# Chapter 4

# Notes on Chapter 4

## Topological Spaces

This section will roughly follow Munkres text on Geeneral Topology, in particular we hope to cover Chapters 2, 3, 4 and 9. The rest of the Chapters should be covered proper by the subsequent section.

**Definition 1.1** *Let* $\mathbf{X}$ *be a non-empty set. A topology* $\mathcal{T}$ *on* $\mathbf{X}$*, sometimes denoted by* $\mathcal{T}_{\mathbf{X}}$ *is a family of subsets of* $\mathbf{X}$*,*

- $\{\varnothing, \mathbf{X}\} \subseteq \mathcal{T}$*,*
- *If* $U_1$ *and* $U_2$ *are elements of* $\mathcal{T}$*, so is their intersection.*
- *If* $\{U_\alpha\}$ *is an arbitrary family of sets in* $\mathcal{T}$*, their union is also contained in* $\mathcal{T}$ *as an element.*

*We call the elements of* $\mathcal{T}$ *open sets. The complements of elements in* $\mathcal{T}$ *are closed sets.*

## Basis of a Topology

**Definition 2.1** *A basis $\mathbb{B}$ is a family of subsets of $\mathbf{X}$, that satisfies:*

- *Every $x \in \mathbf{X}$ belongs (as an element) in some $V \in \mathbb{B}$.*
- *If $B_1$ and $B_2$ are basis elements, such that their intersection is non-empty. Then every $x \in B_1 \cap B_2$ induces a $B_3 \in \mathbb{B}$ with*

$$x \in B_3 \subseteq B_1 \cap B_2$$

*This roughly means a basis is 'finitely' fine at every point in $x$.*

If $\mathbb{B}$ is a basis, it 'generates' a topology $\mathcal{T}$ through

$$\mathcal{T} = \left\{ U \subseteq \mathbf{X},\ \forall x \in U,\ x \in B \subseteq U \text{ for some } B \in \mathbb{B} \right\} \tag{1}$$

Notice this is equivlaent to $\mathcal{T}$ is the collection of all unions of basis elements in $\mathbb{B}$.

**Proposition 2.1.** *Let $\mathbb{B}$ be a basis as defined in Definition 2.1, then $\mathcal{T}$ as defined in Equation (1) is a valid topology on $\mathbf{X}$. And every member of $\mathcal{T}$ is and is precisely the union of elements in $\mathbb{B}$.*

*Proof.* Every point in $\mathbf{X}$ belongs in some basis element, so $\mathbf{X} \in \mathcal{T}$, so does $\varnothing$. Next, if $U_1$ and $U_2$ are in $\mathcal{T}$, then

$$\begin{cases} x \in U_1 \rightsquigarrow x \in B_1 \subseteq U_1 \\ x \in U_2 \rightsquigarrow x \in B_2 \subseteq U_2 \end{cases} \implies x \in B_3 \subseteq B_1 \cap B_2 \subseteq U_1 \cap U_2$$

for some $B_3 \in \mathbb{B}$, so $\mathcal{T}$ is closed under finite intersections (perhaps after a standard induction argument).

If $\{U_\alpha\} \subseteq \mathcal{T}$, and $x$ belongs in the union of all $U_\alpha$, then $x \in B_\alpha \subseteq U_\alpha$, which is a subset of the entire union. So the union over $U_\alpha$ is again contained in $\mathcal{T}$, and $\mathcal{T}$ is a topology on $\mathbf{X}$.

It is worth noting that $\mathbb{B} \subseteq \mathcal{T}$. Finally, if $U \in \mathcal{T}$,

$$U = \bigcup_{x \in U} B_x$$

where $B_x$ is the basis element taken to satisfy $x \in B_x \subseteq U$. Every point in $U$ is included in some $B_x$, and hence is included in the union. For the reverse inclusion, notice the union of subsets of $U$ is again a subset of $U$.

Now, if $E \subseteq \mathbf{X}$ is the union of basis elements in $\mathbb{B}$, if $E$ is non-empty, then every point $x \in E$ belongs in some $B_x$. Recycling the previous argument, and we see that $E$ is open in $\mathcal{T}$. If $E$ is empty, we define the 'union' of no sets as the empty set. So $\mathcal{T}$ is precisely the collection of all unions of basis elements $\mathbb{B}$. ■

We are now in a position to compare the relative 'fineness' of topologies.

**Definition 2.2** *If $\mathcal{T}'$ and $\mathcal{T}$ are both topologies on some non-empty set* $\mathbf{X}$. *We say $\mathcal{T}'$ is finer than $\mathcal{T}$, or $\mathcal{T}$ is coarser than $\mathcal{T}'$ if*

$$\mathcal{T}' \supseteq \mathcal{T}$$

**Proposition 2.2.** *If $\mathbb{B}$ and $\mathbb{B}'$ are bases for $\mathcal{T}'$ and $\mathcal{T}$, the following are equivalent:*

- *$\mathcal{T}'$ is finer than $\mathcal{T}$,*
- *If $B$ is an arbitrary basis element in $\mathbb{B}$, then every point $x \in B$ induces a basis element in $\mathbb{B}'$ with*

$$x \in \mathbb{B}' \subseteq \mathbb{B}$$

*Proof.* Suppose $\mathcal{T}'$ is finer than $\mathcal{T}$. Notice $\mathbb{B} \subseteq \mathcal{T}'$ as well. By Equation (1), each $x \in B$ induces a $B' \in \mathbb{B}'$

$$x \in B' \subseteq B$$

Conversely, fix any open set $U \in \mathcal{T}$, and for each $x \in U$,

$$x \in B' \subseteq B \subseteq U$$

Applying Definition 2.1 tells us $U$ is open in $\mathcal{T}'$. ■

The last of the big three 'generating' definitions for topologies will be the sub-basis. It simply means the first condition (but not necessarily) the second, is satisfied in Definition 2.1

**Definition 2.3** *A sub-basis $S \in \mathbb{P}(\mathbf{X})$ is a family of subsets of $\mathbf{X}$ that satisfies one property. Any point $x$ in $\mathbf{X}$ belongs to at least one member of $S$.*

A sub-basis can be upgraded to a basis by collecting all of its finite intersections.

**Proposition 2.3.** *Let $S$ be a sub-basis of $\mathbf{X}$, then the collection of all finite intersections of $S$ forms a basis $\mathbb{B}$ of $\mathbf{X}$.*

*Proof.* Every point in $\mathbf{X}$ lies in some element of $S$, hence in some element of $\mathbb{B}$. The second basis property is immediate, since $\mathbb{B}$ is closed under finite intersections. ■

## Product Topology

We will start with products of a finite collection of topological spaces.

**Definition 3.1** *Let* $(\mathbf{X}, \mathcal{T}_\mathbf{X})$ *and* $(\mathbf{Y}, \mathcal{T}_\mathbf{Y})$ *be topological spaces. The product topology (denoted by* $\mathcal{T}_{\mathbf{X}\times\mathbf{Y}}$*) on* $X \times Y$ *is defined as the topology generated by the basis*

$$\mathbb{B}_{\mathbf{X}\times\mathbf{Y}} = \left\{U \times V,\ (U, V) \in \mathcal{T}_\mathbf{X} \times \mathcal{T}_\mathbf{Y}\right\} \tag{2}$$

Since bases are easier to describe than topologies, we have the following statement concerning the basis of the product topology.

**Proposition 3.1.** *If* $\mathbb{B}_\mathbf{X}$ *and* $\mathbb{B}_\mathbf{Y}$ *are bases for* $\mathcal{T}_\mathbf{X}$ *and* $\mathcal{T}_\mathbf{Y}$*, then the product topology (as described in Definition 3.1) is also generated by*

$$\mathcal{M} = \left\{U \times V,\ (U, V) \in \mathbb{B}_\mathbf{X} \times \mathbb{B}_\mathbf{Y}\right\} \tag{3}$$

*Proof.* We will introduce (and use) the technique of 'double inclusion' by proving that the topologies generated are both finer than the other. Let us denote the topology generated by $\mathcal{M}$ in Equation (3) by $\mathcal{T}_\mathcal{M}$.

Since $\mathbb{B}_\mathbf{X} \times \mathbb{B}_\mathbf{Y} \subseteq \mathcal{T}_\mathbf{X} \times \mathcal{T}_\mathbf{Y}$, if $U \times V \in \mathcal{M}$ as in Equation (3), then we can pick the same 'open rectangle' again. We trivially have

$$x \in \underbrace{U \times V}_{\text{member of } \mathcal{T}_\mathbf{X}\times\mathcal{T}_\mathbf{Y}} \subseteq U \times V$$

and by WTS 2.2, $\mathcal{T}_{\mathbf{X}\times\mathbf{Y}}$ is finer than $\mathcal{T}_\mathcal{M}$.

Fix any set $U \times V \in \mathbb{B}_{\mathbf{X}\times\mathbf{Y}}$, and if $(p, q) \in U \times V$, each coordinate induces basis elements from $\mathbb{B}_\mathbf{X}$ and $By$, more precisely:

$$\begin{cases} p \in U \implies p \in \text{Basis element of } \mathbb{B}_\mathbf{X} \subseteq U \\ q \in V \implies q \in \text{Basis element of } \mathbb{B}_\mathbf{Y} \subseteq V \end{cases} \implies (p, q) \in \underbrace{}_{\text{in } \mathbb{B}_\mathbf{X}} \times \underbrace{}_{\text{in } \mathbb{B}_\mathbf{Y}} \subseteq U \times V$$

by WTS 2.2, $\mathcal{T}_\mathcal{M}$ is finer than $\mathcal{T}_{\mathbf{X}\times\mathbf{Y}}$ and $\mathcal{T}_{\mathbf{X}\times\mathbf{Y}} = \mathcal{T}_\mathcal{M}$. ∎

The Cartesian Product of an arbitrary family of topological spaces, if equipped with the product topology, preserves a lot of the structure. If $\{X_\alpha\}_{\alpha \in A}$ is a family of topological spaces which are ____, then $\prod X_\alpha$ is ____. Replace ____ with:

1. Hausdorff, (Folland)
2. Regular,
3. Connected,
4. First countable, if $A$ is countable,
5. Second countable, if $A$ is countable,
6. Compact (Tynchonoff, see Folland)

We will discuss Quotient Maps and the Quotient topology here.

Product Topology

## Connectedness

**Definition 4.1** *A topological space* $\mathbf{X}$ *is connected iff* $U$ *and* $V$ *are disjoint open subsets whose union is* $\mathbf{X}$*, then at least one of* $U$ *or* $V$ *is empty.*

See Folland Exercise 4.10 for more properties.

**Proposition 4.1.** *Continuous functions map connected spaces to connected spaces (in the subspace topology).*

*Proof.* Let $\mathbf{X}$ and $\mathbf{Y}$ be topological spaces and $f : \mathbf{X} \to \mathbf{Y}$ be continuous. If $f(\mathbf{X})$ is disconnected, then we can find $U$ and $V$, open and disjoint in $\mathcal{T}_{f(\mathbf{X})}$ such that

$$U \cup V = f(\mathbf{X}) \implies f^{-1}(U) \cup f^{-1}(V) = \mathbf{X}$$

where $f^{-1}(f(\mathbf{X})) = \mathbf{X}$. Both $f^{-1}(U)$ and $f^{-1}(V)$ are open, non-empty, and are pairwise disjoint. So $\mathbf{X}$ is separated. ■

**Proposition 4.2.** *Let* $(\mathbf{X}_\alpha, \mathcal{T}_\alpha)$ *be a family of connected topological spaces indexed by* $\alpha \in A$*. Then* $\prod_{\alpha \in A} \mathbf{X}_\alpha$ *is disconnected in the product topology.*

*Proof.* We will attempt the contrapositive. Suppose $\prod_{\alpha \in A} \mathbf{X}_\alpha$ is disconnected, then ■

## Topology in Analysis

**Definition 4.2** *$A^o$ is defined to be the largest open subset of $A$,*

$$A^o = \bigcup_{U \text{ open}, U \subseteq A} U$$

**Corollary 4.1** *The union of subsets of $A$ is again a subset of $A$, therefore Corollary 4.1 implies $A^o \subseteq A$ for any $A \subseteq \mathbf{X}$.*

**Definition 4.3** *and $\overline{A}$ is the smallest closed superset of $A$,*

$$\overline{A} = \bigcap_{K \text{ closed}, A \subseteq K} K$$

**Proposition 4.3.** *The complement of the closure is the interior of the complement, or equivalently: $(\overline{A})^c = A^{co}$*

*Proof.* Taking complements, and the substitution $U = K^c$ reads

$$\begin{aligned}
(\overline{A})^c &= \left( \bigcap_{K \text{ closed}, A \subseteq K} K \right)^c \\
&= \bigcup_{K \text{ closed}, K^c \subseteq A^c} K^c \\
&= \bigcap_{U \text{ open}, U \subseteq A^c} U \\
&= A^{co}
\end{aligned}$$

■

**Remark 4.1** *Personally, I remember this as pushing the complement inside and flipping the bar to a $c$!*

**Definition 4.4** *A neighbourhood of $x \in \mathbf{X}$ is a set $U \subseteq \mathbf{X}$ where $x \in U^o$. The set of neighbourhoods for a point $x \in \mathbf{X}$ will sometimes be denoted by $\mathcal{N}(()x)$.*

**Proposition 4.4.** *If $W = \left\{x \in \mathbf{X}, \text{ there exists a neighbourhood } U \text{ of } x, U \subseteq A\right\}$, then $W = A^o$.*

*Proof.* If $x \in A^o$, then $A$ is a neighbourhood of $x$, and $A \subseteq A$, so $x \in W$. Conversely, if $x$ is a member of $W$, it has a neighbourhood $U \subseteq A$ (not necessarily open). By monotonicity of the interior,

$$x \in U^o \subseteq A^o$$

and $x \in A^o$. ■

It is easy to see that $A$ is open $\iff A^o = A \iff A$ is a neighbourhood of itself.

- The first equivalence follows from:

  $$E \subseteq \mathbf{X} \implies E^o \subseteq E$$

  and if $A$ is an open set, it is an open subset of itself, by Corollary 4.1 $A \subseteq A^o$. If $A^o = A$, then it suffices to show that $A^o$ is open. Which it is, since it is the arbitrary union of open sets.

- To prove the second equivalence: suppose $A^o = A$, then each $x \in A$ has a neighbourhood contained (as a subset) in $A$, namely $A$ itself. (This statement is hard to parse, the reader is encouraged to really work through this and be honest).

  $$x \in A^o \subseteq A \implies A \subseteq A^o$$

  so $A$ is a neighbourhood of itself. Conversely, if $A \subseteq A^o$, then $A = A^o$, since the reverse inclusion follows immediately from Corollary 4.1.

We will now discuss the closure of a set.

**Proposition 4.5.** *Let $A \subseteq X$, if $W = \left\{ x \in \mathbf{X},\ \text{ every neighbourhood } U \text{ of } x,\ U \cap A \neq \varnothing \right\}$, then $\overline{A} = W$*

*Proof.* Suppose $x \notin W$, then there exists a neighbourhood $U$ of $x$ where

$$U \cap A = \varnothing \iff U \subseteq A^c$$

this is exactly the definition of the interior of $A^c$, so $x \in A^{co}$ and recall (from WTS 4.3) that $(\overline{A})^c = A^{co}$, so $x \notin \overline{A}$. For the reverse inclusion, read the proof backwards, by flipping $\forall \to \exists$ within the set, and we see that

$$W^c = A^{co} = (\overline{A})^c$$

■

## Urysohn's Lemma Notes

Notes on the construction of the countable 'onion' sequence within a normal space $\mathbf{X}$.

If $\mathbf{X}$ is a normal space, and $A$ and $B$ are disjoint closed subsets, then we can easily find an open $U$ with

$$A \subseteq U \subseteq \overline{U} \subseteq B^c \tag{4}$$

We say that $U$ hides in $B^c$ if the closure of $U$ is contained in $B^c$. Define $\Delta_n = \left\{k2^{-n},\ 1 < k < 2^n\right\}$, so that $\Delta_n \subseteq (0,1)$ for all $n \geq 1$. Notice

$$\Delta_1 \supseteq \cdots \supseteq \Delta_n \supseteq \Delta_{n+1}$$

and the even indices for $\Delta_{n+1}$ are contained in $\Delta_n$. Suppose $\Delta_n$ is well defined, it suffices to choose the odd indices for $\Delta_{n+1}$. If $r = j2^{-(n+1)}$, where $j$ is odd, then $r$ sits in between precisely two elements in $\Delta_n \cup \{0,1\}$. If $r$ sits between an endpoint, then define $\overline{U_0} = A$, and $B^c = U_1$. And denote the closest left and neighbours by $s$, $t$ respectively. If $s < r < t$, it is clear that $\overline{U_s}$ and $U_t^c$ are disjoint closed sets.

