
CHAPTER 1

ASSIGNMENT

ASSIGNMENT-1

Some useful Definitions and theorems

Definition 0.1: (LimSup and LimInf)

Given a sequence that is bounded (hence forth, all theorems involving limsup and liminf assumes a bounded sequence as given):

1. $\text{Limsup}(x_n) := \inf(V := \{v \in \mathbb{R} : \exists n_v \in \mathbb{N} \text{ such that } \forall n \geq n_v, x_n \leq v\})$
2. $\text{Liminf}(x_n) := \sup(U = \{u \in \mathbb{R} : \exists n_u \in \mathbb{N} \text{ such that } \forall n \geq n_u, x_n \geq u\})$

Theorem 0.2

The following are equivalent:

1. x is the $\text{LimSup}(x_n)$
2. if $\varepsilon > 0$, then \exists utmost finite $n \in \mathbb{N}$ such that $x + \varepsilon < x_n$ but infinite $n \in \mathbb{N}$ such that $x - \varepsilon < x_n$. This implies $x + \varepsilon \in V$ but $x - \varepsilon \notin V$
3. If $S_m : \{x_m, x_{m+1}, \dots\}$ and $U_m = \sup(S_m)$, then $\lim(U_m) = \inf(U_m) = x$
4. If S is the set of all subsequential limits of x_n , then $\sup(S) = x$

Proof for Theorem.

(1) \implies (2)) Since x is the infimum of V , $\forall \varepsilon > 0$, $\exists z \in V$ such that $z \leq x + \varepsilon$. We see that, $\exists n_z$ such that $\forall n \geq n_z, x_n < z \leq x + \varepsilon$. Hence, $x + \varepsilon \in V$, or rather, there exists utmost finite n such that $x_n > x + \varepsilon$. $x - \varepsilon$ cannot belong in V since x is the infimum, therefore, $\forall k \in \mathbb{N}, \exists n_k \geq k$ such that $x_{n_k} > x - \varepsilon$, or rather, there would exist infinite n such that $x - \varepsilon < x_n$.

(2) \implies (3)) We know that $U_m \geq U_{m+1}$, is a monotone decreasing sequence that

is bounded below. Hence, from monotone convergence theorem, we have $\lim(U_n) = \inf(\{U_n\})$. From (2), we know that $\forall \varepsilon > 0, \exists n_\varepsilon$ such that $\forall n \geq n_\varepsilon$ we have $x_n \leq x + \varepsilon$. Therefore, $U_{n_\varepsilon} \leq x + \varepsilon$. Hence, $\forall \varepsilon > 0, \inf(U_n) = \lim(U_n) \leq x + \varepsilon$. There exists infinite x_n such that $x - \varepsilon < x_n$ which means that $x - \varepsilon < U_n \forall n \in \mathbb{N}$. This implies $x - \varepsilon \leq \inf(U_n)$. Therefore means $\forall \varepsilon > 0, |\inf(U_n) - x| \leq \varepsilon$. From the lemma, $\inf(U_n) = x$.

(3) \implies (4)) Since $\inf(U_n) = x, \forall \varepsilon, \exists n_0(\varepsilon) \in \mathbb{N}$ such that $U_{n_0(\varepsilon)} \leq x + \varepsilon \implies \forall n \geq n_0(\varepsilon), x_n \leq x + \varepsilon$ so for every convergent subsequence, $x_{n_k}, \lim(x_{n_k}) \leq x + \varepsilon$. Since the set of all subsequential limits is bounded (and non empty from Bolzano Weierstrass Theorem), $\sup(S = \text{set of all subsequential limits}) \leq x + \varepsilon. \forall \varepsilon > 0, x - \varepsilon < \inf(U_n) \implies \forall \varepsilon \forall n \in \mathbb{N}, x - \varepsilon < U_n$.

Choose $\varepsilon = 1$ and the set S_1 , for which $\exists x_{n_1} \in S_1$ such that $U_1 - 1 \leq x_{n_1} < U_1$. Choose $\varepsilon = \frac{1}{2}$ and the set S_{n_1} for which $\exists x_{n_2} \in S_{n_1}$ such that $U_{n_1} - \frac{1}{2} \leq x_{n_2} < U_{n_1}$. From construction, $n_2 > n_1$. Having chosen $\varepsilon = \frac{1}{j}$ and the set $S_{n_{j-1}}$ and obtaining n_j such that $\exists x_{n_j} \in S_{n_{j-1}}$ so that $U_{n_{j-1}} - \frac{1}{j} \leq x_{n_j} < U_{n_{j-1}}$ such that $n_j > n_{j-1}$, we choose $\varepsilon = \frac{1}{j+1}$ and the set S_{n_j} . The construction continues and we create a sequence x_{n_j} which from squeeze play, converges to x . To see this, we have that $\forall j \in \mathbb{N}$

$$U_{n_{j-1}} - \frac{1}{j} \leq x_{n_j} < U_{n_{j-1}}$$

Taking limit on both LHS and RHS we see that x_{n_j} converges to x . Therefore x itself is a subsequential limit, which means $x \leq \sup(S)$. We already had $\forall \varepsilon > 0, \sup(S) \leq x + \varepsilon$, which gives, $\forall \varepsilon > 0, x \leq \sup(S) \leq x + \varepsilon$, which means $\sup(S) = x$.

(4) \implies (1)) Consider the set $V := \{v \in \mathbb{R} : \exists n_v \in \mathbb{N} \text{ such that } \forall n \geq n_v, x_n \leq v\}$. if $z \in V$, it means that every subsequential limit of x_n goes below z . Therefore, $\sup(S) = x \leq z \forall z \in V$. This means $x \leq \limsup(x_n)$. Suppose $\sup(S) = x < \limsup(x_n)$. This means $\sup(S) + \delta = \limsup(x_n)$ or $x = \limsup(x_n) - \delta$. $\limsup(x_n)$ is an upper bound to the set of all subsequential limits S . Consider an arbitrary subsequential limit y . $\forall \varepsilon > 0, \exists n_\varepsilon \in \mathbb{N}$ such that $\forall n \in \mathbb{N}, n \geq n_\varepsilon$ we have $y - \varepsilon < x_n < y + \varepsilon < \limsup(x_n) - \delta + \varepsilon$. Choose an ε slightly larger than δ , which would make $\limsup(x_n) - (\delta - \varepsilon)$ slightly smaller than $\limsup(x_n)$. This gives: for the chosen $\varepsilon \exists n_\varepsilon \in \mathbb{N}$ such that $\forall n \in \mathbb{N}, n \geq n_\varepsilon$ we have $x_n < \limsup(x_n) - \delta + \varepsilon < \limsup(x_n)$. This means that a number slightly smaller than $\inf(V)$ exists in V . This is absurd. Hence, $\limsup(x_n) = \sup(S = \text{set of all subsequential limits})$. ■

