

# Folland Reading

Me

October 28, 2022

## Contents

1	Chapter 1	4
1.1	Theorem 1.1 . . . . .	4
1.2	Theorem 1.2 . . . . .	5
1.3	Theorem 1.3 . . . . .	7
1.4	Theorem 1.4 . . . . .	8
1.5	Theorem 1.5 . . . . .	9
1.6	Theorem 1.6 . . . . .	10
1.7	Theorem 1.7 . . . . .	11
1.8	Theorem 1.8 . . . . .	12
1.9	Theorem 1.9 . . . . .	13
1.10	Theorem 1.10 . . . . .	14
1.11	Theorem 1.11 . . . . .	15
1.12	Theorem 1.12 . . . . .	16
1.13	Theorem 1.13 . . . . .	17
1.14	Theorem 1.14 . . . . .	18
1.15	Theorem 1.15 . . . . .	19
1.16	Theorem 1.16 . . . . .	20
1.17	Theorem 1.17 . . . . .	21
1.18	Theorem 1.18 . . . . .	22
2	Chapter 4	23
2.1	Theorem 4.1 . . . . .	23
2.2	Theorem 4.2 . . . . .	24
2.3	Theorem 4.3 . . . . .	25

2.4	Theorem 4.4 . . . . .	27
2.5	Theorem 4.5 . . . . .	29
2.6	Theorem 4.6 . . . . .	30
2.7	Theorem 4.7 . . . . .	31
2.8	Theorem 4.8 . . . . .	32
2.9	Theorem 4.9 . . . . .	33
2.10	Theorem 4.10 . . . . .	34
2.11	Theorem 4.11 . . . . .	35
2.12	Theorem 4.12 . . . . .	36
2.13	Theorem 4.13 . . . . .	38
2.14	Theorem 4.14 . . . . .	40
2.15	Theorem 4.15 . . . . .	43
2.16	Theorem 4.16 . . . . .	45
2.17	Theorem 4.17 . . . . .	47
2.18	Theorem 4.18 . . . . .	48
2.19	Theorem 4.19 . . . . .	49
2.20	Theorem 4.20 . . . . .	50
2.21	Theorem 4.21 . . . . .	52
2.22	Theorem 4.22 . . . . .	53
2.23	Theorem 4.23 . . . . .	54
2.24	Theorem 4.24 . . . . .	55
2.25	Theorem 4.25 . . . . .	56
2.26	Theorem 4.26 . . . . .	57
2.27	Theorem 4.27 . . . . .	58
2.28	Theorem 4.28 . . . . .	59
2.29	Theorem 4.29 . . . . .	60
2.30	Theorem 4.30 . . . . .	62
2.31	Theorem 4.31 . . . . .	64
2.32	Theorem 4.32 . . . . .	66
2.33	Theorem 4.33 . . . . .	68
2.34	Theorem 4.34 . . . . .	69
2.35	Theorem 4.35 . . . . .	70
2.36	Theorem 4.36 . . . . .	72
2.37	Theorem 4.37 . . . . .	73
2.38	Theorem 4.38 . . . . .	74
2.39	Theorem 4.39 . . . . .	75
2.40	Theorem 4.40 . . . . .	76
2.41	Theorem 4.41 . . . . .	77

3	Chapter 6	78
3.1	Theorem 6.15 . . . . .	78
4	Chapter 7	85
4.1	Theorem 7.1 . . . . .	85
4.2	Theorem 7.2 . . . . .	86
4.2.1	Part a . . . . .	89
4.2.2	Part b . . . . .	90
4.2.3	Part c . . . . .	91
4.2.4	Part d . . . . .	91
4.2.5	Part e . . . . .	91
4.2.6	Part f . . . . .	92
4.2.7	Part g . . . . .	94
4.2.8	Part h . . . . .	94
4.2.9	Part i . . . . .	95
4.2.10	Part j . . . . .	96
4.2.11	Part k . . . . .	96
4.2.12	Part l . . . . .	99
4.3	Theorem 7.3 . . . . .	100
4.4	Theorem 7.4 . . . . .	100
4.5	Theorem 7.5 . . . . .	101
4.6	Theorem 7.6 . . . . .	102
4.7	Theorem 7.7 . . . . .	103
4.8	Theorem 7.8 . . . . .	104
4.9	Theorem 7.9 . . . . .	105
4.10	Theorem 7.10 . . . . .	106
5	Chapter 8	107
5.1	Theorem 8.1 . . . . .	107
5.2	Theorem 8.2 . . . . .	108