Use the 'normal space' construction to obtain an superset of $\overline{U_s}$ that hides in $U_t$, denote this open set by $U_r$, and similar to Equation (4)

$$\overline{U_s} \subseteq U_r \subseteq \overline{U_r} \subseteq U_t$$

Now that the construction of this sequence is complete, we wish to prove Urysohn's Lemma. Let $A$ and $B$ be disjoint closed sets. And define

$$f(x) = \inf\left\{r \in \Delta \cup \{1\},\ x \in U_r\right\}$$

where $U_1 = \mathbf{X}$. So that $0 \leq f(x) \leq 1$ is immediate. If $x \in A$, then $x$ is in all $U_r$, and by density of $\Delta \subseteq (0,1)$, we have $f(x) = 0$. Conversely, if $x \in B$ then $x \notin U_r$ for all $r \in \Delta$, if $E$ denotes the indices in $\Delta$ where $x \in U_s$ when $s \in E$,

$$(-\infty,\ r) \subseteq E^c \iff E \subseteq [r,\ +\infty) \iff \inf(E) \geq r \tag{5}$$

Send $r \to 1$ and $f(x) = 1$. Thus $f|_A = 0$ and $f|_B = 1$.

To show continuity, it suffices to show that the inverse images of the open half $\Big\{(x > \alpha),\ (x < \alpha)\Big\}_{\alpha \in \mathbb{R}}$ lines are indeed open in $\mathbf{X}$. Let $\alpha$ be fixed. And if $x \in \{f < \alpha\}$, we can 'wiggle' the infimum towards the right (towards $\alpha$), and using density of $\Delta$ within $(0, 1)$, there exists a $r \in E$ that satisfies $f(x) < r < \alpha$. This is equivalent to

$$x \in \bigcup_{r<\alpha} U_r$$

If there exists an $r < \alpha$ st $x$ belongs to $U_r$ as an element, then $f(x) \leq r < \alpha$.

If $f(x) > \alpha$, then $(-\infty, \alpha) \subseteq E^c$, by Equation (5). Suppose $\alpha < 1$, otherwise $\{f > \alpha\} = \varnothing$. Wiggle $f(x)$ to the left and obtain an $r \in \Delta$, $\alpha < r < f(x)$ with $x \notin U_r$. By density again, take any $s < r$ by a small amount (st $s > \alpha$, $s \in \Delta$), and

$$\overline{U}_s \subseteq U_r \iff U_r^c \subseteq \overline{U}_s$$

so that $x \in \overline{U}_s^c$ for some $s > \alpha$. This is equivalent to

$$x \in \bigcup_{s>\alpha} \overline{U}_s^c$$

Conversely, if $x \notin \overline{U}_s^c$ for some $s > \alpha$, since $\{U_r\}$ (thus $\{\overline{U}_r\}$) is increasing, and $x \notin U_r$ for every $r \leq s$. Hence,

$$(-\infty,\ s] \subseteq E^c \iff E \subseteq (s,\ +\infty) \iff f(x) \geq s > \alpha$$

# Exercises

## Exercise 4.1

**Proposition 1.1.** *If* $\operatorname{card}\mathbf{X} \geq 2$*, there is a topology on* $\mathbf{X}$ *that is* $T_0$ *but not* $T_1$*.*

*Proof.* Let $\mathcal{T}_{\mathbf{X}} = \{\varnothing\} \cup \{\{x\} \cup B,\ B \subseteq \mathbf{X}\}$, where $x \in \mathbf{X}$ is any point in $\mathbf{X}$. Suppose $U_1$, and $U_2$ are open sets in $\mathcal{T}_{\mathbf{X}}$, if either is empty then their intersection must be contained in $\mathcal{T}_{\mathbf{X}}$. Otherwise $U_1 = \{x\} \cup B_1$, and $U_2 = \{x\} \cup B_2$, where $B_1$ and $B_2$ are subsets of $\mathbf{X}$.

$$U_1 \cap U_2 = \{x\}(B_1 \cap B_2) \in \mathcal{T}_{\mathbf{X}}$$

Notice also $\{\varnothing,\ \mathbf{X}\} \subseteq \mathcal{T}_{\mathbf{X}}$. Fix an arbitrary family of open sets $\{U_\alpha\}_{\alpha \in A}$, in similar fashion we have $\bigcup U_\alpha = \{x\} \cup \left(\bigcup B_{\alpha \in A}\right)$ so their union is contained in $\mathcal{T}_{\mathbf{X}}$ as well.

This topology is $T_0$. Fix $y \neq z$ in $\mathbf{X}$, if either $y$ or $z$ is $x$, then choosing $\{x\}$ does the job. So assume $x \neq y \neq z \neq x$, and $\{y\} \cup \{x\}$ is an open set that does not contain $z$. This topology cannot be $T_1$, as $x$ sticks onto every open set, so there are no open sets which separate $x$ from the other points in $\mathbf{X}$. ∎

## Exercise 4.2

**Proposition 2.1.** *If $\mathbf{X}$ is an infinite set, the cofinite topology on $\mathbf{X}$ is $T_1$ but not $T_2$, and is first countable iff $\mathbf{X}$ is countable.*

*Proof.* We will first verify that the cofinite topology $\mathcal{T}_{\mathbf{X}}$ is a topology.

$$\mathcal{T}_{\mathbf{X}} = \left\{ U, \quad U^c \text{ is finite.} \right\} \cup \{\varnothing\}$$

So that $\{\varnothing, \mathbf{X}\} \subseteq \mathcal{T}_{\mathbf{X}}$. Let $U_1$ and $U_2$ be a pair of open sets, assuming if neither of them are empty, then $U_2^c$ and $U_1^c$ are finite sets, so that $U_1^c \cup U_2^c$ is finite as well. Use DeMorgan to see that $U_1 \cap U_2 \in \mathcal{T}_{\mathbf{X}}$.

If $\{U_\alpha\}_{\alpha \in A}$ is an arbitrary collection of open sets, then

$$\bigcap_{\alpha \in A} U_\alpha^c \subseteq U_\beta^c$$

where $\beta \in A$ is arbitrary, so $U_\beta^c$ is finite. And the union $\bigcup U_\alpha$ is contained in $\mathcal{T}_{\mathbf{X}}$.

To show that $\mathcal{T}_{\mathbf{X}}$ is $T_1$, every singleton set is closed. To show that $\mathcal{T}_{\mathbf{X}}$ is not $T_2$, fix $x \neq y$. If $B_x$ and $B_y$ are open sets that contain $x$ and $y$ respectively. If $B_x$ and $B_y$ disjoint, then

$$B_x \subseteq B_y^c$$

Which means $B_x$ is an open, finite subset. But the only open and finite subset of $\mathbf{X}$ is the empty set. This contradicts $x \in B_x$.

If $\mathbf{X}$ is countable, we will find a neighbourhood base $\mathcal{N}_B(x)$ for any $x \in \mathbf{X}$ as follows:

- We can index $\mathbf{X}$ using $\mathbb{N}^+ \cup \{0\}$, so without loss of generality, let $x_0 = x$, and
- Define $U_1 = \{x_1\}^c$, and $U_n = \bigcap_{j=1}^n \{x_j\}^c$ are open sets that contain $x$. Equivalently,

$$U_n = \left\{ x_j, \; j \geq n+1 \right\} \cup \{x_0\}$$

- If $V$ is an open set that contains $x_0$, then $V^c$ is finite, let $M \in \mathbb{N}^+$ be the largest index of $x_j \notin V$ (the negation of this is that if $j \geq M+1$, then $x_j \in V$) then $U_{M+1} \subseteq V$ as needed, and $\mathbf{X}$ is first countable.

Conversely, if $\mathbf{X}$ is first countable, we can find a descending sequence of neighbourhoods which form a neighbourhood base, $\{U_j\}_{j\geq 1} \subseteq \mathcal{T}_{\mathbf{X}}$. And each $U_j^c$ is finite, so $\bigcup U_j^c$ is countable. Assume for contradiction that $\mathbf{X}$ is uncountable, then

$$\bigcup U_j^c = \left(\bigcap U_j\right)^c$$

is countable, hence the intersection $\bigcap U_j$ must be uncountable (hence infinite). Pick $y \neq x$, where $y$ belongs in the intersection of all neighbourhoods $U_j$. This contradicts the fact that $\{U_j\}$ is a neighbourhood base, as $x$ is an element in the open set $\{y\}^c$ therefore there must be a $U_k$

$$x \in U_k \subseteq \{y\}^c$$

But $y \in U_k$ for each $U_k$ and the proof is complete. ■

## Exercise 4.3

**Proposition 3.1.** *Every metric space is normal. (If $A, B$ are disjoint closed sets in the metric space, consider the set of points $x$ where $d(x, A) < d(x, B)$ or $d(x, A) > d(x, B)$).*

*Proof.* First, we show that if $A$ is closed, then $d(x, A) = 0 \iff x \in A$. If $x \in A$, then $d(x, A) \leq d(x, x) = 0$. if $x \notin A$, then there exists a ball of radius $\varepsilon > 0$ where $B(\varepsilon, x) \cap A = \varnothing$. Hence, $\varepsilon$ is a lower bound for the set $\{d(x, y), y \in A\}$, taking the infimum over this set we see that $d(x, A) \geq \varepsilon > 0$.

Fix some $x \in \Phi_A$ where $\Phi_A = \left\{ y \in \mathbf{X}, d(y, A) < d(y, B) \right\}$. We wish to find an open ball about $x$ that is contained in $\Phi_A$. The Triangle Inequality works for this definition of distance as well, as

$$f(a) \leq g(a), \forall a \in A \implies \inf_{a \in A} f(a) \leq \inf_{a \in A} g(a) \tag{6}$$

If $a \in A$, then $d(z, A) \leq d(x, z) + d(x, A)$, using Equation (6) yields

$$\begin{cases} d(z, A) \leq d(x, A) + d(x, z) \\ d(x, B) - d(x, z) \leq d(z, B) \end{cases}$$

where $z \in B(\varepsilon, x)$ so $d(x, z) \precsim \varepsilon$. The second estimate above is found by 'flipping an upper bound to become a lower bound'. We can choose $d(x, z)$ sufficiently small that

$$d(x, A) + d(x, z) < d(x, B) - d(x, z)$$

in order to 'pipe' the two inequalities, so

$$2d(x, z) < d(x, B) - d(x, A) \tag{7}$$

Take $\varepsilon = [d(x, B) - d(x, A)]3^{-1}$, then $z \in B(\varepsilon, x)$ implies $d(x, z) < \varepsilon$, and Equation (7) holds. See Figure 1 for details.

■

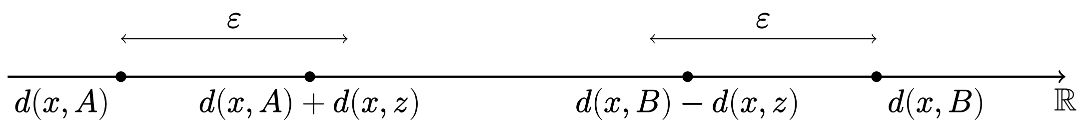


Figure 1: Exercise 4.3: Finding a $\varepsilon$ small enough that fits within $d(x, A) < d(x, B)$

## Exercise 4.4

**Proposition 4.1.**

*Proof.* ■

## Exercise 4.5

**Proposition 5.1.** *Every separable metric space is second countable.*

*Proof.* We wish to show that if $\mathbf{X}$ is a metric space, then

$$\text{second countable} \iff \text{separable}$$

Suppose $\mathbf{X}$ is separable, where $A$ is a countable dense subset in $\mathbf{X}$, and $x \in \mathbf{X}$. Let $U$ be an open set that contains $x$, so $B(\varepsilon,\, x) \subseteq U$ for some $\varepsilon > 0$. $B(\varepsilon/2,\, x)$ is a non-empty open set, therefore contains some $y \in A$ (this follows from the definition of density). If we choose $r \in \mathbb{Q}$ wisely,

$$d(x, y) < r < \varepsilon/2$$

So that $x \in B(r,\, y)$, and if $z \in B(r,\, y)$, then

$$d(x, z) \leq d(x, y) + d(z, y) < r + r < \varepsilon$$

So $x \in B(r,\, y) \subseteq U$. But $\{B(r, y),\ r \in \mathbb{Q}^+,\ y \in A\}$ is countable. Therefore $\mathbf{X}$ is second countable.

Conversely, Proposition 4.5 gives us the $\Longleftarrow$ direction. But we will repeat anyway, if $\mathbf{X}$ is second-countable with $\mathcal{E}$ as a countable base, then take

$$W = \left\{ x_\alpha \in U, \quad U \in \mathcal{E} \right\}$$

by picking a point from each set, we claim $W$ is dense in $\mathbf{X}$, so $\overline{W} = \mathbf{X}$. If not, then $\overline{W}^c \neq \varnothing$, and

$$\overline{W}^c = (W^c)^o \neq \varnothing$$

Pick a point $x \in W^{co}$, which is an open set containing $x$. But the way we chose $W$ does not allow for any open set $U \in \mathcal{E}$ with $x \in \mathcal{E} \subseteq W^{co}$, since

> By picking one point from each of the base sets, grouping these points and call it $W$, and flipping to the complement. Each $U \in \mathcal{E}$ admits a point that escapes $W^{co}$. Therefore we can ensure no $U \in \mathcal{E}$ can be a subset of $W^{co}$.

∎

## Exercise 4.6

**Proposition 6.1.**

*Proof.* ■

## Exercise 4.7

**Proposition 7.1.** *If* $\mathbf{X}$ *is a topological space, a point* $x \in \mathbf{X}$ *is called a cluster point of the sequence* $\{x_j\}$ *if for every neighbourhood* $U \in \mathcal{N}(x)$*,* $x_j \in U$ *for infinitely many* $j$*. If* $\mathbf{X}$ *is first countable,* $x$ *is a cluster point of* $\{x_j\}$ *iff some subsequence of* $\{x_j\}$ *converges to* $x$*.*

*Proof.* Suppose $\{x_n\}$ has a cluster point in $z \in \mathbf{X}$. Fix a descending sequence of neighbourhoods $U_k \subseteq \mathcal{N}(z)$, where

$$U_1 \supseteq U_2 \supseteq \cdots \supseteq U_k$$

Define $n_k = \text{least}\left\{ j \in \mathbb{N}^+,\ j > n_{k-1},\ x_j \in U_k \right\}$ with $n_0 = 0$, so that for every $m \geq k$, $x_{n_m} \in U_k$ eventually. And $\{x_{n_j}\}_{j \geq 1}$ is a subsequence which converges to $z$. This proves ( $\implies$ ).

Conversely (this part does not require that $\mathbf{X}$ be first countable), if $\{x_{n_k}\}_{k \geq 1}$ is a subsequence that converges to $z \in \mathbf{X}$. Every neighbourhood of $z$ must intersect all but infinitely many $x_{n_k}$, therefore $z$ is a cluster point of $\{x_n\}$. ■

## Exercise 4.8

**Proposition 8.1.** *If* $\mathbf{X}$ *is an infinite set with the cofinite topology and* $\{x_j\}$ *is a sequence of distinct points in* $\mathbf{X}$*, then* $x_j \to x$ *for every* $x \in \mathbf{X}$*.*

*Proof.* The intuition here is that the cofinite topology does not distinguish between points, so it acts as a type of jelly that hides the points.

Let $x \in \mathbf{X}$ be arbitrary, if $U \in \mathcal{N}(x)$ then $U^o \in \mathcal{N}(x)$, so that $\{y_j\}_{j \le k}$ are the $k$ points that are required to extend $U^o$ to $\mathbf{X}$. (All but finitely many points are in any open set of $\mathbf{X}$).

There exists a large $N \in \mathbb{N}^+$ so that for every $n \geq N$,

$$x_j \notin \{y_j\}_{j \le k} \implies x_j \in U^o$$

eventually. And $x_j \to x$. ■

## Exercise 4.9

**Proposition 9.1.**

*Proof.* ■

## Exercise 4.10

**Proposition 10.1.** *A topological space* $\mathbf{X}$ *is called disconnected if there exists non-empty, disjoint open sets* $U$, $V$ *and* $U \cup V = \mathbf{X}$*; otherwise* $\mathbf{X}$ *is connected. When we speak of connected or disconnected subsets of* $\mathbf{X}$*, we refer to the relative topology on them*

*(a)* $\mathbf{X}$ *is connected iff* $\varnothing$ *and* $\mathbf{X}$ *are the only two clopen sets.*

*(b) If* $\{E_\alpha\}_{\alpha\in A}$ *is a collection of connected subsets of* $\mathbf{X}$*, and* $bigcapE_{\alpha\in A}$ *is non-empty, then* $\bigcup E_{\alpha\in A}$ *is connected.*

*(c) If* $A \subseteq \mathbf{X}$ *is connected, then* $\overline{A}$ *is connected,*

*(d) Every point in* $x \in \mathbf{X}$ *contained in a unique maximal connected subset of* $\mathbf{X}$*, and this subset is closed. It is called the connected component of* $x$*.*

*Proof.* The proof is rather long, so we will split it in several parts. A topological space is disconnected iff it can be written as a disjoint union of two non-empty open sets. Often it is easier to show that a space is disconnected rather than connected.