Theorem 0.3

The following are equivalent:

1. y is the $\text{Liminf}(x_n)$
2. if $\varepsilon > 0$, then \exists utmost finite $n \in \mathbb{N}$ such that $x_n < y - \varepsilon$ but infinite $n \in \mathbb{N}$ such that $x_n < y + \varepsilon$. This implies $y + \varepsilon \notin U$ but $y - \varepsilon \in U$
3. If $S_m : \{x_m, x_{m+1}, \dots\}$ and $L_m = \inf(S_m)$, then $\lim(L_m) = \sup(L_m) = y$
4. If S is the set of all subsequential limits of x_n , then $\inf(S) = y$

Proof for Theorem.

(1) \implies (2)) Given $y = \text{Liminf}(x_n) := \sup(U = \{u \in \mathbb{R} : \exists n_u \in \mathbb{N} \text{ such that } \forall n \geq n_u, x_n \geq u\})$. If $\varepsilon > 0$ we have a $z \in U$ such that $y - \varepsilon \leq z$. There exists only finite n such that $x_n < z$ which means there exists only finite n such that $x_n < y - \varepsilon$. Therefore, $y - \varepsilon \in U$. Consider $y + \varepsilon$. Since $y + \varepsilon \notin U$, we have that $\forall k \in \mathbb{N} \exists n_k \geq k$ such that $x_{n_k} < y + \varepsilon$ or infinite n_k such that $x_{n_k} < y + \varepsilon$.

(2) \implies (3)) We can see that, if $S_m := \{x_n : n \geq m\}$, and $L_m := \inf(S_m)$, then $L_m \leq L_{m-1}$, which is a monotone increasing sequence, which is bounded, hence is convergent to $\sup(\{L_m\}) = \lim(L_m)$. Since from (2), \exists infinite n_k such that $x_{n_k} < y + \varepsilon$, we see that $\forall m, \inf(S_m) = L_m \leq y + \varepsilon \implies \lim(L_m) \leq y + \varepsilon \forall \varepsilon > 0$. Since there exists only finite n such that $x_n < y - \varepsilon \implies \forall n \geq n_y(\varepsilon), x_n \geq y - \varepsilon$. This means that $y - \varepsilon \leq L_{n_y} \implies y - \varepsilon \leq \lim(L_m) = \sup(L_m)$. Hence $\forall \varepsilon > 0, y - \varepsilon \leq \lim(L_m) \leq y + \varepsilon$, hence $y = \lim(L_m)$.

(3) \implies (4)) Since $y = \sup(L_m) = \lim(L_m)$. For an $\varepsilon > 0$, we have an L_{n_1} such that $y - \varepsilon \leq L_{n_1}$. Since L_{n_1} is the infimum of S_{n_1} , we have $y - \varepsilon < x_n, \forall n \geq n_1$. This would mean that every subsequence converges to a point larger than $y - \varepsilon$. Therefore $y - \varepsilon < t \forall t \in S$ where S is the set of all subsequential limits (This set is non empty from Bolzano Weierstrass, and is bounded, hence has a supremum and infimum). Hence $\forall \varepsilon > 0, y - \varepsilon \leq \inf(S)$. $y + \varepsilon$ is an upper bound for $\{L_m : m \in \mathbb{N}\}$. Choose $\varepsilon = 1$ and the set S_1 . $L_1 + 1 \geq L_1$. Since L_1 is infimum of S_1 , then $\exists x_{n_1} \in S_1$ such that $L_1 \leq x_{n_1} \leq L_1 + 1$. Choose $\varepsilon = \frac{1}{2}$, and the set S_{n_1} . $\exists x_{n_2} \in S_{n_1}$ such that $L_{n_1} \leq x_{n_2} \leq L_{n_1} + \frac{1}{2}$. Having chosen $\varepsilon = \frac{1}{j}$ and the set $S_{n_{j-1}}$, we have an $x_{n_j} \in S_{n_{j-1}}$ such that

$$L_{n_{j-1}} \leq x_{n_j} \leq L_{n_{j-1}} + \frac{1}{j}$$

Notice that, by construction of our sets, $n_j > n_{j-1}$. Hence, we have a subsequence of x_n which is x_{n_j} which, from squeeze play theorem, converges to y . Therefore, $y \in S$, which means $\inf(S) \leq y$. We therefore have $\forall \varepsilon > 0, y - \varepsilon \leq \inf(S) \leq y$. This means $\inf(S) = y$.

(4) \implies (1)) Given y is the infimum of the set of all subsequential limits. Say $\alpha =$

$\liminf(x_n) := \sup(U = \{u \in \mathbb{R} : \exists n_u \in \mathbb{N} \text{ such that } \forall n \geq n_u, x_n \geq u\})$. If $z \in U$, it means that after some n_z , every $x_n \geq z$ which means every subsequence converges above z . Therefore, z is a lowerbound for the set of all subsequential limits S . $z \leq \inf(S) = y, \forall z \in U$. We can see that $\sup(U) = \alpha \leq y$ from this. Suppose $\sup(U) = \alpha < y \implies \alpha = y - \delta$ for some δ . Consider an arbitrary subsequential limit q . $\forall \varepsilon, \exists n_q(\varepsilon) \in \mathbb{N}$ such that $\forall n \in \mathbb{N}, n \geq n_q(\varepsilon)$ we have $y - \varepsilon + \delta - \delta \leq q - \varepsilon < x_n < q + \varepsilon$. $(y - \delta) - (\varepsilon - \delta) = \alpha + (\delta - \varepsilon) \leq q - \varepsilon < x_n < q + \varepsilon$. This means that $\exists n_0$ such that $\forall n \geq n_0, \alpha + (\delta - \varepsilon) < x_n$. This means that, if we choose ε smaller than δ , we would have a number larger than $\sup(U) = \alpha$ being inside U . Absurd. Hence $\alpha = y$. ■

Theorem 0.4

A bounded sequence is convergent if and only if $\limsup(x_n) = \liminf(x_n)$

Proof for Theorem.

\implies) If a bounded sequence is convergent, all its subsequences converge to the same limit x . Therefore x is both the supremum and the infimum of the set of all subsequential limits, which is also the limsup and liminf.