# 1 Chapter 1

## 1.1 Theorem 1.1

WTS. Let  $\mathcal{M}(\mathcal{F})$  be the  $\sigma$ -algebra generated by  $\mathcal{F}$ , if  $\mathcal{E}$  is a subset of  $\mathbb{P}(X)$ , with  $\mathcal{E} \subseteq \mathcal{M}(\mathcal{F})$ , then  $\mathcal{M}(\mathcal{E}) \subseteq \mathcal{M}(\mathcal{F})$ .

Proof. Notice that because  $\mathcal{E} \subseteq \mathcal{M}(\mathcal{F})$ ,

$$\mathcal{M}(\mathcal{F}) \in \{\mathcal{M}, \mathcal{E} \subseteq \mathcal{M}, \mathcal{M} \text{ is a } \sigma\text{-algebra}\}$$

Taking the intersection, noting that  $\mathcal{M}(\mathcal{E})$  is the intersection of all  $\sigma$ -algebras containing  $\mathcal{E}$  as a subset, we have

$$\bigcap \{\mathcal{M}(\mathcal{F})\} \supseteq \bigcap \{\mathcal{M}, \mathcal{E} \subseteq \mathcal{M}, \mathcal{M} \text{ is a } \sigma\text{-algebra}\}$$

And

$$\mathcal{M}(\mathcal{E}) \subseteq \mathcal{M}(\mathcal{F})$$

□

## 1.2 Theorem 1.2

WTS. The Borel  $\sigma$ -algebra of  $\mathbb{R}$ ,  $\mathbb{B}_{\mathbb{R}}$  is generated by the following

- The family of open intervals  $\mathcal{E}_1 = \{(a, b), a < b\}$ ,
- The family of closed intervals  $\mathcal{E}_2 = \{[a, b], a < b\}$ ,
- The family of half-open intervals  $\mathcal{E}_3 = \{(a, b], a < b\}$  or  $\mathcal{E}_4 = \{[a, b), a < b\}$
- The open rays  $\mathcal{E}_5 = \{(a, +\infty), a \in \mathbb{R}\}$  or  $\mathcal{E}_6 = \{(-\infty, a), a \in \mathbb{R}\}$
- The closed rays  $\mathcal{E}_7 = \{[a, +\infty), a \in \mathbb{R}\}$  or  $\mathcal{E}_8 = \{(-\infty, a], a \in \mathbb{R}\}$

Proof. By definition,  $\mathbb{B}_{\mathbb{R}}$  is generated by the family of all open sets in  $\mathbb{R}$ , but every open set is a countable union of open intervals. Therefore

$$\mathcal{T}_{\mathbb{R}} \subseteq \mathcal{M}(\mathcal{E}_1) \implies \mathbb{B}_{\mathbb{R}} \subseteq \mathcal{M}(\mathcal{E}_1)$$

Conversely, every open interval is an open set, hence

$$\mathcal{E}_1 \subseteq \mathcal{T}_{\mathbb{R}} \subseteq \mathbb{B}_{\mathbb{R}} \implies \mathcal{M}(\mathcal{E}_1) \subseteq \mathbb{B}_{\mathbb{R}}$$