Part A: Suppose $\mathbf{X}$ is disconnected, this induces a pair of non-empty open sets, $A$, and $B$ whose union is $\mathbf{X}$, and

$$A \cap B = \varnothing \iff A \subseteq B^c$$

their union is $\mathbf{X}$, hence

$$A \cup B = \mathbf{X} \iff B^c \subseteq A$$

combining the last two estimates, we see that $B = A^c$, so both $A$ and $A^c = B$ are closed. This proves ( $\Longleftarrow$ ).
Now suppose $\{A, A^c\} \neq \{\varnothing, \mathbf{X}\}$ are both clopen. Clearly $A$ is disjoint from its complement, and their union is $\mathbf{X}$.

Part B: We will attempt the contrapositive. Suppose $E = \bigcup E_{\alpha\in A}$ is disconnected. This induces $D$ and $D^c$ which are clopen in the relative topology of $E$, (by Part A). More precisely,

$$\bigcup E_\alpha = \underbrace{\bigcup (E_\alpha \cap D)}_{\neq\varnothing} + \underbrace{\bigcup (E_\alpha \setminus D)}_{\neq\varnothing} \tag{8}$$

The intersection $\bigcap E_{\alpha\in A}$ is non-trivial, hence

$$\bigcap E_\alpha = \underbrace{\bigcap(E_\alpha \cap D)}_{\neq\varnothing} + \bigcap(E_\alpha \setminus D) \neq \varnothing \tag{9}$$

so at least one of the members on the right are non-empty. Assume without loss of generality that $\bigcap(E_\alpha \cap D)$ is not empty. This tells us $E_\alpha \cap D =\neq \varnothing$ for each $\alpha \in A$. But by Equation (8), if we concentrate on the right member,

$$\bigcup(E_\alpha \setminus D) \neq \varnothing \implies \exists\beta \in A,\ E_\alpha \setminus D \neq \varnothing$$

And for this particular $\beta \in A$, we see that both $D$ and $D^c$ are non-trivially open in $E_\beta$, and the proof is complete. A poetic way to summarize the proof would be:

> If the whole is disconnected, and there exists common ground over which the family of sets covers, and because the common ground (intersection) is non-trivial, either $D$ or $D^c$ is non-trivially open in all $E_\alpha$. The intersection gives us "$\forall$", while the union gives us "$\exists$" for a non-trivially open $D$ or $D^c$.

There is an alternate way of proving Part B, without using the clopen definition of connectedness. Let $C$ and $D$ be non-empty, disjoint, open sets in $\bigcup E_\alpha$ whose union is $\bigcup E_\alpha$.

$$\bigcap E_\alpha = \bigcap[E_\alpha \cap C] + \bigcap[E_\alpha \cap D] \neq \varnothing$$

Pick $p \in \bigcap E_\alpha$, without loss of generality, assume $p \in \bigcap[E_\alpha \cap C]$, then for every $\alpha$ we have

$$p \in E_\alpha \cap C \implies E_\alpha \cap C \neq \varnothing$$

Since $E_\alpha$ is connected, $E_\alpha \cap D = \varnothing$ for each $\alpha$. Taking the union over all $E_\alpha \cap D$, we see that

$$\bigcup[E_\alpha \cap D] = \varnothing$$

which contradicts the assumption $D \neq \varnothing$.
Part C: Suppose $\overline{A}$ is disconnected, this induces a non-trivial clopen set $D$ relative to $\overline{A}$.

- Since $\overline{A} \cap D \neq \varnothing$, choose any $y \in \overline{A} \cap D \subseteq \overline{A}$, since $D$ is a neighbourhood of $y$, and $y$ is an adherent point of $A$. It is immediate that $A \cap D$ is non-empty.

- Similarly for $A \setminus D \neq \varnothing$,

therefore $\{D, D^c\}$ is non-trivially clopen in $A$, and $A$ is disconnected.

Part D: The idea here is to use Part B. Let $x$ be fixed, and $\{E_\alpha\}_{\alpha \in A}$ be the family of all connected sets containing $x$, since their intersection is non-trivial, their union, $E$ is connected. The closure of their union is then the maximal connected component containing $x$. Indeed, if $G$ is a connected set containing $x$, then $G \subseteq \bigcup E_\alpha = E$, so $G \subseteq \overline{E}$. ■

## Exercise 4.11

**Proposition 11.1.** *If* $E_1, \ldots E_n$ *are subsets of a topological space, the closure of* $\bigcup_1^n E_j$ *is* $\bigcup_1^n \overline{E_j}$

*Proof.* The finite union of closed sets is again closed, so

$$\forall j \leq n,\; E_j \subseteq \overline{E_j} \implies \overline{\bigcup_1^n E_j} \subseteq \bigcup_1^n \overline{E_j}$$

For the reverse estimate, $E_j \subseteq \bigcup_1^n E_j \subseteq \overline{\bigcup_1^n E_j}$ is a closed set that contains each $E_j$, therefore

$$\forall j \leq n,\; \overline{E_j} \subseteq \overline{\bigcup_1^n E_j} \implies \bigcup_1^n \overline{E_j} \subseteq \overline{\bigcup_1^n E_j}$$

∎

**Corollary 11.1** *The interior operator distributes over intersections. If* $A$ *and* $B$ *are subsets of* $\mathbf{X}$, *then*

$$\begin{aligned}
\overline{(A^c \cup B^c)} &= (\overline{A^c} \cup \overline{B^c}) \\
\left(\overline{(A^c \cup B^c)}\right)^c &= A^o \cap B^o \\
\left(A^c \cup B^c\right)^{co} &= A^o \cap B^o \\
(A \cap B)^o &= A^o \cap B^o
\end{aligned}$$

## Exercise 4.12

**Proposition 12.1.** *Let $\mathbf{X}$ be a set. A Kuratowski closure operator on $\mathbf{X}$ is a map $A \mapsto A^*$ from $\mathbb{P}(\mathbf{X})$ to itself satisfying*

*(i)* $\varnothing^* = \varnothing$ *(does nothing to the empty set),*

*(ii)* $A \subseteq A^*$ *(monotonicity),*

*(iii)* $(A^*)^* = A^*$ *(idempotence)*

*(iv)* $(A \cup B)^* = A^* \cup B^*$ *(distributes over finite unions)*

*Prove*

*(a) If $\mathbf{X}$ is a topological space, the map $A \mapsto \overline{A}$ is a Kuratowski closure operator. (Use Exercise 11.)*

*(b) Conversely, given a Kuratowski closure operator, let $\mathcal{F} = \{A \subseteq \mathbf{X},\, A = A^*\}$ and $\mathcal{T} = \{U \subseteq \mathbf{X},\, U^c \in \mathcal{F}\}$, then $\mathcal{T}$ is a topology on $\mathbf{X}$, and for any set $A \subseteq \mathbf{X}$, $A^*$ will be its closure with respect to $\mathcal{T}$.*

*Proof.* Part A: The empty set is closed, so $\overline{\varnothing} = \varnothing$, and $\overline{A}$ is the smallest closed superset of $A$, so $A \subseteq \overline{A}$ for every $A \subseteq \mathbf{X}$. $A \subseteq \mathbf{X}$ is closed iff $\overline{A} = A$, so idempotence holds. Distributivity follows from Exercise 11 directly.

Part B: We first show that $\mathcal{T}$ is indeed a topology. Fix $U_1$ and $U_2$ in $\mathcal{T}$, so that $U_1^c \cup U_2^c = (U_1 \cap U_2)^c$. The map $A \mapsto A^*$ distributes over finite unions, hence

$$(U_1^c \cup U_2^c)^* = (U_1^c)^* \cup (U_2^c)^* = U_1^c \cup U_2^c$$

Therefore $U_1 \cap U_2 \in \mathcal{T}$. Now suppose $\{U_\alpha\}_{\alpha \in A} \subseteq \mathcal{T}$, then

$$\left(\bigcup U_\alpha\right)^c = \bigcap U_\alpha^c$$

by monotonicity (Property ii): $\bigcap U_\alpha^c \subseteq \left(\bigcap U_\alpha^c\right)^*$. To prove the reverse inclusion, notice if $\alpha$ is held fixed,

$$\bigcap U_\alpha^c \subseteq U_\alpha^c \implies \left(\bigcap U_\alpha^c\right)^* \subseteq U_\alpha^{c*}$$

this follows from 'monotonicity' of the closure operator: if $A$ is a subset of $B$, then we can write

$$B = A + (B \setminus A) \implies A^* \subseteq A^* + (B \setminus A)^* = B^*$$

Take the intersection over all $\alpha \in A$ on the right member,

$$\left(\bigcap U_\alpha^c\right)^* \subseteq \bigcap U_\alpha^{c*} = \bigcap U_\alpha^c$$

Hence $\left(\bigcap U_\alpha^c\right)^* = \bigcap U_\alpha^c$. The empty set and $\mathbf{X}$ are elements of $\mathcal{F}$. Since $\mathbf{X} \subseteq \mathbf{X}^* \subseteq \mathbf{X}$, and $\{\varnothing, \mathbf{X}\} \subseteq \mathcal{T}$. So $\mathcal{T}$ is a topology.

Finally, $A^*$ is a closed superset of $A$ and suppose $K$ is another closed superset,

$$A \subseteq K \implies A^* \subseteq K^*$$

So $A^*$ is the smallest closed superset of $A$ and this proves the last claim. ■

## Exercise 4.13

**Proposition 13.1.** *If* $\mathbf{X}$ *is a topological space,* $U$ *is open in* $\mathbf{X}$ *and* $A$ *is dense in* $\mathbf{X}$*, then* $\overline{U} = \overline{U \cap A}$*.*

*Proof.* The takeaway here is that if $A$ is dense in $\mathbf{X}$, every point $z \in U$ can be approximated by points in $U \cap A$. And and important technique of 'demoting' the neighbourhood to become the interior of the neighbourhood can yield some nice properties. Since the interior of a neighbourhood is again a neighbourhood. This allows intersection with open sets to inherit the 'neighbourhoodness' of the set.

Let $z \in \overline{U}$, and fix a neighbourhood $V \in \mathcal{N}(z)$, so that the interior of $V$ is also a neighbourhood. By the alternate definition of $\overline{U}$ in terms of adherent points (see WTS 4.5) of $\overline{U}$, $V^o \cap U \neq \varnothing$. This is a non-empty open set, therefore it must intersect $A$ non-trivially.

$$x \in (V^o \cap U) \cap A = V^o \cap (U \cap A)$$

and $z \in \overline{U \cap A}$.

■

**Remark 13.1** *We simply used the fact*

$$\overline{E} = \left\{ x \in \mathbf{X},\, \forall V \in \mathcal{N}(x),\, V \cap E \neq \varnothing \right\}$$

*and the following equivalent characterization of density*

$$E \text{ is dense in } \mathbf{X} \iff \text{For every non-empty open set } U,\ U \cap E \neq \varnothing$$

## Exercise 4.14

**Proposition 14.1.** *If* $\mathbf{X}$ *and* $\mathbf{Y}$ *are topological spaces,* $f : \mathbf{X} \to \mathbf{Y}$ *is continuous iff* $f(\overline{A}) \subseteq \overline{f(A)}$ *for every* $A \subseteq \mathbf{X}$ *iff* $\overline{f^{-1}(B)} \subseteq f^{-1}(\overline{B})$ *for all* $B \subseteq Y$*.*

*Proof.* *First Equivalence:* If $f$ is continuous, fix any $A \subseteq \mathbf{X}$, and $z \in \overline{A}$, by WTS 4.5 (I will spare you the flipping by including):

$$\overline{A} = \{x \in \mathbf{X},\ \forall U \in \mathcal{N}(X),\ U \cap A \neq \varnothing\}$$

Let $U \in \mathcal{N}(f(z))$, so that $f^{-1}(U^o)$ is an open set containing $z$ and $f^{-1}(U^o) \in \mathcal{N}(z)$, so

$$f^{-1}(U^o) \cap A \neq \varnothing \implies U^o \cap f(A) \subseteq U \cap f(A)$$

so $f(\overline{A}) \subseteq \overline{f(A)}$. Conversely, suppose $f(\overline{A}) \subseteq \overline{f(A)}$ holds for every $A \subseteq \mathbf{X}$. The following is a sequence of symbolic manipulations that I found but have zero intuitive understanding about. First take the inverse image

$$\overline{A} \subseteq f^{-1}\left(f(\overline{A})\right) \subseteq f^{-1}\left(\overline{f(A)}\right)$$

Next, let $F$ be a closed set in $\mathbf{Y}$, and make the substitution $A = f^{-1}(F)$, hence

$$\overline{f^{-1}(F)} \subseteq f^{-1}\left(\overline{f(f^{-1}(F))}\right) \subseteq f^{-1}(\overline{F}) = f^{-1}(F)$$

for the second inclusion we used the monotonicity of the closure, and since $\overline{f^{-1}(F)} = f^{-1}(F)$, we are done.

*Second Equivalence:* Suppose $f \in C(\mathbf{X}, \mathbf{Y})$, then $\overline{B} \subseteq \mathbf{Y}$ is a closed set, so $f^{-1}(\overline{B})$ is closed in $\mathbf{X}$. By monotonicity of the inverse image,

$$f^{-1}(B) \subseteq f^{-1}(\overline{B}) \implies \overline{f^{-1}(B)} \subseteq f^{-1}(\overline{B})$$

Conversely, if $\overline{f^{-1}(B)} \subseteq f^{-1}(B)$ for any $B \subseteq \mathbf{Y}$, take any closed $B \subseteq \mathbf{Y}$, and

$$\overline{f^{-1}(B)} \subseteq f^{-1}(B) \subseteq \overline{f^{-1}(B)}$$

so $f^{-1}(B)$ is closed, and $f$ is in $C(\mathbf{X}, \mathbf{Y})$. ∎

# Exercise 4.16

**Proposition 15.1.**

*Proof.*

(a) Let $x \in \{f \neq g\}$, then there exists disjoint open subsets of $\mathbf{Y}$, $f(x) \in U$ and $g(x) \in V$, $U \cap V = \varnothing$, but $f^{-1}(U) \cap g^{-1}(V)$ is an open set in $\mathbf{X}$ that contains $x$. Therefore $\{f \neq g\}$ is open in $\mathbf{X}$.

(b) Suppose $\{f = g\} = E$ is dense in $\mathbf{X}$. Let $x \in E$, induces two disjoint open sets exactly like in part a. This is an open set that contains $x$, and $y \in f^{-1}(U) \cap g^{-1}(V) \cap E$. Since $y \in E$, it follows that $f(y) = g(y)$, and

$$\begin{cases} y \in f^{-1}(U) \implies & f(y) \in U \\ y \in g^{-1}(V) \implies & g(y) \in V \end{cases}$$

■

## Exercise 4.17

## Theorem 4.1

**Proposition 1.1.** *Suppose that $A$ is a subset of $X$, let $\operatorname{acc} A$ be the set of accumulation points of $A$, then*

$$\overline{A} = A \cup \operatorname{acc}(A) \tag{10}$$

*and $A$ is closed if and only if $\operatorname{acc}(A) \subseteq A$.*

*Proof.* Suppose that $x \notin \overline{A}$, then $x \in (\overline{A})^c = A^{co}$, then $A^c \in \mathcal{N}_B(x)$. But this means that $x \notin \operatorname{acc}(A)$, since there exists a neighbourhood of $x$ (in the form of $A^c$), such that

$$A \cap A^c \setminus \{x\} = A \cap A^c = \varnothing$$

Also, $A \subseteq \overline{A} \implies (\overline{A})^c \subseteq A^c$ which means that

$$x \notin \overline{A} \implies x \notin A$$

Since $x \notin \overline{A} \implies x \notin A$ and $x \notin \operatorname{acc}(A)$,

$$(\overline{A})^c \subseteq A^c \cap \operatorname{acc}(A)^c = (A \cup \operatorname{acc}(A))^c$$

Now, if $x \notin \operatorname{acc}(A) \cup A$, then $x \notin \operatorname{acc}(A)$, therefore there exists some $U \in \mathcal{N}_B(x)$ such that

$$A \cap U \setminus \{x\} = A \cap U = \varnothing$$

Where for the second last equality we used the fact that $x \notin A \implies A \setminus \{x\} = A$, and taking complements gives us

$$U \subseteq A^c$$

And since $U \in \mathcal{N}_B(x)$, then $x \in U^o \subseteq A^{co}$ (since $U^o$ is an open subset of $A^c$). then

$$x \in A^{co} = (\overline{A})^c \implies x \notin (\overline{A})^c$$

Therefore $(A \cup \operatorname{acc}(A))^c \subseteq (\overline{A})^c$. ■

## Theorem 4.2

**Proposition 2.1.** *If $\mathcal{T}_X$ is a topology on $X$ and $\mathcal{E} \subseteq \mathcal{T}_X$ then $\mathcal{E}$ is a base for $\mathcal{T}_X$ if and only if for every*

$$\forall U \in \mathcal{T}_X,\, U \neq \varnothing,\, \implies U = \bigcup_{V \in B} V$$

*Where $B$ is a subset of $\mathcal{E}$.*

*Proof.* Suppose that $\mathcal{E}$ is a base, then fix any non-empty $U \in \mathcal{T}_X$, then for every $x \in U$, there exists a neighbourhood base for this $x$ and a member $V \in \mathcal{E}$ such that $x \in V_x \subseteq U$. Take the union over all $V_x$ and

$$U \subseteq \bigcup_{x \in U} V_x$$

But each $V_x \subseteq U$, so $U = \bigcup_{x \in U} V_x$, where $\{V_x\} \subseteq \mathcal{E}$.