\impliedby) If $\limsup = \liminf$, then the set of all subsequential limits has infimum and the supremum equal. This means that the set of all subsequential limits is singleton, with $x \in S$. If x_n is bounded and all its convergent subsequences converge to x , then x_n converges to x . ■

Theorem 0.5: (A perhaps useful theorem for LimSup LimInf)

If $A + B := \{a + b : a \in A, b \in B\}$, then $\gamma = \sup(A + B) = \sup(A) + \sup(B) = \alpha + \beta$.

Proof for Theorem.

$\alpha \geq a, \forall a \in A$ and $\beta \geq b, \forall b \in B$. We hence see that $\alpha + \beta \geq a + b, \forall a \in A, b \in B$. Therefore, $\alpha + \beta \geq \gamma$.

Now consider $a + b \leq \gamma, \forall a \in A, b \in B$. This means that $\alpha + b \leq \gamma, \forall b \in B$. From here we see that $\alpha + \beta \leq \gamma$ whence we see that $\gamma = \alpha + \beta$. ■

Lemma 0.6

If α is the supremum of a set S , then $-\alpha$ is the infimum of the set $-S$ defined as

$$-S := \{-x : x \in S\}$$

Proof for Lemma

If α is the supremum, then $\alpha \geq x, \forall x \in S$ and $\alpha \leq M, \forall M$ such that $M \geq x, \forall x \in S$. This means that $-\alpha \leq -x, \forall x \in S$ and $-\alpha \geq -M, \forall -M$ such that $-M \leq -x, \forall -x \in S$. If we re-notate the whole thing we have:

$-\alpha \leq z, \forall z \in -S$ and $-\alpha \geq L, \forall L$ such that $L \leq z \forall z \in -S$. This is precisely the definition for infimum of $-S$, whence we see, we are done. ■

Recall the definitions:

$$\text{LimSup}(x_n) := \inf(U_n : U_n := \sup(\{x_n, x_{n+1} \cdots\}))$$

$$\text{LimInf}(x_n) := \sup(L_n : L_n := \inf(\{x_n, x_{n+1} \cdots\}))$$

Problem 2

Let x be $\limsup(-x_n)$.

$$\begin{aligned} x &= \inf(U_n : U_n = \sup\{-x_n, -x_{n+1} \cdots\}) \\ \implies x &= \inf(U_n : U_n = -\inf\{x_n, x_{n+1}, \cdots\}) \\ \implies x &= \inf(-\inf\{x_n, x_{n+1} \cdots\}, -\inf\{x_{n+1}, x_{n+2} \cdots\}, \cdots) \\ \implies x &= -\sup(\inf\{x_n, x_{n+1} \cdots\}, \inf\{x_{n+1}, x_{n+2} \cdots\}, \cdots) \end{aligned}$$

Whence, we are done.

Problem 3

x_n and y_n are given bounded sequences in \mathbb{R} . Consider

$$V_z := \{v \in \mathbb{R} : \exists n_v \text{ such that } \forall n \geq n_v, z_n = x_n + y_n \leq v\}$$

Then $\limsup(x_n + y_n) = \inf(V_z)$. Consider V_x and V_y , defined as $V_x := \{v \in \mathbb{R} : \exists n_v \text{ such that } \forall n \geq n_v, x_n \leq v\}$ and $V_y := \{v \in \mathbb{R} : \exists n_v \text{ such that } \forall n \geq n_v, y_n \leq v\}$. Look at $V_x + V_y := \{u + w : u \in V_x, w \in V_y\}$. This is basically $V_x + V_y = \{u + w : \exists n_u, n_w \in \mathbb{N} \text{ such that } \forall x_n \leq u \text{ and } y_l \leq w, \forall n \geq n_u, l \geq n_w\}$. Notice that $V_x + V_y$ is a subset of the set $\{u + w : \exists n_{u,w} \in \mathbb{N} \text{ such that } x_n + y_n \leq u + w, \forall n \geq n_{u,w}\}$ which is itself a subset of V_z . This means that $\inf(V_z) \leq \inf(V_x + V_y) = \inf(V_x) + \inf(V_y) \implies \limsup(x_n + y_n) \leq \limsup(x_n) + \limsup(y_n)$.

Consider $U_z := \{u \in \mathbb{R} : \exists n_u \in \mathbb{N} \text{ such that } \forall n \geq n_u, u \leq z_n = x_n + y_n\}$, $U_x := \{u \in \mathbb{R} : \exists n_u \in \mathbb{N} \text{ such that } \forall n \geq n_u, u \leq x_n\}$ and $U_y := \{u \in \mathbb{R} : \exists n_u \in \mathbb{N} \text{ such that } \forall n \geq n_u, u \leq y_n\}$. Look at $U_x + U_y := \{u + w : u \in U_x, w \in U_y\}$ which is basically $\{u + w : \exists n_u, n_w \in \mathbb{N} \text{ such that } \forall n \geq n_u, u \leq x_n, \forall q \geq n_w, w \leq y_q\}$. If $u + w$ is an element in $U_x + U_y$, then there exists n_u and n_w so that $\forall n \geq n_u$, we have $u < x_n$ and for every $q \geq n_w$, $w < y_q$, which means, after a particular integer $n_{u,w}$, $u + w < x_n + y_n$ for all $n \geq n_{u,w}$. Hence, $U_x + U_y \subseteq U_0$ where $U_0 := \{u + w : \exists n_{u,w} \in \mathbb{N} \text{ so that } u + w < x_n + y_n = z_n, \forall n \geq n_{u,w}\}$ which is itself a subset of U_z . This means that $\sup(U_x + U_y) = \sup(U_x) + \sup(U_y) \leq \sup(U_z)$ which means $\liminf(x_n) + \liminf(y_n) \leq \liminf(x_n + y_n)$.

Problem 4

Suppose $\forall n \geq N$, we have $x_n \leq y_n$. It is clear to see that for every $n \geq N$, $U_n^x = \sup(x_n, x_{n+1}, \dots) \leq U_n^y = \sup(y_n, y_{n+1}, \dots)$. We have, in other words: $U_n^x \leq U_n^y$ for all $n \geq N$. Hence, $\text{Limsup}(x_n) \leq \text{limsup}(y_n)$.