Every closed interval can also be written as a countable intersection of open intervals, for every  $[a, b]$ , with  $a < b$ , we have

$$[a, b] = \bigcap_{n \geq 1} (a - n^{-1}, b + n^{-1}) \quad (1)$$

Indeed, fix any  $x \in [a, b]$  then for every  $n \geq 1$ ,

$$a - n^{-1} < a \leq x \leq b < b + n^{-1}$$

So  $x \in \bigcap_{n \geq 1} (a - n^{-1}, b + n^{-1})$ . If  $x$  an element of the left member, then for every  $n \geq 1$ ,

$$a - n^{-1} < x \implies a - x \leq 0$$

Similarly for  $x \leq b$ , therefore equation (1) is valid, and  $\mathcal{E}_2 \subseteq \mathbb{B}_{\mathbb{R}} = \mathcal{M}(\mathcal{E}_1)$ . To show the reverse estimate, every open interval can be written as a countable union of closed intervals,

$$(a, b) = \bigcup_{n \geq 1} [a + n^{-1}, b - n^{-1}] \quad (2)$$

To show that the above estimate is indeed true, fix any  $x \in (a, b)$ , then

$$\begin{aligned} a < x < b &\iff a < a + n^{-1} \leq x \leq b - n^{-1} < b \\ &\iff x \in \bigcup_{n \geq 1} [a + n^{-1}, b - n^{-1}] \end{aligned}$$

So that equation (2) holds. By similar argumentation we have  $\mathcal{E}_1 \subseteq \mathcal{M}(\mathcal{E}_2) \implies \mathcal{M}(\mathcal{E}_2) = \mathcal{M}(\mathcal{E}_1)$ .

For  $\mathcal{E}_3, \mathcal{E}_4$

- $(a, b] = \bigcap_{n \geq 1} (a, b + n^{-1})$ , proves  $\mathcal{M}(\mathcal{E}_3) \subseteq \mathcal{M}(\mathcal{E}_1)$ ,
- $(a, b) = \bigcup_{n \geq 1} (a, b - n^{-1}]$ , proves  $\mathcal{M}(\mathcal{E}_1) \subseteq \mathcal{M}(\mathcal{E}_3)$ ,
- $[a, b) = \bigcup_{n \geq 1} [a, b - n^{-1}]$ , proves  $\mathcal{M}(\mathcal{E}_4) \subseteq \mathcal{M}(\mathcal{E}_2)$ ,
- $[a, b] = \bigcap_{n \geq 1} [a, b + n^{-1})$ , proves  $\mathcal{M}(\mathcal{E}_2) \subseteq \mathcal{M}(\mathcal{E}_4)$

So that  $\mathcal{M}(\mathcal{E}_1) = \mathcal{M}(\mathcal{E}_2) = \mathcal{M}(\mathcal{E}_3) = \mathcal{M}(\mathcal{E}_4) = \mathbb{B}_{\mathbb{R}}$ . By taking complements of each element we get  $\mathcal{M}(\mathcal{E}_5) = \mathcal{M}(\mathcal{E}_8)$  and  $\mathcal{M}(\mathcal{E}_6) = \mathcal{M}(\mathcal{E}_7)$ . Notice also that

- $(a, b] = (a, +\infty) \cap (-\infty, b]$ , proves  $\mathcal{E}_3 \subseteq \mathcal{M}(\mathcal{E}_5)$ , and  $\mathcal{M}(\mathcal{E}_3) \subseteq \mathcal{M}(\mathcal{E}_5)$ .
- $(a, +\infty) = \bigcup_{n \geq 1} (a, a + n]$ , proves  $\mathcal{E}_5 \subseteq \mathcal{M}(\mathcal{E}_3)$ , and  $\mathcal{M}(\mathcal{E}_5) \subseteq \mathcal{M}(\mathcal{E}_3)$ .
- $[a, b) = [a, +\infty) \cap (-\infty, b)$ , proves  $\mathcal{E}_4 \subseteq \mathcal{M}(\mathcal{E}_6)$ , and  $\mathcal{M}(\mathcal{E}_4) \subseteq \mathcal{M}(\mathcal{E}_7)$ ,
- $[a, +\infty) = \bigcup_{n \geq 1} [a, a + n)$ , proves  $\mathcal{E}_7 \subseteq \mathcal{M}(\mathcal{E}_4)$ , and  $\mathcal{M}(\mathcal{E}_7) \subseteq \mathcal{M}(\mathcal{E}_4)$ .