Conversely, if every non-empty $U$ is a union of members in $\mathcal{E}$ then fix any $x \in X$, we claim that we have a neighbourhood base in

$$\{V \in \mathcal{E},\, x \in V\}$$

The reason is as follows

- $x$ belongs to every $E \in \{V \in \mathcal{E},\, x \in V\}$ and
- For every open $U$, if $x \in U$ then there exists a union of members of $\mathcal{E}$ such that $U = \bigcup E_\alpha$, then $x \in U \iff \exists E_\alpha \in \{V \in \mathcal{E},\, x \in V\}$ and
- Using this particular $E_\alpha \in \mathcal{E}$ that we just found, $x \in E_\alpha \subseteq U$, and we are done.

■

## Theorem 4.3

**Proposition 3.1.** *For every $\mathcal{E} \subseteq \mathbb{P}(X)$, $\mathcal{E}$ is base for a topology on $X$ if and only if*

*(a) each $x \in X$ is contained in some $V \in \mathcal{E}$, and*

*(b) if $U, V \in \mathcal{E}$, and $x \in U \cap V$, then there must exist some $W \in \mathcal{E}$ with $x \in W \subseteq U \cap V$.*

*Proof.* Suppose that $\mathcal{E}$ is a base, then we get a), and b) follows since for every $U, V \in \mathcal{E} \subseteq \mathcal{T}_X$, and by closure over finite intersections, $U \cap V \in \mathcal{T}_X$ implies that there exists some $W \in \mathcal{E}$ with

$$x \in W \subseteq U \cap V$$

Now, suppose both a) and b) hold, then we claim that this $\mathcal{E} \subseteq \mathbb{P}(X)$ induces a topology on $X$

$$\mathcal{T} = \{U \subseteq X,\, \forall x \in U,\, \exists V \in \mathcal{E},\ \text{with } x \in V \subseteq U\}$$

Intuitively speaking, this means that $\mathcal{T}$ is just fine (and not too fine) to satisfy the conditions for $E \subseteq \mathcal{T}$ to be a base of $\mathcal{T}$.

We first show that $\mathcal{T}$ is a topology.

- $\varnothing \in \mathcal{T}$ and $X \in \mathcal{T}$, the first is trivial and the second is from a)
- Closure under unions: fix $\{U_\alpha\}_{\alpha \in A} \subseteq \mathcal{T}$, and $U = \bigcup U_\alpha$, and for every $x \in U$ there exists some $V_\alpha \in \mathcal{E}$ such that $x \in V_\alpha \subseteq U_\alpha \subseteq U$, therefore $U \in \mathcal{T}$.
- Closure under finite intersections, fix any $U_1$, $U_2$ as elements in $\mathcal{T}$, then suppose that they are not disjoint (if they are disjoint then their intersection is the empty set, which is also contained in $\mathcal{T}$). If $U_1 \cap U_2 \neq \varnothing$, then for every $x \in U_1 \cap U_2$ induces two sets $V_1, V_2 \in \mathcal{E}$ with $x \in V_1 \subseteq U_2$ and $x \in V_2 \subseteq U_2$, taking their intersection and applying b) gives us some $V \subseteq V_1 \cap V_2$ with $V \in \mathcal{E}$ therefore $x \in V \subseteq U_1 \cap U_2$, and $\mathcal{T}$ is closed under finite intersections.

Now to show that $\mathcal{E}$ is a base for $\mathcal{T}$, $\mathcal{E} \subseteq \mathcal{T}$ is obvious since very $V \in \mathcal{E}$ satisfies the properties laid out by $\mathcal{T}$ by simply choosing $V$ again for any $x \in V$. Now fix any member $U \in \mathcal{T}$, then for every $x \in U$, there exists some $V \in \mathcal{E}$ with

$$x \in V \subseteq U$$

(This is an immediate consequence of how we defined $\mathcal{T}$). And we can conclude that $\mathcal{E}$ is a base for this induced topology $\mathcal{T}$. ■

# Theorem 4.4

**Proposition 4.1.** *If $\mathcal{E} \subseteq \mathbb{P}(X)$, the topology $\mathcal{T}(\mathcal{E})$ generated by $\mathcal{E}$ consists of $\varnothing, X$ and all unions of finite intersections of $\mathcal{E}$, in symbols*

$$\mathcal{T}(\mathcal{E}) = \{\varnothing, X\} \cup \left\{\bigcup W_\alpha,\ W_\alpha = \bigcap E_{j\le n},\ E_j \in \mathcal{E}\right\}$$

*Proof.* Denote the set

$$W = \{X\} \cup \left\{\bigcap V_{j\le n},\ \ V_j \in \mathcal{E}\right\}$$

We claim this set $W$ satisfies Theorem 4.3. Since 4.3a) is satisfied with $X \in W$. 4.3b) follows since the right member in $W$ is closed under intersections.

And if we are taking an element from each member, $E_1 \in \{\varnothing, X\}$ and $E_2$ is an element in the right member, then it is trivial to verify that their intersection is always contained within $W$. Therefore $W$ induces a topology by Theorem 4.2, and we call this topology $\mathcal{T}$ — and for the sake of completeness

$$\mathcal{T} = \{U \subseteq X,\ \forall x \in U,\ \exists V \in \mathcal{E},\ x \in V \subseteq U\}$$

We so claim that if we define $\overline{W}$ as the union of all members $w \in W$, together with the empty set, is equal to the set $\mathcal{T}$.

$$\overline{W} = \left\{\bigcup_{w\in W} w\right\} \cup \{\varnothing\}$$

- We want to show $\mathcal{T} \subseteq \overline{W}$, since $W$ is a base for the topology $\mathcal{T}$, every (non-empty) $U \in \mathcal{T}$ is the union of members in $W$ (Theorem 4.2), and there exists some $B \subseteq W$ with

  $$U = \bigcup E_{\alpha\in B} \in \overline{W}$$

  Now if $U$ is the empty set then it is trivially contained within $\overline{W}$.

- Next, we show that $\overline{W} \subseteq \mathcal{T}$, fix any element $E \in \overline{W}$, if $E = \varnothing$ then there is nothing to prove since $\mathcal{T}$ is a topology. Now for every $x \in E$,

  $$x \in E = \bigcup_{w\in W} w \implies x \in w$$

  Therefore $E \in \mathcal{T}$ by definition. This proves that $\mathcal{T} = \overline{W}$.

Now that $\overline{W}$ is a topology, that contains $\mathcal{E}$ as a subset, and by definition of $\mathcal{T}(\mathcal{E})$

$$\mathcal{T}(\mathcal{E}) = \bigcap \{A, \text{ is a topology, and } \mathcal{E} \subseteq A\}$$

Tells us

$$\mathcal{T}(\mathcal{E}) \subseteq \overline{W}, \quad \text{since } \overline{W} \in \{A, \text{ is a topology, and } \mathcal{E} \subseteq A\}$$

Conversely, fix any member $E \in \overline{W}$, if $E = \varnothing$ then $E \in \mathcal{T}(\mathcal{E})$, if not, then there exists some subset $B \subseteq W$ such that

$$E = \bigcup_{w \in B} w = \bigcup_{w \in B} \bigcap_{j \leq n} V^{w}_{j \leq n} V_j \in \mathcal{E} \cup \{X\}$$

Since $\mathcal{T}(\mathcal{E})$ is closed under finite intersections and unions, and it contains $\mathcal{E}$ as a subset, $\overline{W} = \mathcal{T}(\mathcal{E})$ and we are done. ■

## Theorem 4.5

**Proposition 5.1.** *Every second countable space is separable. (Countable dense subset).*

*Proof.* What we wish to prove is that if a space $X$ has a countable base, then it has a countable dense subset. Denote this base of $X$ by $\mathcal{E}$ as usual, then we claim that

$$W = \{x_u,\, U \in \mathcal{E}\}$$

Is a dense subset in $X$. Note that $(\overline{W})^c = W^{co} \in \mathcal{T}_X$. If $W^{co} = \varnothing$ then we simply take complements and we get $\overline{W} = X$. So suppose that $W^{co}$ is non-empty, then for each $x \in W^{co}$ (by definition of a base), it should induce some $V_x \in \mathcal{E}$ with

$$x \in V_x \subseteq W^{co}$$

But clearly, for every element in $\mathcal{E}$, the second estimate can never be satisfied, since for every $U \in \mathcal{E}$, $x_U \notin W^{co}$ for this particular set $W^{co}$. Therefore $W^{co}$ must be empty, and this completes the proof. ∎

## Theorem 4.6

**Proposition 6.1.** *If $X$ is first countable, then for every $A \subseteq X$, $x \in \overline{A} \iff$ there exists some sequence $\{x_j\}_{j\geq 1} \subseteq A$ such that $x_j \to x$.*

*Proof.* Suppose that $X$ is first countable, and $A \subseteq X$, and fix any element $x \in \overline{A}$. Since $X$ is first countable, there is a sequence of descending neighbourhoods of $\{U_j\}_{j\geq 1}$ of $x$ such that

$$U_1 \supseteq U_2 \supseteq \cdots \supseteq U_j \supseteq U_{j+1}$$

If $x \in A$, take $x_n = x$ for all $n \geq 1$. If $x \in \operatorname{acc}(A)$, then take $x_n \in U_n \cap A \setminus \{x\} = U_n \cap A$, which is not empty. Then it remains to show that this sequence converges to $x$. Fix any neighbourhood $U \in \mathcal{N}_B(x)$ then there exists some $N$, for every $n \geq N$

$$x \in U^o \implies \exists N \in \mathbb{N}^+, x \in U_N \subseteq U^o$$

Then every $x_n \in A \cap U_N \subseteq A \cap U^o \subseteq U^o$. And this establishes $\implies$.

Now suppose that $x \notin \overline{A}$, so that $x \notin A$ and $x \notin \operatorname{acc}(A)$, then fix any sequence $\{x_j\} \subseteq A$. We wish to show that $x_j \not\to x$.

Since $x \notin \operatorname{acc}(A)$, there exists some $V \in \mathcal{N}_B(X)$ with

$$A \cap V \setminus \{x\} = \varnothing \implies V \subseteq A^c$$

Since $\{x_j\}_{j\geq 1} \subseteq A \implies x_j \notin A^c$ for every $j \geq 1$, then choose $V$ as the neighbourhood around $x$, and $x_j \not\to x$ for any arbitrary sequence $x_j$ in $A$. ∎

**Remark 6.1** *To truly understand what is going on one should recall that all metric space spaces are first countable.*

## Theorem 4.7

**Proposition 7.1.** *$X$ is a $T_1$ space $\iff$ $\{x\}$ is closed for every $x \in X$.*

*Proof.* If $X$ is $T_1$ and $x \in X$, then for every $y \neq x$ there exists some open $U_y$ that contains $y$ but not $x$. Following Folland's argument closely, every $y \neq x$ is is in $\cup U_{y \neq x}$. Hence $\{x\}^c \subseteq \cup U_{y \neq x}$. To show the converse, for every $z \in \cup U_{y \neq x}$ that is open, there exists a $y \neq x$ such that $z \in U_y$. But every $U_y$ does not contain $x$ as an element, so $z \neq x$ implies that $z \notin \{x\}$. And $z \in \{x\}^c$. Hence $\cup U_{y \neq x} = \{x\}^c$.

Now conversely if every $x \in X$ satisfies the fact that $\{x\}^c$ is open, then $\{x\}^c$ is an open set that contains every $y \neq x$. Now fix some $y \neq x$, since $\{y\}$ is also closed, we have $X \cap \{x\}^c$ is an open set that contains $x$ but not y. Also, $\{x\}^c$ is an open set that contains $y$ but not $x$. And therefore $X$ is $T_1$. ■

## Theorem 4.8

**Proposition 8.1.** *The map $f : X \to Y$ is continuous if and only if at $f$ is continuous at every $x \in X$.*

*Proof.* Suppose that $f$ is continuous, then fix any $f(x) \in Y$ and any of its neighbourhood $V \in \mathcal{N}_B(f(x))$,

$$f(x) \in V^o \implies f^{-1}(V^o) \in \mathcal{N}_B(x)$$

But by continuity, $f^{-1}(V^o)$ is an open set that contains $x$, with

$$f\left(f^{-1}(V^o)\right) \subseteq V^o$$

Therefore $f$ is continuous at $x$. Now suppose that $f$ is continuous at every $x \in X$, then for every open subset $V \subseteq Y$, and for every point $f(x) \in V = V^o$ means that $V \in \mathcal{N}_B(f(x))$ for all such points $f(x)$. By continuity, for every $x$ in $f^{-1}(V)$, implies that $f^{-1}(V)$ is a neighbourhood of all of its elements, therefore $f^{-1}(V) \subseteq (f^{-1}(V))^o$, and $f^{-1}(V)$ is open. ■

## Theorem 4.9

**Proposition 9.1.** *If $\mathcal{E}_Y$ generates the topology on $Y$, and $f$ is a mapping from $X \to Y$, then $f : X \to Y$ is continuous if and only if $f^{-1}(V) \in \mathcal{T}_X$ for every $V \in \mathcal{E}_Y$.*

*Proof.* The inverse image commutes with intersections, complements, and unions. To prove $\Longleftarrow$, use Theorem 4.4, since every $U \in \mathcal{T}_Y$ can be represented the union of finite intersections of elements $\mathcal{E}_Y$, and use the fact that $\mathcal{T}_X$ is closed under arbitrary unions and finite intersections.

To show $\Longrightarrow$, since $\mathcal{E}_Y \subseteq \mathcal{T}_Y$, if $f^{-1}$ is open for every $U \in \mathcal{T}_Y$, then it is open for every $U \in \mathcal{E}_Y$ as well. ■

# Theorem 4.10

**Proposition 10.1.** *If $X_\alpha$ is Hausdorff for each $\alpha \in A$, then $X = \prod_{\alpha \in A} X_\alpha$ is Hausdorff.*

*Proof.* If two elements in $X$, $x \neq y$ then there exists some $\alpha \in A$ such that $\pi_\alpha(x) \neq \pi_\alpha(y) \in X_\alpha$, but this $X_\alpha$ is Hausdorff, then there exists two open, disjoint sets $V_x, V_y \subseteq X_\alpha$ such that

- $x \in \pi_\alpha^{-1}(V_x)$, and $y \in \pi_\alpha^{-1}(V_y)$
- $\pi_\alpha^{-1}(V_x) \cap \pi_\alpha^{-1}(V_y) = \pi_\alpha^{-1}(V_x \cap V_y) = \varnothing$
- $\pi_\alpha^{-1}(V_x), \pi_\alpha^{-1}(V_y) \in \mathcal{T}_X$

Where for the last bullet point we used the fact that the product topology makes all the projection maps continuous. This proves that $X$ is Hausdorff. ∎

## Theorem 4.11

**Proposition 11.1.** *If $X_\alpha$ and $Y$ are topological spaces, and $X = \prod_{\alpha \in A} X_\alpha$, and $f : Y \to X$ is a mapping. Then $f$ is continuous if and only if $\pi_\alpha \circ f$ is continuous for each $\alpha \in A$.*

*Proof.* If $\pi_\alpha \circ f$ is continuous at each $\alpha$, this means that

$$\forall \alpha \in A,\ \forall E_\alpha \in \mathcal{T}_\alpha,\ f^{-1}(\pi_\alpha^{-1}(E_\alpha)) \in \mathcal{T}_Y$$

But it is exactly sets of the form $\pi_\alpha^{-1}(E_\alpha)$ which generate the weak topology for $\mathcal{T}_X$. Therefore $f$ is continuous.