Again consider $\forall n \geq N$, $x_n \leq y_n$. This means that $\forall n \geq N$, $L_n^x = \inf(x_n, x_{n+1}, \dots) \leq y_n$. Since for a given n , we have $L_n^x \leq y_n$, and owing to the fact that L_n^x is a monotone increasing sequence, we see:

$$\begin{aligned} L_n^x &\leq y_n \\ L_n^x &\leq L_{n+1}^x \leq y_{n+1} \\ &\vdots \end{aligned}$$

Therefore, we see that $L_n^x \leq \inf\{y_n, y_{n+1}, \dots\} = L_y^x$. From here we can conclude that $\text{Liminf}(x_n) \leq \text{Limsup}(y_n)$.

Problem 5

Consider $(x_n)^{\frac{1}{n}}$ and $\frac{x_{n+1}}{x_n}$. Where x_n is a positive, bounded sequence.

Suppose that $\limsup(x_{n+1}/x_n) = L$. That means that $\inf_{k \in \mathbb{N}}(\sup_{n \geq k}(x_{n+1}/x_n) = u_k) = L$ which means that for any $\varepsilon > 0$, we have a k_0 so that $u_0 < L + \varepsilon$ which means that for every $n \geq k_0$, $x_{n+1}/x_n < L + \varepsilon$. \implies

$$\begin{aligned} x_{k_0+1}/x_{k_0} &< L + \varepsilon \\ x_{k_0+2}/x_{k_0+1} &< L + \varepsilon \\ x_{k_0+3}/x_{k_0+2} &< L + \varepsilon \\ &\vdots \\ x_{k_0+(n-k_0)}/x_{k_0+(n-k_0-1)} &< L + \varepsilon \end{aligned}$$

Multiplying throughout we get:

$$x_n < x_{k_0}(L + \varepsilon)^{n-k_0} \implies (x_n)^{1/n} < \frac{x_{k_0}}{(L + \varepsilon)^{k_0}}^{1/n} (L + \varepsilon) = \mathfrak{L}(\varepsilon, \mathbf{n})$$

We note that $\mathfrak{L}(\varepsilon, \mathbf{n})$ converges to $L + \varepsilon$ which means that for every $\varepsilon' > 0$, $\exists n_0$ so that $\forall n \geq n_0$, $L + \varepsilon - \varepsilon' < \mathfrak{L}(\varepsilon, \mathbf{n}) < L + \varepsilon + \varepsilon'$. This means that for every $\varepsilon > 0$ and $\varepsilon' > 0$, there exists n_0 so that $\forall n \geq n_0$, $(x_n)^{1/n} < L + \varepsilon + \varepsilon'$. Replacing $\varepsilon + \varepsilon'$ with a singular choice of ε we have that for every $\varepsilon > 0$, there exists n_0 so that $\sup_{n \geq n_0}(x_n^{1/n}) \leq L + \varepsilon$ which finally means that for every ε , $\limsup(x_n^{1/n}) \leq L + \varepsilon$. This would mean that $\limsup(x_n^{1/n}) \leq L = \limsup(x_{n+1}/x_n)$.

Consider A similar argument for the \liminf . Suppose $M = \liminf(x_{n+1}/x_n) = \sup_{k \in \mathbb{N}}(Q_k = \inf_{n \geq k}(x_{n+1}/x_n))$. For every $\varepsilon > 0$, $\exists Q_{k_0}$ so that $L - \varepsilon < Q_{k_0} \implies$ for every $n \geq k_0$, $L - \varepsilon < x_{n+1}/x_n$

$$L - \varepsilon < x_{k_0+1}/x_{k_0}$$

$$\begin{aligned}
L - \varepsilon &< x_{k_0+2}/x_{k_0+1} \\
&\vdots \\
L - \varepsilon &< x_{k_0+(n-k_0)}/x_{k_0+(n-k_0-1)}
\end{aligned}$$

Multiplying throughout gives us

$$\mathfrak{J}(\varepsilon, \mathbf{n}) = (L - \varepsilon) \left(\frac{x_{k_0}}{(L - \varepsilon)^{k_0}} \right)^{1/n} < (x_n)^{1/n}$$

Note that $\mathfrak{J}(\varepsilon, \mathbf{n})$ converges to $L - \varepsilon$. We can then conclude (like above) that for every $\varepsilon > 0$, there exists an n_0 so that $L - \varepsilon < (x_n)^{1/n}$ for every $n \geq n_0$. This means that for every $\varepsilon > 0$, there exists an n_0 so that $L - \varepsilon < \inf_{n \geq n_0} (x_n^{1/n})$ which directly gives us that for every $\varepsilon > 0$, $L - \varepsilon < \liminf (x_n^{1/n}) \implies \liminf (x_{n+1}/x_n) \leq \liminf (x_n^{1/n})$.

Since $\liminf (x_{n+1}/x_n) \leq \liminf (x_n^{1/n}) \leq \limsup (x_n^{1/n}) \leq \limsup (x_{n+1}/x_n)$, if x_{n+1}/x_n converges, its \limsup and \liminf are both the same, which forces $x_n^{1/n}$ sequence's \limsup and \liminf to be the same, which makes it convergent (and to the same limit).

ASSIGNMENT-2

Problem 2

c) Let

$$\limsup(A_n) := \cap_{n=1}^{\infty} (\cup_{k=n}^{\infty} A_k)$$

which means $\cap_{n=1}^{\infty} (C_n = \{x \in X : \exists n' \geq n \text{ such that } x \in A_{n'}\})$. $\limsup(A_n) = \{x \in X : x \in C_j, \forall j \in \mathbb{N}\}$ which means $\{x \in X : \exists n_1 \geq 1 \text{ so that } x \in A_{n_1}; \exists n_2 \geq 2 \text{ so that } x \in A_{n_2}; \exists n_3 \geq 3 \text{ so that } x \in A_{n_3} \dots\}$ which is equivalent to saying there exists infinitely many n so that $x \in A_n$ (since we do have n_1, n_2, \dots , an infinite collection of natural numbers so that $x \in A_{n_j}$).

d) Let

$$\liminf(A_n) := \cup_{n=1}^{\infty} (\cap_{k=n}^{\infty} A_k)$$

which gives us $\cup_{n=1}^{\infty} (D_n = \{x \in X : x \in A_k, \forall k \geq n\})$ which gives us $\liminf(A_n) = \{x \in X : \exists j \in \mathbb{N} \text{ so that } x \in D_j\}$ which means $\{x \in X : \exists j \in \mathbb{N} \text{ such that } \forall n \geq j, x \in A_n\}$ which is equivalent to saying that there are only at most finite possible integers n so that $x \notin A_n$

a) Note that, from (c) and (d), we have a characterisation of $\limsup(A_n)$ as the set of all $x \in X$ so that there are infinitely many n so that $x \in A_n$, and a characterisation of $\liminf(A_n)$ as the set of all $x \in X$ so that there are utmost finite n so that $x \notin A_n$ which means that for $x \in \liminf(A_n)$, after some n_0 , every $n \geq n_0$ is so that $x \in A_n$, which makes $\liminf(A_n)$ a subset of $\limsup(A_n)$. Hence $\liminf(A_n)$

b) $\liminf((A_n)^C)$ is the set of all $x \in X$ so that there are at most finite n so that $x \notin A_n^C$ which means there are at most finite n so that $x \in A_n$.

