any $n, m > N$, $q_m \in I_N$ and $q_n \in I_N$. Therefore,

$$d(q_m, q_n) \leq \mathcal{L}(I_N) < \varepsilon$$

□

Thus, $\{q_n\}_1^\infty$ is Cauchy, and $\{q_n\}_1^\infty \subseteq [a, b]$, so $\{q_n\}_1^\infty$ is bounded. By the completeness of \mathbb{R} , $\{q_n\}_1^\infty$ converges.