Now, suppose that $f$ is continuous, by definition of the weak topology (as it is generated by the set of inverse projections), for every $\alpha \in A$, $\pi_\alpha^{-1}(E_\alpha) \in \mathcal{T}_X$ and by continuity of $f$, its inverse image is open in $Y$ as well. ■

**Remark 11.1** *The take-away intuition here is that if the range space is generated by some $\mathcal{E}$, then a function is continuous if and only if all inverse images of sets in $\mathcal{E}$ are open in the domain space. Furthermore, if the range space is endowed with the product topology (which is generated by sets of the form $\pi_\alpha^{-1}(E_\alpha)$, where $E_\alpha \in \mathcal{T}_\alpha$), then it suffices to check all inverse images of those. And this is equivalent to checking that $\pi_\alpha(\cdot) \circ f$ is continuous at each $\alpha$.*

## Theorem 4.12

**Proposition 12.1.** *If $X$ is a topological space, and $A$ is any non-empty set, $\{f_n\} \subseteq X^A$ is a sequence, then $f_n \to f$ with respect to the product topology if and only if $f_n \to f$ pointwise.*

*Proof.* Suppose that $f_n \to f$ pointwise. Since the product topology $\mathcal{T}_X$ is generated from sets of the form

$$\pi_\alpha^{-1}(E_\alpha),\ E_\alpha \in \mathcal{T}_\alpha$$

And by Theorem 4.4, $\mathcal{T}_X$ consists of $\varnothing, X$ and unions of finite intersections of $\pi_\alpha^{-1}(E_\alpha)$. We claim that for every $f \in X^A$, the following is a valid neighbourhood base for $f$

$$\left\{ \bigcap_{j \leq n} \pi_{\alpha_j}^{-1}(E_{\alpha_j}),\ E_{\alpha_j} \in \mathcal{T}_{\alpha_j} \cap \mathcal{N}_B(\pi_{\alpha_j}(f)) \right\}$$

A couple things to note

- Each $E_{\alpha_j}$ is open in $X_{\alpha_j}$, so that its inverse image is also open (in $X$). Since any neighbourhood base has to be a subset of $\mathcal{T}_X$.
- Only finitely many intersections are involved, so each element in the above set is open in $X$.
- Each $E_{\alpha_j}$ is a neighbourhood of $\pi_{\alpha_j}(f)$, meaning $f \in E_{\alpha_j}^o = E_{\alpha_j}$.
- Last and perhaps most importantly for intuition, fix any non-empty open set $U \in \mathcal{T}_X$ then by Theorem 4.4 (or my reading of it), $U$ can be written as the union of sets like

  $$\bigcap_{j \leq m} \pi_{\alpha_j}^{-1}(E_{\alpha_j}), \quad E_{\alpha_j} \in \mathcal{T}_{\alpha_j}$$

  Then applying Theorem 4.2, the family of finite intersections of $\pi_\alpha^{-1}(E_\alpha)$ is a base for $\mathcal{T}_X$. Then,

  $$N_{base}(f) = \left\{ V = \bigcap_{j \leq m} \pi_{\alpha_j}^{-1}(E_{\alpha_j}), \quad E_{\alpha_j} \in \mathcal{T}_{\alpha_j}, \quad f \in V \right\}$$

  Has to be a neighbourhood base for any $f \in X$.

Now to show that $f_n \to f$ in the product topology, fix any neighbourhood $U \in \mathcal{N}_B(f)$, then $f \in U^o$, and by definition of a neighbourhood base, there exists some $E \in N_{base}(f)$ such that $f \in E \subseteq U^o$, but this $E$ is just the finite intersection of $\pi_{\alpha_j}^{-1}(E_{\alpha_j})$, then at every $\alpha_j$

- Let $N_j$ be an integer such that for every $n \geq N_j$, $\pi_{\alpha_j}(f_n) \in E_{\alpha_j}$
- Set $N = \sum_{j \leq m} N_j \geq N_j$ for every $j \leq m$.

Then for every $n \geq N$, $f_n \in E \subseteq U^o \subseteq U$ for any arbitrary neighbourhood $U$ of $f$. So $f_n \to f$ in the product topology.

Conversely, suppose that $f_n \to f$ in the product topology, then fix any $\alpha \in A$, and for every neighbourhood $E_\alpha$ of $\pi_\alpha(f)$, $\pi_\alpha^{-1}(E_\alpha)$ is a neighbourhood of $f$. Hence for every $\alpha \in A$, and for every neighbourhood $E_\alpha$ of $\pi_\alpha(f)$, $pi_\alpha(f_n)$ is eventually in $E_\alpha$. This completes the proof. ■

## Theorem 4.13

**Proposition 13.1.** *If $X$ is a topological space then* $\mathrm{BC}(X)$ *is a closed subspace of $B(X)$ in the uniform metric, and $BC(X)$ is complete.*

*Proof.* We will prove four things, the last two are just book-keeping. Parts (b, d) imply Part (c), as the closure of any set under a complete metric space is again complete.

(a) $B(X)$ endowed with the uniform norm of an $f \in B(X)$

$$\|f\|_u = \sup\{|f(x)|,\ x \in X\}$$

Is indeed a normed vector space.

(b) $B(X)$ with its norm (and induced metric), is a complete metric space. So that our $\{f_n\} \to f$ at worst, converges to $f \in B(X)$.

(c) If $\{f_n\}_{n\geq 1} \subseteq \mathrm{BC}(X)$ is a uniformly Cauchy sequence, and $f_n \to f$, then $f \in \mathrm{BC}(X)$.

(d) If $f$ is an adherent point of $\mathrm{BC}(X)$, then $f \in \mathrm{BC}(X)$.

To show that $B(X)$ is a normed vector space, for any $k \in \mathbb{C}$, $f_1, f_2 \in B(X)$, then at every $x \in X$

$$|f_1(x) + kf_2(x)| \leq |f_1(x)| + |k| \cdot |f_2(x)| \leq \|f_1\|_u + |k|\|f_2\|_u$$

And to show absolute homogeneity, note that $\sup |kA| = |k| \cdot \sup A$ for any non-empty bounded above set of reals $A$. This proves (a).

To show (b), fix any Cauchy sequence in $B(X)$ (with respect to the uniform metric), then for every $\varepsilon > 0$, there exists an $N$ so large that for every $n, m \geq N$ we have

$$|f_n(x) - f_m(x)| \leq \|f_n - f_m\|_u < \varepsilon$$

This shows that $\{f_n(x)\}_{n\geq 1} \subseteq \mathbb{C}$ is Cauchy, and it makes sense to call its limit $f(x) = \lim f_n(x)$. To show that for this $f$,

- $f_n \to f$ uniformly, and

- $f \in B(X)$

Fix an $\varepsilon > 0$, and there exists an $N$ so large that for every $m, n \geq N$ implies that
$$\|f_n(x) - f_m(x)\|_u < \varepsilon$$
Since $\lim_{n\to\infty} f_n(x) = f(x)$, this means that

$$\lim_{n\to\infty} |f_n(x) - f_m(x)| = |f(x) - f_m(x)| \leq \varepsilon$$

The above holds for any $x$, hence

$$\|f_m - f\|_u \leq \varepsilon \implies \|f\|_u \leq \|f_m - f\|_u + \|f_m\|_u < +\infty$$

This proves both bullet points.

Proof of (c): Now we will prove Theorem 4.13, for any sequence $\{f_n\} \subseteq \mathrm{BC}(X)$, if it does converge to some $f$ uniformly, then we claim that $f \in \mathrm{BC}(X)$. Note that $f \in B(X)$, so it suffices to show continuity at every $x_0 \in X$.

Fix any ball with radius $\varepsilon > 0$ at $f(x_0) \in \mathbb{C}$, and since

- $\varepsilon/3 > 0$ induces some $N$ such that for every $n \geq N$, at every point $x \in X$
$$|f_n(x_0) - f(x_0)| \leq \|f_n - f\|_u < \varepsilon/3$$
- Another $\varepsilon/3$ gives us an open ball around $f_n(x_0)$ in $\mathbb{C}$ (using the same point $x_0 \in X$). Continuity of $f_n$ gives us
$$f_n^{-1}(\ B(\varepsilon/3,\ f_n(x_0))\ ) = U \in \mathcal{T}_X$$
- If $x$ is a point in $U$,
$$|f_n(x) - f(x)| \leq \|f_n - f\|_i < \varepsilon/3$$
this gives us the last $\varepsilon/3$.

Combining these three,

$$|f(x) - f(x_0)| \leq \underbrace{|f(x) - f_n(x)| + |f(x_0) - f_n(x_0)|}_{\text{uniform convergence}} + \underbrace{|f_n(x_0) - f_n(x)|}_{\text{continuity of } f_n} < \varepsilon$$

So there exists some open set $U \in \mathcal{T}_X$ (and hence neighbourhood of every $x$), for every open ball of radius $\varepsilon > 0$, around every $f(x) \in \mathbb{C}$, such that

$$f(U) \subseteq B \in \mathcal{T}_{\mathbb{C}}$$

Since the open balls are a neighbourhood base at every point in $\mathbb{C}$, and $f$ is continuous at every point $x \in X$, we must conclude that $f \in \mathrm{BC}(X)$.

Part (d): Let $f \in \overline{\mathrm{BC}(X)}$. Notice $\mathrm{BC}(X)$ is a metric space, hence first countable. There exists a sequence $\{f_n\} \subseteq \mathrm{BC}(X)$ that converges to $f$. Convergent sequeneces in any metric space is Cauchy, apply Part (c) finishes the proof. ■

## Theorem 4.14

**Proposition 14.1.** *Suppose that $A$ and $B$ are disjoint closed subsets of the normal space $X$, and let $\Delta = \{k2^{-n} : n \geq 1$ and $0 < k < 2^n\}$ be the set of dyadic rationals in $(0, 1)$. There is a family $\{U_r : r \in \Delta\}$ of open sets such that*

1. *$A \subseteq U_r \subseteq B^c$ for every $r \in \Delta$,*
2. *$\overline{U_r} \subseteq U_s$ for $r < s$, and*
3. *For every $r < s$, $\overline{U}_r \subseteq U_s$*

*Proof.* The goal of this proof is to show that for every $r \in \Delta$, there exists a open $U_r$ that satisfies the above. As usual for these types of proofs we will proceed by induction. We can divide the problem by 'layers' (as I will hereinafter explain).

Let us suppose that for some $N \geq 1$ that all previous $U_r$ in previous layers have been constructed properly, meaning if $r = k/2^n$, then for every $1 \leq n \leq N - 1$, we have

$$r = \frac{k}{2^n},\ 1 \leq n \leq N - 1,\ 1 \leq k \leq 2^{n-1}$$

And by 'constructed properly', we mean that for each $U_r$,

- $A \subseteq U_r \subseteq B^c$ and
- $U_r \in \mathcal{T}_X$

Then for this fixed layer $N \geq 1$, we only have to construct the $U_{k/2^N}$ for every odd $k$, this is because if $k$ is an even number, then $k = 2j$ and $r = 2j/2^N = j/2^{N-1}$ and for this particular $U_r$ is already constructed. So for every odd $k = 2j + 1$, the sets of the form $U_{(k-1)/2^N}$ and $U_{(k+1)/2^N}$ are already defined, and satisfy

$$A \subseteq \overline{U}_{(k-1)/2^N} \subseteq U_{(k+1)/2^N} \subseteq B^c$$

For every $k - 1 \neq 0$ and $k + 1 \neq 1$. (We will consider these cases later). We claim that for every pair of open sets, $E_1, E_2 \in \mathcal{T}_X$, then there exists some open set $G \in \mathcal{T}_X$ such that if $(E_1, E_2) \in H \subseteq (\mathcal{T}_X \times \mathcal{T}_X)$ where $H$ is defined as the set

$$H = \left\{(E_1, E_2) \subseteq (\mathcal{T}_X \times \mathcal{T}_X) : \overline{E_1} \cap E_2^c = \varnothing\right\}$$

Then there exists some $G = \mathcal{J}(E_1, E_2) \in \mathcal{T}_X$ such that

$$E_1 \subseteq \overline{E_1} \subseteq G \subseteq \overline{G} \subseteq E_2$$

Now consider any any $(E_1, E_2) \in H$, then this pair induces a pair of disjoint sets $\overline{E_1}$ and $E_2^c$ since

$$\overline{E_1} \subseteq E_2 \implies \overline{E_1} \cap E_2^c = \varnothing$$

And by normality, there exists disjoint open sets $G_1$, $G_2$ such that

- $\overline{E_1} \subseteq G_1 \in \mathcal{T}_X$
- $E_2^c \subseteq G_2 \in \mathcal{T}_X$
- $G_1 \cap G_2 = \varnothing \implies G_1 \subseteq G_2^c \subseteq E_2$
- Since $G_2^c$ is a closed set that contains $G_1$ as a subset, $\overline{G_1} \subseteq G_2^c \subseteq E_2$

It is at this point that we will make no further mention of $G_2$ (so we may discard the notion of $G_2$ in our minds). Let us now replace $G$ with $G_1$ then it is an easy task to verify that $G = G_1 = \mathcal{J}(E_1, E_2)$ has the required properties.

Now define for every odd $k$, since $(U_{(k-1)/2^N}, U_{(k+1)/2^N}) \in H$ (we note in passing that $\mathcal{J}$ is not a function as the set $G$ may not be unique).

$$U_{k/2^N} = \mathcal{J}\left(U_{(k-1)/2^N}, U_{(k+1)/2^N}\right)$$

Then, if $U_{(k-1)/2^N}$ and $U_{(k+1)/2^N}$ is 'well constructed' we have

$$A \subseteq \overline{U}_{(k-1)/2^N} \subseteq U_{(k+1)/2^N} \subseteq B^c$$

Therefore $U_{k/2^N} = \mathcal{J}(U_{(k-1)/2^N}, U_{(k+1)/2^N})$ sits 'right inbetween' the two sets so that

- $A \subseteq \overline{U}_{(k-1)/2^N} \subseteq U_{k/2^N}$ and
- $\overline{U}_{k/2^N} \subseteq U_{(k+1)/2^N} \subseteq B^c$

Combining the above two estimates will give us a 'well constructed' $U_{k/2^N}$ for every $k-1 \neq 0$ and $k+1 \neq 1$. Now let us deal with the remaining pathological cases.

If $k-1$ so happens to be 0, then no $r \in \Delta$ satisfies $r = 0/2^N$, and we substitute

$$\overline{U}_0 = A, \qquad \text{or alternatively, } U_0 = A^o$$

Then $U_0 \in \mathcal{T}_X$, $\overline{U}_0 = A \subseteq B^c$. It is at this point that we must mention that $0, 1 \notin \Delta$, so $U_0$ and $U_1$ do not have to obey the rules we have laid out for $U_{r\in\Delta}$.

Now if $k+1$ is equal to $2^N$ (this makes $r = (k+1)/2^N = 1$) we define

$$U_1 = B^c \in \mathcal{T}_X$$

With this, for every $0 \leq m \leq 2^N - 1, U_{m/2^N}$ must staisfy

$$\overline{U}_{m/2^N} \subseteq B^c = U_1$$

And the pair $(U_{(k-1)/2^N}, U_{(k+1)/2^N}) \in H$ (even for when $N = 1$, since $A = \overline{U}_0 \subseteq U_1 = B^c$) and a corresponding $U_{k/2^N} = \mathcal{J}(\cdot, \cdot)$ such that

- $A \subseteq \overline{U}_{(k-1)/2^N} \subseteq U_{k/2^N}$
- $\overline{U}_{(k+1)/2^N} \subseteq B^c$

Now as a final step, we complete the base case for when $N = 1$. We would only have to construct for $k = 1$, since

$$U_{1/2} = \mathcal{J}(U_0, U_1) = \mathcal{J}(A, B^c)$$

Apply the induction step, and the proof is complete, at long last. ■

## Theorem 4.15

**Proposition 15.1.** *Urysohn's Lemma. Let $X$ be a normal space, if $A$ and $B$ are disjoint closed subsets of $X$, then there exists a $f \in C(X, [0,1])$ such that $f = 0$ on $A$ and $f = 1$ on $B$.*

*Proof.* Let $r \in \Delta$ be as in Lemma 4.14, and set $U_r$ accordingly except for $U_1 = X$. Define

$$f(x) = \inf\{k : x \in U_k\}$$

Let us also write $W = \{k : x \in U_k\}$, Then for every $x \in A$ we have $f(x) = 0$, since by the construction of the 'onion' function in Lemma 4.14, for each $r \in \Delta \cap (0, 1)$,

$$x \in A \subseteq U_r \implies f(x) \leq r$$

Since $r > 0$ is arbitrary, and $0 \in W$, we can use a classic $\varepsilon$ argument. If $f(x) > 0$ then there exists some $0 < r < f(x)$ by density of the dyadic rationals on the line, if $f(x) < 0$ then this implies that there exists some $f(x) < r < 0$ such that $x \in U_r$, but no $r \in \Delta$ can be negative, hence $f(x) = 0$.

Now, for every $x \in B$, since $A$ and $B$ are disjoint, and $A \subseteq U_r \subseteq B^c$, then for every $x \in B$ means that $x$ is not a member of any $U_r$, but we set $U_1 = X$. Since none of the $r \in (0, 1)$ is a member of the set we are taking the infimum, and $x \in U_1 = X$. The $\varepsilon$ argument follows: suppose for every $\varepsilon > 0$, $(1 - \varepsilon) \notin W$, and $1 \in W$, then $f(x) = 1$.