Consider $(\limsup(A_n))^C$ which is the complement of the set of all $x \in X$ so that there are

infinitely many n so that $x \in A_n$, or more precisely, $\forall k \in \mathbb{N}, \exists n_k \geq k$ so that $x \in A_{n_k}$. The complement would be the negation of the previous statement which amounts to: $x \in X$ so that $\exists k \in \mathbb{N}$ so that $\forall n \geq k, x \notin A_{n_k}$ which again is equivalent to saying there are at most finite n so that $x \in A_n$. Hence $\liminf(A_n^C) = (\limsup(A_n))^C$

Problem 3

$d(x, y) = \sqrt{|x - y|} = 0$ if and only if $x = y$. Moreover, $d(x, y) \geq 0, \forall x, y \in \mathbb{R}$.
 $d(x, y) = \sqrt{|x - y|} \leq \sqrt{|x - z + z - y|} \leq \sqrt{|x - z| + |z - y|} \leq \sqrt{|x - z|} + \sqrt{|z - y|} = d(x, z) + d(z, y)$ which proves the triangle criteria.

Problem 4

i) In the extended real line, $\overline{\mathbb{R}}$, we append the points $\infty, -\infty$ to \mathbb{R} . $d(x, y) := |\arctan(x) - \arctan(y)|$. Obviously, $d(x, y) \geq 0$ (from the absolute value there). $d(x, y) = 0 \implies |\arctan(x) - \arctan(y)| = 0 \implies \arctan(x) = \arctan(y)$ which means $x = y$ (since \arctan is left invertible), hence $d(x, y) = 0 \iff x = y$.

Next we check the triangle inequality: consider $d(x, y) = |\arctan(x) - \arctan(y)| \leq |\arctan(x) - \arctan(z)| + |\arctan(z) - \arctan(y)| = d(x, z) + d(y, z)$.

ii) Consider $d(x, y) = |f(x) - f(y)|$ given by

$$f(x) = \begin{cases} |x|/1 + |x| & \text{if } x \text{ is finite} \\ 1 & \text{if } x = \infty \\ -1 & \text{if } x = -\infty \end{cases}$$

Consider $d(x, y) = 0$ which means that $|f(x) - f(y)| = 0$ which gives $f(x) = f(y)$. Since f is injective, $d(x, y) = 0 \iff x = y$. Consider the case where x and y are finite (and $f(z)$), $d(x, y) = |f(x) - f(z) + f(z) - f(y)| \leq d(x, z) + d(y, z)$. If x, y are finite but z is infinite, then $d(x, y) < \infty$ will certainly hold. If any $x = \infty$ and $y = \infty$, then positivity will take care of triangle inequality. If $x = \infty$ but $y = -\infty$, then $d(x, y) = \infty$ but $d(x, z) = \infty$ and $d(y, z) = \infty$ (from the absolute value condition). Hence in all cases triangle inequality is satisfied.

Problem 5

i) Let $f : X \rightarrow X$ be an injective map. $D_1(x, y) := d(f(x), f(y))$. If $x = y$, then $f(x) = f(y)$ obviously, which means $d(f(x), f(y)) = D_1(x, y) = 0$. If $D_1(x, y) = 0$, that means $d(f(x), f(y)) = 0$ which happens only if $f(x) = f(y)$ or $x = y$. Let $D_1(x, y) = d(f(x), f(y)) \leq d(f(x), f(z)) + d(f(z), f(y)) = D_1(x, z) + D_1(y, z)$ which proves triangle inequality. Hence (X, D_1) is a metric space.

ii) Suppose A, B is a partition of X .

$$D_2(x, y) := \begin{cases} d(x, y) + 1 & \text{if exactly one of } x \text{ or } y \text{ is in } A \\ d(x, y) & \text{else} \end{cases}$$

Consider $D_2(x, y) = 0$. If x, y are both in the same partition, then they must be the same. If they are not in the same partition, then they cannot have 0 distance. Hence $D_2(x, y) = 0 \iff x = y$. If x and y are in the same space, and z is a point in the same space, then $D_2(x, y) \leq D_2(x, z) + D_2(y, z)$ trivially. If z is not the same space (as x and y), then $D_2(x, z) = d(x, z) + 1$ and $D_2(y, z) = d(y, z) + 1$ which gives $D_2(x, y) = d(x, y) \leq d(x, z) + d(y, z) + 2$ which is also clear from the original metric. If say x and y are from different partitions so that $D_2(x, y) = d(x, y) + 1$. Obviously another element z must be such that either $D_2(x, z) = d(x, z)$ (in which case $D_2(y, z) = 1 + d(y, z)$) or $D_2(y, z) = d(y, z)$ (whence $D_2(x, z) = d(x, z) + 1$). Then $D_2(x, y) = d(x, y) + 1 \leq d(x, z) + d(y, z) + 1$. Depending on where z is, the bracketing can be done such that $D_2(x, y) \leq D_2(x, z) + D_2(y, z)$, which proves triangle.

iii) Define the map

$$f(x) \begin{cases} x + 1 & \text{if } x \in \mathbb{R}^+ \\ x & \text{else} \end{cases}$$

Obviously, this map is injective since $f(x) = f(y)$ for x, y in the same side would mean $x = y$. If x and y are on different sides, i.e, say x is positive but y negative, then $f(x) = x + 1 > 0$ while $f(y) = y \leq 0$.

Consider $D_1(x, y) = |f(x) - f(y)|$ for points x and y on the same side. This is simply just $|x - y|$ which in this case is the same as $D_2(x, y)$. Suppose $x > 0$ and $y \leq 0$. This means that $d(x, y) = |f(x) - f(y)| = |x + 1 - y| = |x - y| + 1$ (since it is positive) which is the same as $D_2(x, y)$ in such a case. Due to symmetry of $||$, we needn't check the $y > 0$ case. Hence, for this injective function, D_1 is the same as D_2 .