Since $x \in U_1 = X$, for every $x \in X$, $f(x) \leq 1$, and $f(x)$ cannnot be negative as $r > 0$ for every $r \in \Delta$. So $0 \leq f(x) \leq 1$. Now we have to show that this $f(x)$ is continuous. The remainder of the proof is divided into two parts. We would like to show that the inverse images of the half lines are open in $X$. So $f^{-1}((-\infty, \alpha)) \in \mathcal{T}$ and $f^{-1}((\alpha, +\infty)) \in \mathcal{T}$.

Suppose that $f(x) < \alpha$, so $\inf W < \alpha$, and using the density of $\Delta$, there exists an $r$, $f(x) < r < \alpha$ such that $x \in U_r$ such that $x \in \bigcup_{r<\alpha} U_r$. So $f^{-1}((-\infty, \alpha)) \subseteq \bigcup_{r<\alpha} U_r$.

Fix an element $x \in \bigcup_{r<\alpha} U_r$, this induces an $r$ such that $\inf W \leq r < \alpha$ therefore $f(x) < \alpha$, and $\bigcup_{r<\alpha} U_r \subseteq f^{-1}((-\infty, \alpha))$.

For the second case, suppose that $f(x) > \alpha$, then $\inf W > \alpha$, and there exists an $r$ (by density) such that $\inf W > r > \alpha$ such that for every $k \in W$, $k \neq r$. Therefore $x \notin U_r$, but by density again, and using the property of the onion function: for every $s < r$ we get $\overline{U_s} \subseteq U_r$, taking complements (which reverses the estimate) — we have $x \notin \overline{U_s}$, but $\left(\overline{U_s}\right)^c$ is open in $X$. It immediately follows that

$$x \in f^{-1}((\alpha, +\infty)) \implies x \in (U_r)^c \subseteq \left(\overline{U_s}\right)^c \subseteq \bigcup_{s>\alpha} \left(\overline{U_s}\right)^c$$

So $f^{-1}((\alpha, +\infty))$ is a subset of $\bigcup_{s>\alpha} \left(\overline{U_s}\right)^c$. To show the reverse, fix an element $x$ in the union, then this induces some $x \in \left(\overline{U_s}\right)^c \subseteq (U_s)^c$. Then for this $s > \alpha$, $(-\infty, s)$ contains no elements of $W$. This is because for every $p < s$ implies that $(U_s)^c \subseteq (U_p)^c$, so $p \notin W$. Our chosen $s$ is a lower bound for $W$, and $\alpha < s \leq \inf W = f(x)$.

Since all of the inverse images from the generating set of $(\mathbb{R}, \mathcal{T}_{\mathbb{R}})$ are open in $X$, using Theorem 4.9 finishes the proof. ■

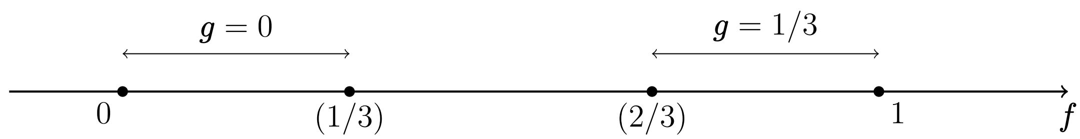


Figure 2: Lemma 16.1 for Theorem 4.16: Separate the range of $f \in C(A, [0,1])$ into three parts. Subtract an additional $g$ that reduces the error even further.

## Theorem 4.16

**Proposition 16.1.** *The Tietze's Extension Theorem. Let $X$ be a normal space, and for any closed subset $A \subseteq X$, and $f \in C(A, [a,b])$, there exists an $F \in C(X, [a,b])$ which extends $f$.*

*Proof.* We begin with an important lemma that will serve as a 'black box' for the induction.

**Lemma 16.1** *For every $f \in C(A, [0,1])$, there exists a $g \in C(X, [0,1/3])$ such that*

$$0 \leq f - g \leq 2/3 \quad \textit{pointwise on } A \tag{11}$$

*Proof.* Since $f$ is continuous, $B = f^{-1}([0,1/3])$, and $C = f^{-1}([2/3,1])$ are closed, disjoint subsets. Applying Urysohn's Lemma (Theorem 4.15) we get a continuous function $g \in C(X, [0,1])$ such that $g|_B = 0$ and $g|_C = 1$. Rescale $g$ by a factor of $1/3$, and $g \in C(X, [0,1/3])$.

To show that Equation (11) holds, suppose $x \in B$, then $f(x) \in [0,1/3]$ and $g(x) = 0 \implies 0 \leq f - g \leq 1/3 \leq 2/3$. Now suppose that $x \in C$, then $f(x) \in [2/3,1]$ and $g(x) = 1/3$ (recall that we relabelled $g$). So we have $0 \leq 1/3 \leq f - g \leq 2/3$. Lastly, for the case where $x \notin (B \cup C)$, then $f(x) \in (1/3, 2/3)$, and $g(x) \in [0,1/3]$ implies that

$$\begin{aligned} 1/3 < f(x) < 2/3 \quad &\implies 1/3 \leq f(x) \leq 2/3 \\ 0 \leq g(x) \leq 1/3 \quad &\implies -1/3 \leq -g(x) \leq 0 \end{aligned}$$

Therefore $0 \leq f(x) - g(x) \leq 2/3$. See Figure 2.

■

We can assume that $f \in C(A, [0,1])$, since we can relabel $f = (f-a)/(b-a)$. The main part of this proof consists of constructing a sequence of $\{g_n\} \subseteq C(X, \mathbb{R})$ where $0 \leq g_n \leq (2/3)^n(1/2)$, and $0 \leq f - \sum_{j \leq n} g_j \leq (2/3)^n$ on $A$. Let us begin with the base case with $n = 1$. We can apply Lemma 16.1 to get $g_1 \in C(X, [0, 1/3])$

$$0 \leq f - g_1 \leq (2/3)^1$$

Now let us suppose that $\{g_j\}_{j \leq n}$ has been chosen, we will find our $g_{n+1}$ by noting that

$$0 \leq f(x) - \sum_{j \leq n} g_j(x) \leq (2/3)^n$$

Here is where my proof deviates from that of Folland's, we multiply both sides by $(2/3)^{-n}$ and we obtain a new function in $C(A, [0,1])$.

$$0 \leq \left( f(x) - \sum_{j \leq n} g_j(x) \right) \left( \frac{3}{2} \right)^n \leq 1$$

Applying Lemma 16.1, we get a function $h \in C(X, [0, 1/3])$ that reduces the error between $f$ and the partial sums of $g_{j \leq n-1}$. For every $x \in A$

$$0 \leq \left( f(x) - \sum_{j \leq n} g_j(x) \right) \left( \frac{3}{2} \right)^n - h \leq 2/3$$

Multiplying across gives

$$0 \leq \left( f(x) - \sum_{j \leq n} g_j(x) \right) - h \left( \frac{2}{3} \right)^n \leq \left( \frac{2}{3} \right)^{n+1}$$

Set $g_{n+1} = h \left( \frac{2}{3} \right)^n$ and $g_{n+1} \in C(X, [0, 2^n/3^{n+1}])$. Furthermore, the sum of all $g_j$ pointwise converges uniformly, as

$$\sum_{j \geq 1} \|g_j\|_u \leq \sum_{j \geq 1} \left( \frac{2}{3} \right)^j \cdot \frac{1}{2} < +\infty$$

Denote the pointwise sum $F = \sum g_j$, then this $F \in BC(X)$ (by Theorem 4.13 and 5.1). And

$$\left\| f - \sum_{j \leq n} g_j \right\|_u \leq \left( \frac{2}{3} \right)^n \longrightarrow 0$$

So $F = f$ on $A$, now if we want to obtain our $F$ on $[a, b]$ we simply relabel $F = F(b-a) + a$. This finishes the proof. ■

## Theorem 4.17

**Proposition 17.1.** *If $X$ is a normal space, and $A$ is a closed subspace of $X$, and $f \in C(A)$, then there exists an $F \in C(X)$ such that $F$ extends $f$.*

*Proof.* First we suppose that $f$ is real valued, so $f \in C(X, \mathbb{R})$. And define a $g \in C(A, (-1, +1)) \subseteq C(A, [-1, +1])$, using

$$g = \frac{f}{1 + |f|}$$

Since $g$ satisfies the assumption of Theorem 4.16 (note that we do not require $g$ to be injective), there exists a $G \in C(X, [-1, +1])$ such that $G|_A = g$. Since the set $\{-1, +1\}$ is closed in $\mathbb{R}$, $G^{-1}(\{-1, +1\})$ is closed as well. Since $G^{-1}((-1, +1)) \subseteq A$, this makes $A$ and $B =^{-1} (\{-1, +1\})$ disjoint closed sets in $X$.

By Urysohn's Lemma, there exists a continuous function $h \in C(X, [0, 1])$ such that $h|_B = 0$ and $h|_A = 1$, so that the product $|hG| < 1$ for all $x \in X$. We can think of this $h$ as a continuous indicator function that filters out the parts we do not want, namely $G^{-1}\{-1, +1\}$. Now define $F$ in the following manner, since division is permissible

$$F = \frac{hG}{1 - |hG|}$$

We will show that $F|_A = g/(1 - |g|) = f$ indeed. Since $|g| = \frac{|f|}{1+|f|}$, and $g(1 + |f|) = f$ implies that $g/(1 - |g|) = f$, because $g \in C(A, (-1, +1))$ This completes the proof for any $f \in \mathbb{R}$ if $f \in C(A)$, then

1. $\mathrm{Re}(f) = f_1 \in C(A, \mathbb{R})$
2. $\mathrm{Im}(f) = f_2 \in C(A, \mathbb{R})$

And by our previous argumentation, there exists two functions in $C(X, \mathbb{R})$ that extends $f_1$ and $f_2$, and $F_1 + iF_2 = f$ on $A$ and $F_1 + iF_2 \in C(X)$, and the proof is complete. ■

## Theorem 4.18

**Proposition 18.1.** *If $X$ is a topological space, and $E \subseteq X$ and $x \in X$, then $x \in \operatorname{acc} E \iff$ there exists a net in $E \setminus \{x\}$ that converges to $x$, and $x \in \overline{E} \iff$ there exists a net in $E$ that converges to $x$.*

*Proof.* Suppose that $x \in \operatorname{acc} E$, then for every neighbourhood $U \in \mathcal{N}(x)$, $E \cap U \setminus \{x\} \neq \varnothing$, then choose $\mathcal{N}(x)$ as the set of neighbourhoods directed by reverse inclusion (and this makes $(\mathcal{N}(x), \lesssim)$ a directed set), and we will define the net as follows.

Map each $U \in \mathcal{N}(x)$ to some $x_U \in E \cap U \setminus \{x\}$, then this net converges to $x$. Suppose that we fix a neighbourhood, $V \in \mathcal{N}(x)$, then for every $U \gtrsim V$ we have $x_u \in U \subseteq V$. So $\langle x_U \rangle$ is eventually in $V$.

Conversely, if $\langle x_\alpha \rangle \subseteq E \setminus \{x\}$, and $x_\alpha \to x$, then every $U \in \mathcal{N}(x)$ there exists a $x_\alpha \in E \cap U \setminus \{x\}$ that makes

$$E \cap U \neq \varnothing \quad \forall U \in \mathcal{N}(x)$$

Hence $x \in \operatorname{acc} E$.

Now for the second part of the Theorem, suppose that $x \in \overline{E}$, if $x \notin E$ then $E = E \setminus \{x\}$ and $x \in \operatorname{acc} E$, so there exists a net in $E \setminus \{x\} \subseteq E$ such that $x_\alpha \to x$. If $x \in E$ then simply choose $\langle x_\alpha \rangle = x$ for every $\alpha \in A$.

Now, suppose that there is a net that converges to $x$, and this net $\langle x_\alpha \rangle \subseteq E$, if $x \in E$ then there is nothing to prove, since $E \subseteq \overline{E}$, so suppose that $x \notin E$, then there exists a net in $E \setminus \{x\} = E$ such that

$$x_\alpha \to x \implies x \in \operatorname{acc} E \subseteq \overline{E}$$

∎

## Theorem 4.19

**Proposition 19.1.** *Let $X$ and $Y$ be topological spaces, then every $f : X \to Y$ is continuous at a point $x \in X \iff$ every net $\langle x_\alpha \rangle$ that converges to $x$ implies that $\langle f(x_\alpha) \rangle$ converges to $f(x)$.*

*Proof.* If $f$ is continuous at a point $x \in X$, then $V \in \mathcal{N}(f(x)) \implies f^{-1}(V) \in \mathcal{N}(x)$, then for every net $\langle x_\alpha \rangle$ that converges to this $x$, there there exists an $\alpha_0$ such that for every $\alpha \gtrsim \alpha_0$ implies that $x_\alpha \in f^{-1}(V)$. Hence

$$f(x_\alpha) \in f\left(f^{-1}(V)\right) \subseteq V$$

And this is equivalent to saying that for every $V \in \mathcal{N}(f(x))$, $\langle f(x_\alpha) \rangle$ is eventually in $V$, and this proves convergence.

Now suppose that $f$ is not continuous at some $x$, then there exists a $V \in \mathcal{N}(f(x))$ such that $f^{-1}(V) \notin \mathcal{N}(x)$, so

$$x \notin \left(f^{-1}(V)\right)^o \implies x \in \left(f^{-1}(V)\right)^{oc} = \overline{f^{-1}(V^c)}$$

Where for the last equality we pulled the complement inside the inverse image. Then by Theorem 4.18, our $x \in \overline{f^{-1}(V^c)}$ induces a net $\langle x_\alpha \rangle \subseteq f^{-1}(V^c)$ that converges to $x$. But every element in the net is contained within $f^{-1}(V^c)$, and for every $\alpha \in A$

$$f(x_\alpha) \in f\left(f^{-1}(V^c)\right) \subseteq V^c$$

gives $f(x_\alpha) \notin V$, but $V$ is a neighbourhood of $f(x)$, hence there exists some $x_\alpha \to x$ and $f(x_\alpha) \not\to f(x)$. ■

## Theorem 4.20

**Proposition 20.1.** *If $\langle x_\alpha \rangle$ is a net in $X$, and $x \in X$ is a cluster point of $\langle x_\alpha \rangle \iff$ there exists a subnet of $\langle x_\alpha \rangle$ that converges to $x$.*

*Proof.* Suppose that $\langle y_\beta \rangle_{\beta \in B}$ is a subnet of $\langle x_\alpha \rangle$ that converges to $x$, then for every neighbourhood $U \in \mathcal{N}(x)$ , there exists a $\beta_1$ such that for every $\beta \gtrsim \beta_1$ we get $y_\beta = x_{\alpha_\beta} \in U$.

Furthermore, let us fix a $\alpha_0 \in A$ to attempt to show that $\langle x_\alpha \rangle$ is frequently in $U$, then by the subnet property of $\langle y_\beta \rangle$, there exists some $\beta_2 \in B$ such that for every $\beta \gtrsim \beta_2$, $\alpha_\beta \gtrsim \alpha_0$. (Intuitively this property means that the directed set of $B$ 'grows' as much as the directed set of $A$, so we can always find elements that are greater than any fixed $\alpha_0$.)

Since $\langle y_\beta \rangle$ is a net, we there exists some $\beta \in B$ such that $\beta \gtrsim \beta_1$ and $\beta \gtrsim \beta_2$, we then apply the $\beta \mapsto \alpha_\beta$ map and we obtain some $\alpha = \alpha_\beta$ that satisfies:

- $\alpha = \alpha_\beta \gtrsim \alpha_0$
- $x_\alpha = x_{\alpha_\beta} \in U$

Where for the second property we used the fact that $\beta \gtrsim \beta_1$ so that $y_\beta$ falls into $U$.

Conversely, suppose that $x$ is a cluster point of $\langle x_\alpha \rangle$, then by definition

$$\forall U \in \mathcal{N}(x),\ \forall \alpha_0 \in A,\ \exists \alpha \gtrsim \alpha_0,\ x_\alpha \in U$$

Denote the directed neighbourhoods of $x$ by $\mathcal{N}(x)$, and construct our directed set $B$ for our subnet as follows, define

$$B = \mathcal{N}(x) \times A$$

Where for every $(U, \gamma) \in B$ we can map it to some $\alpha_{(U,\gamma)} \in A$, if we choose some $\alpha_{(U,\gamma)} \gtrsim \gamma$ and $\alpha_{(U,\gamma)} \in U$.

To show that $B$ is a directed set, we say that $(U, \gamma) \gtrsim (U', \gamma')$ if and only if $U \subseteq U'$ and $\gamma \gtrsim \gamma'$. And to show that $\langle y_\beta \rangle = \langle x_{\alpha_{(U,\gamma)}} \rangle$ is indeed a subnet of $\langle x_\alpha \rangle$, fix any $\alpha_0 \in A$, then simply take any neighbourhood $U$ of $x$ (we always have $X \in \mathcal{N}(x)$) — and therefore $(U, \alpha_0) \in B$.

Now for every $(U', \alpha_0') \gtrsim (U, \alpha_0)$ implies that $\alpha_0' \gtrsim \alpha_0$, therefore we have

$$\alpha_{(U', \alpha_0')} \gtrsim \alpha_0' \gtrsim \alpha_0$$

And this satisfies the subnet property. Now to show that $\langle y_\beta \rangle$ indeed converges to $x$, fix any $V \in \mathcal{N}(x)$, then with any $\alpha_0 \in A$, and for every $(V', \alpha_0') \gtrsim (V, \alpha_0) \in B$, we have

$$x_{\alpha_{(V', \alpha_0')}} \in V' \subseteq V$$

So $\langle x_{\alpha_{(U,\gamma)}} \rangle$ converges to $x$. ■

## Theorem 4.21

**Proposition 21.1.** *A topological space $X$ is compact $\iff$ every family of closed sets, $\{F_\alpha\}_{\alpha\in A}$ that has the finite intersection property, implies that*

$$\bigcap_{\alpha\in A} F_\alpha \neq \varnothing$$

*Proof.* We first examine the assertion, Theorem 4.21 proposes for any family of closed sets $\{F_\alpha\}_{\alpha\in A}$, and for every finite subset $B \subseteq A$ then,

$$\bigcap_{\alpha\in B} F_\alpha \neq \varnothing \implies \bigcap_{\alpha\in A} F_\alpha \neq \varnothing$$

Taking the contrapositive (which is logically equivalent), we get

$$\bigcap_{\alpha\in A} F_\alpha = \varnothing \implies \text{there exists a finite } B \subseteq A, \bigcap_{\alpha\in B} F_\alpha = \varnothing$$

Applying DeMorgan's theorem, and since every $\{F_\alpha\}_{\alpha\in A}$ induces a family of open sets (and vice versa), where $U_\alpha = F_\alpha^c$, so for any familiy of open sets $\{U_\alpha\}_{\alpha\in A}$ we have

$$\bigcup_{\alpha\in A} U_\alpha = X \implies \text{there exists a finite } B \subseteq A, \bigcup_{\alpha\in B} U_\alpha = X$$

Which is equivalent to saying that $X$ is compact. ■

## Theorem 4.22

**Proposition 22.1.** *A closed subset of a compact space $X$ is compact.*

*Proof.* Suppose $F \subseteq X$ and $F$ is open, then fix an open cover for $F$, so

$$F \subseteq \bigcup_{\alpha \in A} U_\alpha$$

Since $F^c$ is an open set, we can obtain a valid open cover for $X$, then we pick out a finite subcover, for some finite $B \subseteq A$

$$X = F \cup F^c \subseteq F^c \cup \left( \bigcup_{\alpha \in B} U_\alpha \right)$$

Taking the intersection with $F$ on both sides yields

$$\begin{aligned}
&F = X \cap F \subseteq (F^c \cap F) \cup \left( F \cap \left( \bigcup_{\alpha \in B} U_\alpha \right) \right) \\
&F = \left( F \cap \left( \bigcup_{\alpha \in B} U_\alpha \right) \right) \iff \\
&F \subseteq \bigcup_{\alpha \in B} U_\alpha
\end{aligned}$$

Therefore every open cover of $F$ has a finite subcover, and $F$ is compact. ∎

## Theorem 4.23

**Proposition 23.1.** *If $F$ is a compact subset of a Hausdorff space $X$, and $x \notin F$, there are disjoint open sets $U, V$ such that $x \in U$ and $F \subseteq V$.*

*Proof.* Since $x \in F^c$, for every $y \in F$, $x \neq y$ induces two sets $U_y, V_y$ (because $X$ is $T_2$).

- $U_y \cap V_y = \varnothing$
- $x \in U_y$
- $y \in V_y$

But $\{V_y\}_{y \in F}$ is an open cover for the compact set $F$, then there exists a finite subcollection $H \subseteq F$ such that

$$F \subseteq \bigcup_{y \in H} V_y$$

Since $H$ is finite, $U = \bigcap_{y \in H} U_y$ is an open set that contains $x$, also define $V = \bigcup_{y \in H} V_y$. If for every $y \in H$, $U_y \cap V_y = \varnothing$, then $U \cap V_y = U \cap V = \varnothing$. This completes the proof. ■

**Remark 23.1** *Every metric space $(X, d)$ is first countable, and $T_2$ (it is actually $T_4$, but that will require some effort to prove, see Exercise 3). The first claim is easily verified if we fix any element $x \in X$ and we notice that $W_x = \{V_r(x), r \in \mathbb{Q}^+\}$ is a countable neighbourhood base for every $x$. To show that $(X, d)$ is $T_2$, for every pair of elements $x \neq y$, we can take $r = d(x, y)/2$ and there exists disjoint open sets $V_r(x)$ and $V_r(y)$ such that $x \in V_r(x)$ and $y \in V_r(y)$.*

# Theorem 4.24

**Proposition 24.1.** *Every compact subset of a Hausdorff ($T_2$) space is closed.*

*Proof.* If $F$ is compact, then for every $x \in F^c$, by Theorem 4.23, there exists two disjoint open sets such that $x \in U$ and $F \subseteq V$, but

$$U \cap V = \varnothing \implies U \cap F = \varnothing \implies U \subseteq F^c$$

But since $x \in F^c$ is arbitrary, and $U$ is an open subset of $F^c$,

$$x \in U \subseteq F^{co} \implies F^c \subseteq F^{co}$$

Which shows that $F^c$ is open and $F$ is closed. ■

## Theorem 4.25

**Proposition 25.1.** *Every compact Hausdorff ($T_2$) space is normal ($T_4$).*

*Proof.* Fix $A$, $B$ which are disjoint closed subsets of $X$, by Theorem 4.22, we know that these two sets are compact. Hence for every $y \in B$ there exists two disjoint open sets $U, V_y$ (by Theorem 4.23)

$A \subseteq U_y$ and $y \in V_y$. But the family $\{V_y\}_{y \in B}$ is s a valid open cover for the compact set $B$, hence there exists a finite subcollection $H \subseteq B$ such that

$$B \subseteq \bigcup_{y \in H} V_y, \quad U_y \cap V_y = \varnothing$$

The second equality holds for every $y \in H$ so that $U_y \cap (\cup V_{y \in H}) = \varnothing$. Define $U = \cap U_{y \in H}$ and $V = \cup V_{y \in H}$, where both of these are disjoint open sets that that contain $A$ and $B$ as subsets, since for each $y \in H$, $A \subseteq U_y$ hence the intersection of all $U_y$ also contains $A$ as a subset. Therefore $X$ is normal. ■

## Theorem 4.26

**Proposition 26.1.** *If $X$ is compact, and $f : X \to Y$ is continuous, then $f(X)$ is compact.*

A small lemma.

> **Lemma 26.1** *For every $\{E_j\} \subseteq X, f(\cup E_j) = \cup f(E_j)$.*

The proof is trivial.

*Proof.* If $\{V_{\alpha\in A}\}$ is an open cover for $f(X)$, then

$$X \subseteq f^{-1}(f(X)) = f^{-1}\left(\bigcup_{\alpha\in A} V_\alpha\right) = \bigcup_{\alpha\in A} f^{-1}(V_\alpha) \subseteq X$$

Since $f$ is continuous, we have an open cover in the form of $\{f^{-1}(V_\alpha)\}$ for $X$, then there exists a finite subset $B \subset A$ such that

$$X \subseteq \bigcup_{\alpha\in B} f^{-1}(V_\alpha)$$

Then we wish to show that for this $B \subseteq A$, $\{V_{\alpha\in B}\}$ is a finite open cover for $f(X)$. Fix any element $y \in f(X)$, then this induces a $x \in X$ such that $y = f(x)$, but because $\{f^{-1}(V_{\alpha\in B})\}$ is an open cover for $X$, there exists some $\alpha \in B$ such that $x \in f^{-1}(V_\alpha)$, hence by definition of the inverse image

$$f(x) \in V_\alpha \implies f(X) \subseteq \bigcup_{\alpha\in B} V_\alpha$$

Therefore $f(X)$ is compact and this completes the proof. ■

## Theorem 4.27

**Proposition 27.1.** *If $X$ is compact, then $C(X) = BC(X)$.*

*Proof.* Notice that $BC(X) \subseteq C(X)$, so we only have to show the reverse estimate. Fix any $f \in C(X)$, since $X$ is compact, by Theorem 4.26 we know that $f(X)$ is also compact. Since $\mathbb{C} = \mathbb{R}^2$ is a complete metric space, $f(X)$ is bounded and $f \in BC(X)$. ∎

# Theorem 4.28

**Proposition 28.1.** *If $X$ is compact, and if $Y$ is Hausdorff, then any continuous bijection $f : X \to Y$ is a homeomorphism.*

*Proof.* If $E \in X$ is closed, then since $X$ is compact, $E$ is compact as well. By continuity of $f$, $f(X)$ is a compact set in $Y$, but compact subsets of $Y$ are closed, so $f$ is continuous.

We used the fact that the inverse of $f^{-1}$ is $f$, since it suffices to check that every inverse image of a closed set is also closed, $f^{-1}$ is continuous. And by definition of a homeomorphism ($f$ has to be bijective and both $f$ and $f^{-1}$ hav eto be continuous), $f$ is a homeomorphism. ∎

## Theorem 4.29

**Proposition 29.1.** *If $X$ is any topological space, the following are equivalent.*

*(a) $X$ is compact.*

*(b) Every net has a cluster point.*

*(c) Every net in $X$ has a convergent subnet.*

*Proof.* By Theorem 4.20, every net in $X$ has a cluster point $\iff$ there exists a subnet that converges to this cluster point, so these two points are equivalent.

Suppose $a$) holds, then $X$ is compact, and fix an arbitrary net $\langle x_\alpha \rangle$ in $X$. and define the 'tail' of the net

$$E_\alpha := \{x_\beta,\ \beta \gtrsim \alpha\}$$

We wish to show that the arbitrary intersection of $\bigcap_{\alpha \in A} \overline{E}_\alpha \neq \varnothing$. Where $\overline{E}_\alpha$ is closed, so it suffices to check that every finite $B \subseteq A$, the intersection over $\overline{E}_\alpha$ is non-empty.

Suppose we are given a finite $B \subseteq A$, then fix any two elements $\alpha$ and $\beta \in B$, by the definition of a net there exists a $\gamma \in A$ such that $\gamma \gtrsim \alpha$ and $\gamma \gtrsim \beta$, and

$$\varnothing \neq \subseteq E_\alpha \cap E_\beta \implies \overline{E}_\alpha \cap \overline{E}_\beta \neq \varnothing$$

Therefore for any finite collection of $\{\overline{E}_{\alpha \in B}\}$, then

$$\bigcap_{\alpha \in A} \overline{E}_\alpha \neq \varnothing$$

Now fix an element $x \in \bigcap_{\alpha \in A} \overline{E}_\alpha$. Then for every $\alpha \in A$, $x \in \overline{E}_\alpha$, and for every neighbourhood $U \in \mathcal{N}(x)$, $U \cap E_\alpha \neq \varnothing$. This is because if $x \in E_\alpha$, then $U \cap E_\alpha$ contains at least $\{x\}$, if $x \in \operatorname{acc} E_\alpha$, then by definition of an accumulation point, $U \cap E_\alpha \setminus \{x\} \neq \varnothing$, so the intersection is non empty.

Now let us turn our attention to how we defined the 'tail' of the net, $E_\alpha$, if for every $\alpha \in A$, $x \in E_\alpha$ if and only if there exists some $\gamma \gtrsim \alpha$, $x_\gamma \in U \cap E_\alpha$, this is equivalent to saying that $x$ is a cluster point of $\langle x_\alpha \rangle$. So $a) \implies b)$.

Now let us suppose that $X$ is not compact, then there exists an open cover $\{U_{\alpha \in A}\}$ of $X$ that has no finite subcover. Let $\mathbb{B}$ be the collection of all finite subsets of $A$, directed by set inclusion (we will show that this set is indeed a directed set at another time, for now it is a needless distraction).

Now for every $B \in \mathbb{B}$, find some $x_B \in (\bigcup_{\alpha \in B} U_\alpha)^c$. So we have a net in $X$. Now we will show that no $x \in X$ can be a cluster point of this net. Suppose not, then take a neighbourhood $U_\beta$ with $\beta \in A$ such that $U_\beta$ belongs to the open cover we first discussed. Then for any $B \in \mathbb{B}$ such that $B \gtrsim \{\beta\}$ (meaning that $\{\beta\} \subseteq B$, where $B$ is a finite set), then

$$x_B \in \left(\bigcup_{\alpha \in B} U_\alpha\right)^c \implies x_B \notin \left(\bigcup_{\alpha \in \{\beta\}} U_\beta\right) \implies x_B \in U_\beta^c$$

Hence no point in $X$ can be a cluster point for this net, and the proof is complete. ■

## Theorem 4.30

**Proposition 30.1.** *If $X$ is a LCH space, and for every $U \in \mathcal{N}_B(x) \cap \mathcal{T}_X$, there exists a compact $N \subseteq U$ where $N \in \mathcal{N}_B(x)$.*

*Proof.* For every $U \in \mathcal{N}_B(x) \cap \mathcal{T}_x$, we can find an $E$ open subset of $U$ that has a compact closure, since every $x \in X$ induces some compact $F \in \mathcal{N}_B(x)$, therefore

$$E := U \cap F^o \implies \overline{E} \subseteq F$$

Since closed subsets of compact sets are compact (by Theorem 4.22), $\overline{E}$ is compact. More is true, since $E$ is open,

$$x \in U \cap F^o \implies x \in E^o \implies E \in \mathcal{N}_B(x)$$

Now it suffices to show that there exists some compact $N \subseteq E \subseteq U$ such that $N \in \mathcal{N}_B(x)$. Since $\overline{E}$ is compact, the closed subset $\partial E = \overline{E} \cap \overline{E^c}$ of $\overline{E}$ is also compact.

Since $\partial E \cap E^o = \varnothing$, $x \in E^o = E$ means that $x \notin \partial E$. Applying Theorem 4.23 to the compact set $\partial E$ and $x \notin \partial E$ gives us two disjoint open sets $V'$ and $W'$. We list their properties

1. $V', W' \in \mathcal{T}_X$
2. $x \in V'$
3. $\partial E \subseteq W'$
4. $V' \cap W' = \varnothing$

The two disjoint pairs induce another pair of open sets relative to $\overline{E}$, recall the definition of the topology relative to $\overline{E}$,

$$\mathcal{T}_{\overline{E}} = \left\{ A \cap \overline{E} : A \in \mathcal{T}_X \right\}$$

We now agree to define

- $V = V' \cap \overline{E}$
- $W = W' \cap \overline{E}$

Then evidently $V, W \in \mathcal{T}_{\overline{E}}$ and

1. $x \in V' \cap \overline{E} \implies x \in V$
2. $\partial E \subseteq \overline{E} \implies \partial E \subseteq W$
3. $V' \cap W' = \varnothing \implies V \cap W = \varnothing$

Furthermore,

$$\partial E \subseteq W \implies W^c \subseteq (\partial E)^c = E^o \cup E^{co}$$

Taking the intersection over $\overline{E}$ gives us

$$\overline{E} \setminus W \subseteq \overline{E} \cap (E^o \cup E^{co})$$

Note that $E^{co} = (\overline{E})^c$, since $(E^c)^{oc} = \overline{(E^{cc})} = \overline{E}$ therefore $\overline{E} \cap E^{oc} = \varnothing$, hence

$$\overline{E} \setminus W \subseteq \overline{E} \cap E^o = E^o$$

Using the fact from 3, $V \subseteq W^c$ and $V \subseteq \overline{E}$ and $V \subseteq W^c$ implies that $V \subseteq \overline{E} \setminus W$. Compiling everything, we have

$$V \subseteq \overline{E} \setminus W \subseteq E$$

Note that the set $\overline{E} \setminus W$ is closed in $\mathcal{T}_X$ (and hence closed in $\overline{E}$) by closure over intersections, $\overline{V}$ is therefore a closed subset of $\overline{E} \setminus W$, and $\overline{V}$ is compact. Also

$$\overline{V} \subseteq \overline{E} \setminus W \subseteq E$$

To check that $\overline{V} \in \mathcal{N}_B(x)$, note that

$$x \in V^o \subseteq (\overline{V})^o \implies \overline{V} \in \mathcal{N}_B(x)$$

The subset relation $V^o \subseteq \overline{V}^o$ comes from the fact that $V^o$ is an open subset of $\overline{V}$, and hence is contained in $(\overline{V})^o$ as a subset. Now let us define $N = \overline{V}$, and $N$ satisfies the assertions in the Theorem, since

- $N \in \mathcal{N}_B(x)$
- $N$ is compact
- $N \subseteq E \subseteq U$

And this completes the proof. ■

**Remark 30.1** *Intuitively speaking, this means that if $X$ is any LCH space, then for every open neighbourhood $U \in \mathcal{N}_B(x)$, there exists a compact $E \in \mathcal{N}_B(x)$ such that $x \in E \subseteq U^o$. This property is indeed a very strong one as it allows us to have effectively 'infinite' descending compact neighbourhoods of $x$.*

## Theorem 4.31

**Proposition 31.1.** *$X$ is a LCH space, and $K \subseteq U \subseteq X$ where $K$ is compact, and $U$ is open, then there exists some precompact, open $V$ with*

$$K \subseteq V \subseteq \overline{V} \subseteq U$$

*Proof.* For every $x \in K$, we can apply Proposition 4.30, since $x \in K \subseteq U$, this induces some compact $F_x \subseteq U$ where $F_x \in \mathcal{N}_B(x)$. Then we can obtain an open cover of $U$ in the form of $\{F_x^o\}_{x \in K}$. By compactness of $K$, there exists a finite $B \subseteq K$ such that

$$K \subseteq \bigcup_{x \in B} F_x^o$$

Let $V = \bigcup_{x \in B} F_x^o$, then clearly $V$ is open, and $K \subseteq V$. Since each $F_x$ is closed (compact sets are closed in any Hausdorff Space), we have

$$V \subseteq \bigcup_{x \in B} F_x \implies \overline{V} \subseteq \bigcup_{x \in B} F_x$$

Since $\bigcup_{x \in B} F_x$ is a finite union of compact sets, we claim that it is also compact. Consider two compact sets $E_1$ and $E_2$, then if $\{U_\alpha\}_{\alpha \in A}$ is any open cover of $E_1 \cup E_2$, it must be an open cover for $E_1$ and $E_2$ as well, because

$$E_1, E_2 \subseteq E_1 \cup E_2 \bigcup_{\alpha \in A} U_\alpha$$

Since $E_1$ and $E_2$ are both compact sets, they each induce two finite subsets of $B_1$, $B_2$ of $A$ whose union $B = B_1 \cup B_2$ is also compact. Therefore

$$E_1 \cup E_2 \subseteq \bigcup_{\alpha \in B} U_\alpha$$

Then a simple proof by induction will show that if $\{E_{j \leq n}\}$ is a family of compact sets, then $E = \bigcup E_{j \leq n}$ is also compact.