Problem 6

Let $X := \{x, y\}$. Non-negotiable's are $d(x, x) = d(y, y) = 0$. The only choice we have is $d(x, y) = s$. s can be any positive (incl 0) real number. The metrics, though, are all *equivalent*.

Problem 7

Let X be the set of all 3 - *tuples* consisting of 0s and 1s.

$$d(x, y) := \text{number of places where } x \text{ and } y \text{ are different}$$

. Consider $d(x, y) = 0$. That means no place is different $\implies x = y$. Also obvious that $d(x, y) = d(y, x)$. (Positivity is also obvious from definition). If $x = (x_1, x_2, x_3)$ and $y = (y_1, y_2, y_3)$ with $x_i, y_j \in \{0, 1\}$, then we can write a formula for the hamming distance: $d(x, y) := \sum_{i=1}^3 |x_i - y_i|$. This exactly captures the definition of the hamming distance. From here it is easy to see that Hamming metric is a special case of the Manhattan metric. $d(x, y) = \sum_{i=1}^3 |x_i - z_i| + \sum_{i=1}^3 |z_i - y_i| \leq \sum_{i=1}^3 |x_i - z_i| + \sum_{i=1}^3 |z_i - y_i| = d(x, z) + d(y, z)$ which proves triangle.

Problem 8

d does not define a metric on \mathbb{R}^2 since consider $(x_1, 0)$ and $(y_1, 0)$, whose distance is 0. This is, though, a pseudometric, since it obeys all the other properties (inherited from $||$).

Assignment 3

Problem 2:

Say X is a metric space. $R(x, \varepsilon) := \{y \in X : d(y, x) > \varepsilon\}$. Consider an arbitrary point $z \in R(x, \varepsilon)$ whose distance from x is $d(x, z) = t_{xz} > \varepsilon$. Which means $t_{xz} - \varepsilon > 0$. From density theorem, choose a real number r so that $t_{xz} - \varepsilon > r > 0$. Consider the ball $B(r, z)$ around z and a point q in this ball so that $d(q, z) < r$. Is $q \in R(x, \varepsilon)$? $d(x, z) \leq d(q, x) + d(q, z) \implies t_{xz} \leq d(q, x) + d(q, z) < d(q, z) + r$ which gives $\varepsilon < t_{xz} - r < d(q, z)$. Hence, $q \in R(x, \varepsilon)$. Hence, there is an r -ball, for every point in $R(\varepsilon, x)$ so that this ball is fully contained.

Problem 3

Say $x_n \rightarrow x$ and $x_n \rightarrow y$ which means $(\forall \varepsilon > 0)(\exists n_0 \in \mathbb{N})(\forall n \in \mathbb{N})((n \geq n_0) \implies d(x_n, x) < \varepsilon/2)$

and $(\forall \varepsilon > 0)(\exists n'_0 \in \mathbb{N})(\forall n \in \mathbb{N})((n \geq n'_0) \implies d(x_n, y) < \varepsilon/2)$

This means that $\forall \varepsilon, \exists q = \max\{n_0, n'_0\}$ so that $\forall n \geq q$ $d(x, y) \leq d(x_n, y) + d(x_n, x) < \varepsilon$. This means that $x = y$.

Problem 4

Let $\{X_1, d_1\}, \{X_2, d_2\} \cdots \{X_n, d_n\}$ be n metric spaces. $x = (x_1, x_2 \cdots, x_n)$ and $y = (y_1, y_2 \cdots, y_n)$ are points in $X = \prod_{i=1}^n X_i$.

i) $d_1(x, y) := \max\{d_i(x_i, y_i) : i \leq n\}$. Say $x = y$, that means $d_i(x_i, y_i) = 0$ for every i which makes $d_1(x, y) = 0$. Consider $d_1(x, y) = 0$. That means $\max\{d_i(x_i, y_i) : i \leq n\} = 0$ which means that every $d_i(x_i, y_i) = 0$ but this happens if and only if $x_i = y_i$, hence we have that $d_1(x, y) = 0 \iff x = y$. Symmetry is clear from the positivity of d_i for every i . Consider $d_i(x_i, y_i) \leq d_i(x_i, z_i) + d_i(y_i, z_i)$ for every $i \leq n$. This means that $d_i(x_i, y_i) \leq \max\{d_i(x_i, z_i) + d_i(z_i, y_i) : i \leq n\} \leq \max\{d_i(x_i, z_i)\} + \max\{d_i(z_i, y_i)\}$. This immediately gives us $\max\{d_i(x_i, y_i)\} \leq \max\{d_i(z_i, x_i)\} + \max\{d_i(z_i, y_i)\} \implies d_1(x, y) \leq d_1(x, z) + d_1(y, z)$. Hence, X, d_1 forms a metric space.

ii) $d_2(x, y) = \sum_{i=1}^n d_i(x_i, y_i)$. Say $d_2(x, y) = 0$. That means that individually $d_i(x_i, y_i) = 0 \iff x_i = y_i$ which makes $x = y$. It is clear that if $x = y$, $d_2(x, y) = 0$. Positivity is also obvious since it is the sum of positive numbers. Consider $d_2(x, y) = \sum_{i=1}^n d_i(x_i, y_i) \leq \sum_{i=1}^n d_i(x_i, z_i) + \sum_{i=1}^n d_i(z_i, y_i) \implies d_2(x, y) \leq d_2(x, z) + d_2(y, z)$. Hence, X, d_2 is a metric space.

iii) $d_3(x, y) := (\sum_{i=1}^n d_i(x_i, y_i)^2)^{1/2}$. Again, positivity and $d_3(x, y) = 0 \iff x = y$ is obvious. $d_3(x, y) := [\sum_{i=1}^n (d_i(x_i, y_i)^2)]^{1/2}$. Note that $d_i(x_i, y_i) \leq d_i(x_i, z_i) + d_i(y_i, z_i)$ gives us

$d_i(x_i, y_i)^2 \leq (d_i(x_i, z_i) + d_i(z_i, y_i))^2$ which implies $[\sum_{i=1}^n (d_i(x_i, y_i))^2]^{1/2} \leq [\sum_{i=1}^n (d_i(x_i, z_i) + d_i(z_i, y_i))^2]^{1/2}$. From minkowski inequality, we can split the inner sum further to get $[\sum_{i=1}^n (d_i(x_i, y_i))^2]^{1/2} \leq [\sum_{i=1}^n (d_i(x_i, z_i))^2]^{1/2} + [\sum_{i=1}^n (d_i(z_i, y_i))^2]^{1/2}$ which gives us $d_3(x, y) \leq d_3(x, z) + d_3(z, y)$.