Returning to the main part of the proof, $\bigcup_{x \in B} F_x$ is a compact set, therefore $\overline{V}$ is also compact. Moreover

$$\forall x \in K,\ F_x \subseteq U \implies \overline{V} \subseteq \bigcup_{x \in B} F_x \subseteq U$$

Combining, we have

- $K \subseteq V \subseteq \overline{V}$,
- $V$ is open and $\overline{V}$ is compact, and
- $\overline{V} \subseteq U$

This completes the proof. $\blacksquare$

## Theorem 4.32

**Proposition 32.1.** *Urysohn's Lemma, Locally Compact Version. For any LCH space $X$, and if $K \subseteq U \subseteq X$ where $K$ is compact and $U$ is open, then there exists some $f \in C(X, [0,1])$ with*

- $f = 1$ *on* $K$
- $f = 0$ *outside some compact* $\overline{V} \subseteq U$

*Proof.* Let $V$ be as in Theorem 4.31, for our fixed $K \subseteq U \subseteq X$, there exists a pre-compact, open $V$ that satisfies

$$K \subseteq V \subseteq \overline{V} \subseteq X$$

It follows that this $(\overline{V}, \mathcal{T}_{\overline{V}})$ is a normal space by Theorem 4.25 (compact Hausdorff spaces are normal), and by Urysohn's Lemma (Theorem 4.15) on normal spaces, since we can easily find two disjoint closed subsets of $\overline{V}$ in the form of

- $K \subseteq V^o = V \subseteq \overline{V}$ (compact sets in Hausdorff spaces are closed)
- $\partial V = \overline{V} \cap \overline{V^c}$ (closed sets in compact spaces are compact)
- $K \subseteq V^o$ implies that $K \cap \partial V = K \cap (\overline{V} \setminus V^o) = \varnothing$

Then there exists a continuous $f|_{\overline{V}} \in C(\overline{V}, [0,1])$ that evaluates to

- $f|_{\overline{V}} = 1$ on closed $K$
- $f|_{\overline{V}} = 0$ on closed $\partial V$

Now let us extend $f|_{\overline{V}}$ to $f$ by defining

$$f|_{(\overline{V})^c} = 0$$

We will show that this extension of $f$ is indeed continuous. Indeed, for every closed set $E \subseteq [0,1]$ that does not contain 0, we have:

$$0 \notin E \implies \{0\} \cap E = \varnothing \implies f^{-1}(\{0\}) \cap f^{-1}(E) = \varnothing$$

But $(\overline{V})^c \subseteq f^{-1}(\{0\})$ therefore

$$(\overline{V})^c \cap f^{-1}(\{0\}) \cap f^{-1}(E) = (\overline{V})^c \cap f^{-1}(E) = \varnothing \implies f^{-1}(E) \subseteq \overline{V}$$

We can write
$$f^{-1}(E) = f|_{\overline{V}}^{-1}(E)$$
But we know that $f|_{\overline{V}}$ is continuous, so $f|_{\overline{V}}^{-1}(E)$ must be closed (with respect to $\overline{V}$), and therefore is closed wrt $X$, since $\overline{V}$ is closed wrt X.

For the case where $0 \in E$, note that
$$f^{-1}(E) = \left(f^{-1}(E) \cap \overline{V}\right) \cup \left(f^{-1}(E) \cap (\overline{V})^c\right) = \left(f|_{\overline{V}}\right)^{-1}(E) \cup \left(f|_{\overline{V}^c}\right)^{-1}(E)$$
The above equalities are messy in print. They are but a simple consequence of disjoint decomposition of the pre-images, since
$$\overline{V} \cap f^{-1}(E) = \{x \in \overline{V} : f(x) \in E\} = f|_{\overline{V}}^{-1}(E)$$
Back to our main discussion, recall that for every $x \in \partial V$
$$f(x) = 0 \in f^{-1}(\{0\}) \subseteq f^{-1}|_{\overline{V}}(E)$$
Therefore $\partial V \subseteq f^{-1}|_{\overline{V}}(E)$, and $(\overline{V})^c = f^{-1}|_{(\overline{V})^c}(E)$ gives us (since $V^c$ is closed),
$$\begin{aligned} f^{-1}(E) &= f^{-1}|_{\overline{V}}(E) \cup \partial V \cup (\overline{V})^c \\ &= f^{-1}|_{\overline{V}}(E) \cup \overline{(V^c)} \cup (\overline{V})^c \\ &= f^{-1}|_{\overline{V}}(E) \cup (V^c \cup V^{co}) \\ &= f^{-1}|_{\overline{V}}(E) \cup V^c \end{aligned}$$

Since $f^{-1}|_{\overline{V}}(E)$ and $V^c$ are closed subsets of $X$, then $f^{-1}(E)$ is also closed, and $f \in C(X, [0,1])$. ■

## Theorem 4.33

**Proposition 33.1.** *Every LCH space is completely regular (or $T_{3.5}$).*

*Proof.* Recall that a space $X$ is completely regular if it is $T_1$ and every closed subset $A$ and every $x \notin A$ there exists some

$$f \in C(X, [0,1]), \quad f(x) = 1,\ f|_A = 0$$

Fix a closed set $A \subseteq X$, then for every $x \in A^c$, there exists a compact $E_x \in \mathcal{N}_B(x)$ with $E_x \subseteq A^c$ (by Theorem 4.30).

Note that $E_x \subseteq A^c$ where $E_x$ is compact and $A^c$ is closed, then an application of Theorem 4.31 tell us that there exists an $f \in C(X, [0,1])$ such that for every $x \in E_x$, $f(x) = 1$ and for points $y \notin A^c$ (which means that $y \in A$), $f(y) = 0$. Therefore $X$ is completely regular. ■

## Theorem 4.34

**Proposition 34.1.**

*Proof.* ∎

## Theorem 4.35

**Proposition 35.1.** *If $X$ is a LCH space, we claim that*

$$\overline{\mathrm{C}_c(X)} = \mathrm{C}_0(X)$$

*Proof.* We begin by proving several things that are mentioned before this Theorem, namely

$$\mathrm{C}_c(X) \subseteq \mathrm{C}_0(X) \subseteq \mathrm{BC}(X)$$

Fix an $f \in \mathrm{C}_c(X)$, and for every $\varepsilon > 0$,

$$x \in |f|^{-1}([\varepsilon, +\infty)) \implies |f(x)| \geq \varepsilon > 0$$

Therefore $|f|^{-1}([\varepsilon, +\infty))$ is a closed subset of $\mathrm{supp}\,(f)$, since $(-\infty, \varepsilon)$ is open in $\mathbb{R}$, then $[\varepsilon, +\infty)$ is a closed set. And by continuity of $|\cdot| \circ f$ (a composition of two continuous functions), $|f|^{-1}([\varepsilon, +\infty))$ is closed. Using the fact that closed subsets of compact $\mathrm{supp}\,(f)$ are also compact, we get $f \in \mathrm{C}_0(X)$.

Next, we show that $\mathrm{C}_0(X) \subseteq \mathrm{BC}(X)$. Fix any element $f$ of $\mathrm{C}_0(X)$ with an arbitrary $\varepsilon > 0$, then $E_\varepsilon = \{x \in X : |f(x)| \geq \varepsilon\}$ is compact. The continuity of $f$ guarantees that the direct image of a compact set is another compact set (Theorem 4.26)

$$|f|(E_\varepsilon) \text{ is a compact subset of } \mathbb{R}$$

And therefore for every $x \in E_\varepsilon \implies |f(x)| \in f(E\varepsilon)$, then by Heine-Borel, there exists some $M \geq 0$ such that $|f(x)| \leq M$. If $x \notin E_\varepsilon$, then by definition of $E_\varepsilon$, implies that $|f(x)| < \varepsilon$. Then $|f(x)| \leq M + \varepsilon$ for every $x \in X$. Hence $f \in \mathrm{BC}(X)$.

Here I wish to offer an alternate proof for $\mathrm{C}_0(X) \subseteq \mathrm{BC}(X)$, we begin by constructing an open cover for $\mathrm{supp}\,(f)$ such that

$$\{U_n\}_{n>0} = \{x \in X | f(x)| < n\}$$

Then there exists a finite subcollection of $\{U_n\}_{n \in B}$ where $B$ is a finite set, then define $M = 1 + \sum_{n \in B} n$ and for every $x \in \mathrm{supp}\,(f)$ we have $|f(x)| < n$ and since $n > 0$ this holds for every $x \in X$ too. Therefore $f \in \mathrm{BC}(X)$.

For the main proof of Theorem 4.35, since $\mathrm{BC}(X)$ is endowed with the uniform metric, it is also first countable, and therefore by Theorem 4.6, it suffices to show that every sequence $\{f_n\}_{n\geq 1} \subseteq \mathrm{C}_c(X)$ converges in $\mathrm{C}_0(X)$. And every element $f \in \mathrm{C}_0(X)$ has a convergence sequence in $\mathrm{C}_c(X)$.

Fix a convergent sequence $\{f_n\}_{n\geq 1} \subseteq \mathrm{C}_c(X)$ that converges uniformly to some $f \in \mathrm{BC}(X)$ (since $\mathrm{BC}(X)$ is a closed subset of $C(X)$ with respect to the uniform norm), then for every $\varepsilon > 0$, there exists some $n \geq 1$ with

$$\|f_n - f\|_u < \varepsilon$$

We aim to show that $(\mathrm{supp}\,(f_n))^c \subseteq |f|^{-1}((-\infty, \varepsilon))$, so fix any $x \notin \mathrm{supp}\,(f_n)$, then

$$|f(x) - f_n(x)| = |f(x)| \leq \|f - f_n\|_u < \varepsilon$$

This establishes the estimate, and taking complements

$$|f|^{-1}([\varepsilon, +\infty)) \subseteq \mathrm{supp}\,(f_n)$$

Therefore for any arbitrary $\varepsilon > 0, \{x \in X,\ |f(x)| \geq \varepsilon\}$ is compact, and $\overline{\mathrm{C}_c(X)} \subseteq \mathrm{C}_0(X)$. Conversely, fix any $f \in \mathrm{C}_0(X)$, and for every $n \geq 1$, define

$$K_n = \{x \in X,\ |f(x)| \geq 1/n\}$$

Using Urysohn's Lemma for our LCH space $X$, there exists some $g_n$ that has a compact support, and $g_n(x) = 1$ for every $x \in K_n$. We then write $f_n = g_n \cdot f \in \mathrm{C}_c(X)$. We wish to show that $f_n \to f$ uniformly. Notice that for any fixed $n \geq 1$, if $x \in K_n$ then

$$f_n(x) = f(x) \implies |f_n - f|(x) = 0$$

If $x \notin K_n$, $|f(x)| < 1/n$ (recall what $K_n$ does), and $f_n = g_n \cdot f \in [0,1]$ by definition of $g_n$ from Theorem 4.32, hence

$$|f_n(x) - f(x)| = |f(x)| \cdot |1 - g_n| \leq |f(x)| < 1/n$$

Taking the supremum over $x \in X$, we have

$$\|f_n - f\|_u < 1/n \to 0$$

As we send $n$ to $+\infty$, and $f_n \to f$ uniformly. This completes the proof. ■

## Theorem 4.36

**Proposition 36.1.**

*Proof.* ■

## Theorem 4.37

**Proposition 37.1.** *If $X$ is an LCH space and $E \subseteq X$. $E$ is closed if and only if $E \cap K$ is closed for every compact $K \subseteq X$.*

*Proof.* Suppose that $E$ is closed, then $E \cap K$ is closed, since compact subsets of Hausdorff spaces are closed, and $E \cap K \subseteq K$ tells us that $E \cap K$ is indeed compact.

Now suppose that $E$ is not closed, by Theorem 4.1, $E \neq \overline{E}$, so pick some $x \in (\overline{E} \setminus E) = \operatorname{acc}(E) \cap E^c$, since $X$ is locally compact, let $K_x$ be a compact neighbourhood of $x$, then for every neighbourhood $U \in \mathcal{N}_B(x)$, we have

$$x \in U^o,\ x \in K_x^o, \implies x \in (U^o \cap K_x^o) \subseteq (U \cap K_x)^o$$

Since $(U^o \cap K_x^o)$ is an open subset of $(U \cap K_x)$, then $(U \cap K_x) \in \mathcal{N}_B(x)$, and recall that $x \in \operatorname{acc}(E)$, therefore

$$(U \cap K_x) \cap E \setminus \{x\} = U \cap (K_x \cap E) \neq \varnothing$$

But $x \notin E \implies x \notin E \cap K_x$. So $x$ is an accumulation point of $E \cap K_x$ that is not in $E \cap K_x$. Therefore there exists some $E \cap K_x$ (with $K_x$ compact) that is not closed. ■

## Theorem 4.38

**Proposition 38.1.** *If* $\mathbf{X}$ *is an LCH space,* $C(\mathbf{X})$ *is a closed subspace of* $\mathbb{C}^{\mathbf{X}}$ *in the topology of uniform convergence on compact sets. (We will sometimes refer to this as the topology of compact convergence.)*

*Proof.* Let $E \subseteq \mathbf{X}$ be closed and endowed with the subspace topology.

$$\mathcal{T}_E = \left\{ U \cap E,\, U \in \mathcal{T}_{\mathbf{X}} \right\}$$

Then $A \cap E$ is closed relative to $E$ iff it it is closed relative to $\mathbf{X}$. The proof for for this can be found in the Notes.

Let $f$ be an adherent point of $C(\mathbf{X})$ endowed with the topology of compact convergence. If $W$ is closed in $\mathbb{C}$, let $K$ range through compact sets of $\mathbf{X}$. $f|K$ is in the closure of $C(K, \mathbb{C})$, therefore continuous by Proposition 4.13, as $C_c(K) \subseteq BC(K)$. So $f|K$ is continuous, and $(f|K)^{-1}(W)$ is closed Rel. $K$. Notice

$$(f|K)^{-1}(W) = f^{-1}(W) \cap K \tag{12}$$

since we can write $(f|K)(x) = (f \circ \iota_K)(x)$. Where $\iota_K : K \to \mathbf{X}$ is the inclusion map, which is an embedding. Equation (12) follows immediately. Therefore $f^{-1}(W) \cap K = (f|K)^{-1}(W)$ is closed Rel. $K$, so it is closed Rel. $\mathbf{X}$. This holds for every compact $K$, so $f^{-1}(W)$ is closed for any closed $W \subseteq \mathbb{C}$, and $f$ is continuous. ∎

## Theorem 4.39

**Proposition 39.1.**

*Proof.* ■

## Theorem 4.40

**Proposition 40.1.**

*Proof.* ■

## Theorem 4.41

**Proposition 41.1.**

*Proof.* ■