Problem 5

$$d_1(x, y) := \max\{d_i(x_i, y_i) : i \leq n\}$$

$$d_2(x, y) := \sum_{i=1}^n d_i(x_i, y_i)$$

$$d_3(x, y) := \left(\sum_{i=1}^n (d_i(x_i, y_i))^2\right)^{\frac{1}{2}}$$

Obviously, $d_1(x, y) = \max\{d_i(x_i, y_i)\} \leq d_2(x, y)$ and $d_3(x, y)$.

lemma: $\sqrt{|x_1|^2 + |x_2|^2 \cdots + |x_n|^2} \leq |x_1| + |x_2| \cdots + |x_n|$ for any real numbers $x_1, x_2 \cdots x_n$.

Proof. for $n = 1$, quite obvious. Assume for n the above fact. Consider

$$\begin{aligned} & \sqrt{(\sqrt{|x_1|^2 + |x_2|^2 \cdots + |x_n|^2})^2 + |x_{n+1}|^2} \\ & \leq \sqrt{|x_1|^2 + |x_2|^2 \cdots + |x_n|^2} + |x_{n+1}| \leq |x_1| + |x_2| \cdots + |x_n| + |x_{n+1}| \end{aligned}$$

□

From this lemma, we have that

$$\left(\sum_{i=1}^n d_i(x_i, y_i)^2\right)^{1/2} \leq \sum_{i=1}^n d_i(x_i, y_i)$$

which means for every x, y , $d_3(x, y) \leq d_2(x, y)$. We now have the hierarchy: $d_1 \leq d_3 \leq d_2$.

Consider $d_i(x_i, y_i)$ for arbitrary x, y . $d_i(x_i, y_i) \leq \max\{d_i(x_i, y_i) : i \leq n\}$ which means $\sum_{i=1}^n d_i(x_i, y_i) \leq \sum_{i=1}^n \max\{d_i(x_i, y_i) : i \leq n\} = nd_1(x, y)$ which completes the proof.

Problem 6:

i) Let $x \in X$, $x = (x_1, x_2 \cdots x_n)$. Consider the d_1 metric $d_1(x, y) = \max\{d_i(x_i, y_i) : i \leq n\}$. $B_r(x) := \{z \in X : d_1(x, z) < r\}$ or $B_r(x) := \{z \in X : \max\{d_i(x_i, z_i) : i \leq n\} < r\}$ which means that for every $i \leq n$, $d_i(x_i, z_i) < r$ which means that $z_i \in B_r(x_i)$ for every n . This means that $B_r(x) \subseteq \prod_{i=1}^n B_r(x_i)$. Consider a point q in $\prod_{i=1}^n B_r(x_i)$ which means $q = (q_1, q_2 \cdots q_n)$ where $q_j \in B_r(x_j)$ which means $d_j(q_j, x_j) < r$ for every $j \leq n$ which gives us $\max\{d_j(q_j, x_j) : j \leq n\} < r$ which means $d_1(q, x) < r$. This means $B_r(x) = \prod_{i=1}^n B_r(x_i)$

ii) Let $A_i \subseteq X_i$ for all $i \leq n$. Consider $A = \prod_{i=1}^n A_i \subseteq X$. $A^o := \{z \in X : \exists \varepsilon_z \text{ such that } B_{\varepsilon_z}(z) \subseteq A\}$ which translates to: z is a point of A^o if there exists ε_z so that $\prod_{i=1}^n B_{\varepsilon_z}(z_i) \subseteq \prod_{i=1}^n A_i$. We want that, for any arbitrary point $q = (q_1, q_2 \cdots q_n)$ such that $q_j \in B_{\varepsilon_z}(z_j)$, q must be in A which is equivalent to saying q_j must be in A_j for all $j \leq n$. This means that there exists an ε_z so that $B_{\varepsilon_z}(z_j) \subseteq A_j$. This would make z_j a part of A_j^o . Therefore, if z is any point in the interior of A , then each coordinate is a point of the interior of A_j which translates to $A^o \subseteq \prod_{i=1}^n A_i^o$. Consider $s = (s_1, s_2 \cdots s_n)$ a point in $\prod_{i=1}^n A_i^o$. This means that s_j is a point in A_j^o for every $j \leq n$. This means that there exists a ε_j ball around s_j that is fully contained in A_j , for every $j \leq n$. Find the minima $\varepsilon = \min\{\varepsilon_j : j \leq n\}$ (**). This means that for every s_j , there exists an ε -ball around s_j that is fully contained in A_j . $B_\varepsilon(s_j) \subseteq A_j$ which means that $B_\varepsilon(s) \subseteq A$. Therefore, s , which was initially thought of as a point of $\prod_{i=1}^n A_i^o$, is such that there exists an ε so that $B_\varepsilon(s) \subseteq A$, which means s is also in A^o . Hence, $A^o = (\prod_{i=1}^n A_i)^o = \prod_{i=1}^n A_i^o$.

Remark.

Note that (**) tells us that this theorem may fail if the set product is infinite, i.e, we have sequences of the kind $q = (q_1, q_2 \cdots)$ where $q_j \in X_j : j \in \mathbb{N}$. This is because (**) asserts that we are able to find a minima given a finite set of points. But if we are given an infinite set of points, we may not be able to find a minima that is strictly positive. (thinkingg of an example where this fails)

iii) Let G_i be open in X_i which means that for every point $z_i \in G_i$, there exists ε_{z_i} so that $B_{\varepsilon_{z_i}}(z_i) \subseteq G_i$. Consider $q \in \prod_{i=1}^n G_i$ which means that $q_j \in G_j$ for every $j \leq n$. This means that there exists ε_{q_j} so that $B_{\varepsilon_{q_j}}(q_j) \subseteq G_j$. Collect the minimum of these ε_{q_j} , i.e, $\varepsilon_q := \min\{\varepsilon_{q_j} : j \leq n\}$. For all $j \leq n$, we have that $B_{\varepsilon_q}(q_j) \subseteq G_j$. This would mean that $\prod_{i=1}^n B_{\varepsilon_q}(q_j) = B_{\varepsilon_q}(q) \subseteq \prod_{i=1}^n G_i$, which means that if q is in $\prod_{i=1}^n G_i$, then there exists a ε_q so that $B_{\varepsilon_q}(q) \subseteq \prod_{i=1}^n G_i$. Hence, $\prod_{i=1}^n G_i$ is open in X .

ASSIGNMENT-4

Problem 2:

\implies) Let x_n be a sequence in X convergent to x (known to be unique). This means that $\forall \varepsilon > 0, \exists n_0 \in \mathbb{N}$ so that $\forall n \in \mathbb{N}$, if $n \geq n_0$, then $d(x_n, x) < \varepsilon$. More specifically, if x_{n_k} is a subsequence of x_n , then we have that $k \leq n_k$ and $n_1 < n_2 < \cdots$ which means that for a given $\varepsilon > 0, \exists n_0$ so that $\forall n_k \geq n_0, d(x_{n_k}, x) < \varepsilon$ which means that every subsequence converges to x . (To see this more clearly, note if x_n converges to x , the set $\{x_n : n \in \mathbb{N}\}$ has only one limit point, that is x itself. So every subsequence of x_n converges to x). This implies, in turn, that every subsequence of a subsequence (which is yet again a subsequence) converges to x .

\impliedby) Suppose every subsequence of x_n has a subsequence that converges to x , but $x_n \not\rightarrow x$. This means that there exists an $\varepsilon > 0$ so that for every $k \in \mathbb{N}$, there exists an $n_k \geq k$ so that $d(x_{n_k}, x) \geq \varepsilon$. We can take these $n_1, n_2 \cdots$ to generate a subsequence $x_{n_1}, x_{n_2} \cdots$ such that $d(x_{n_k}, x) \geq \varepsilon$ for every $k \in \mathbb{N}$ (*). This subsequence has a further subsequence that converges to x . This means that for a small neighbourhood around x , there exists infinite points of x_{n_k} ,

but this contradicts (*).

Problem 3:

Definition: $\text{diam}(A) := \sup\{d(x, y) : x \in A, y \in A\}$, if it is finite.

We are told $A \cap B \neq \emptyset$. $\text{diam}(A \cup B) := \sup\{d(x, y) : x \in A \cup B, y \in A \cup B\}$.

Suppose contrary to hypothesis, $\text{diam}(A \cup B) := \sup\{d(x, y) : x, y \in A \cup B\} > \text{diam}(A) + \text{diam}(B) = \sup\{d(p, q) : p, q \in A\} + \sup\{d(a, b) : a, b \in B\}$. This means that there exists $x_0, y_0 \in A \cup B$ so that $d(x_0, y_0) > \sup\{d(p, q) : p, q \in A\} + \sup\{d(a, b) : a, b \in B\}$. If x_0 and y_0 belong, both, to either A or B , then it clearly is absurd. So one is in A and the other in B . without loss of generality assume $x_0 \in A$ and $y_0 \in B$. Choose $z \in A \cap B$, and apply triangle inequality to get $d(x_0, z) + d(z, y_0) \geq d(x_0, y_0) > \sup\{d(p, q) : p, q \in A\} + \sup\{d(a, b) : a, b \in B\}$ (**). In (**), clearly $d(x_0, z)$ is a distance between points in A alone, and $d(z, y_0)$ is a distance between points in B alone. From here it is clear that this is absurd. Hence:

$$\text{diam}(A \cup B) \leq \text{diam}(A) + \text{diam}(B)$$

Strict inequality is possible if we simply consider closed balls in \mathbb{R} . Consider $[-1, 1/2]$ and $[-1/2, 1]$. $\text{Diam}(A \cup B) = 2$ but $\text{diam}(A) + \text{diam}(B) = 3$.

Problem 4:

Lemma:

$$(A^\circ)^C = \overline{(A^c)}$$

Proof. A° is the largest open set that is contained in A . $A^\circ \subset A \implies A^C \subseteq (A^\circ)^C$ where $(A^\circ)^C$ is a closed set. Closure of A^C , which is $\overline{A^c}$ is the smallest closed set that contains A^c . Hence, $\overline{A^c} \subseteq (A^\circ)^C$ (1). We know $A^c \subseteq \overline{A^c}$ which means $(\overline{A^c})^c \subseteq A$ where $(\overline{A^c})^c$ is an open set. Therefore, $(\overline{A^c})^c \subseteq A^\circ \implies (A^\circ)^C \subseteq \overline{A^c}$ (2). From (1) and (2) we get:

$$(A^\circ)^C = \overline{(A^c)}$$

□

a) $\overline{A} = \overline{(A^c)^C} = ((A^c)^0)^c$. Since $(A^\circ)^c = \overline{(A^c)}$, taking complements on both sides give $A^\circ = (\overline{A^c})^C$

b) $\partial(A) := \overline{A} \setminus A^\circ$ and $\partial(A^c) := \overline{A^c} \setminus (A^c)^0 = (A^\circ)^C \setminus \overline{A^c} =$ set of all elements *not in* A° and in \overline{A} . Hence, $\partial A = \partial A^c$

c) $\partial A := \overline{A} \setminus A^\circ$ which is the set of all elements in the closure, but not in the interior. Therefore, $\partial(A) \cup A^\circ = \overline{A} \setminus A^\circ \cup A^\circ = \overline{A}$

d) We showed that $\partial(A) \cup (A^0) = \overline{A}$. We have $(A^c)^0 \cup \overline{A} = (\overline{A})^c \cup \overline{A}$ (from the results of (a)) which is nothing but X .

e) If A is closed, $\overline{A} = A$. From part (c) we showed that $A = \overline{A} = \partial A \cup A^0$. Hence, $\partial(A) \subseteq A$. Suppose conversely, that $\partial(A) \subseteq A$. This means $\partial(A) \cup (A^0) \subset A$ which means $\overline{A} \subset A$. Hence, $A = \overline{A}$, or equivalently, A is closed.

Problem 5:

Lemma: Every open set in \mathbb{R} is a atmost countable union of disjoint open intervals.

Proof. We note that \mathbb{R} is separable because \mathbb{Q} is a dense set in \mathbb{R} that is countable. Consider any open set G in \mathbb{R} . For every point x in G , there exists an ε_x so that $(x - \varepsilon_x, x + \varepsilon_x) \subseteq G$. Collect all the rational points in G (which is non empty) as an enumeration $\{r_1, r_2, \dots\}$. Note that if there are no rational points in an open set, that means that the open set is empty. To see this, consider a point in the open set, which has an epsilon neighbourhood within the open set that contains no rational points. from density, this is absurd. Hence every non empty open set has rational points. Let ε_j be such that $B_{\varepsilon_j}(r_j) \subset G$. Collect all such $B_{\varepsilon_j}(r_j)$. Note that \square