Finally,  $\mathcal{M}(\mathcal{E}_3) = \mathcal{M}(\mathcal{E}_5) = \mathcal{M}(\mathcal{E}_8) = \mathbb{B}_{\mathbb{R}}$  and  $\mathcal{M}(\mathcal{E}_4) = \mathcal{M}(\mathcal{E}_6) = \mathcal{M}(\mathcal{E}_7) = \mathbb{B}_{\mathbb{R}}$ .  $\square$

### 1.3 Theorem 1.3

WTS. If  $A$  is countable, then  $\otimes_{\alpha \in A} \mathcal{M}_\alpha$  is the  $\sigma$ -algebra generated by

$$W := \left\{ \prod_{\alpha \in A} E_\alpha, E_\alpha \in \mathcal{M}_\alpha \right\}$$

Proof. We agree to define

$$V := \left\{ \pi_\alpha^{-1}(E_\alpha), E_\alpha \in \mathcal{M}_\alpha \right\}$$

By definition,  $V$  generates  $\otimes_{\alpha \in A} \mathcal{M}_\alpha$ . Fix any element in  $x = \pi_\alpha^{-1}(E_\alpha) \in V$ , then

$$\pi_\alpha(x) \in E_\alpha, \pi_{\beta \neq \alpha}(x) \in X_\beta$$

Then  $x \in W$  if we choose  $x = \prod_{c \in A} E_c$ , for  $E_c = E_\alpha$  if  $c = \alpha$ , and  $E_c = X_c$  if  $c \neq \alpha$ .  $\square$

1.4 Theorem 1.4

WTS.

Proof.





1.5 Theorem 1.5

WTS.

Proof.



1.6 Theorem 1.6

WTS.

Proof.



1.7 Theorem 1.7

WTS.

Proof.

□

1.8 Theorem 1.8

WTS.

Proof.



1.9 Theorem 1.9

WTS.

Proof.

□

1.10 Theorem 1.10

WTS.

Proof.

□

1.11 Theorem 1.11

WTS.

Proof.



1.12 Theorem 1.12

WTS.

Proof.





1.13 Theorem 1.13

WTS.

Proof.



1.14 Theorem 1.14

WTS.

Proof.



1.15 Theorem 1.15

WTS.

Proof.



1.16 Theorem 1.16

WTS.

Proof.



1.17 Theorem 1.17

WTS.

Proof.



1.18 Theorem 1.18

WTS.

Proof.



## 2 Chapter 4

### 2.1 Theorem 4.1

WTS. Suppose that  $A$  is a subset of  $X$ , let  $\text{acc } A$  be the set of accumulation points of  $A$ , then

$$\overline{A} = A \cup \text{acc } (A) \quad (3)$$

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

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

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

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  $x \notin \text{acc } (A)$ ,

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

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

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

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  $x \in U^\circ \subseteq A^\circ$  (since  $U^\circ$  is an open subset of  $A^c$ ). then

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

Therefore  $(A \cup \text{acc } (A))^c \subseteq (\overline{A})^c$ . □

## 2.2 Theorem 4.2

WTS. 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

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

Where  $\mathcal{B}$  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.

□



### 2.3 Theorem 4.3

WTS. 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  $\mathcal{E} \subseteq \mathcal{T}$  to be a base of  $\mathcal{T}$ .

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

- $\emptyset \in \mathcal{T}$  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  $U_1 \cap U_2 \neq \emptyset$ , then for every  $x \in U_1 \cap U_2$  induces two sets  $V_1, V_2 \in \mathcal{E}$  with  $x \in V_1 \subseteq U_1$  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 every  $V \in \mathcal{E}$  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  $\mathcal{T}$ .  $\square$

## 2.4 Theorem 4.4

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

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

Proof. Denote the set

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

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,  $E_1 \in \{\emptyset, X\}$  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  $\mathcal{T}$ .

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

- 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  $E = \emptyset$  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  $E = \emptyset$  then  $E \in \mathcal{T}(\mathcal{E})$ , if not, then there exists some subset  $B \subseteq W$  such that

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

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.  $\square$

## 2.5 Theorem 4.5

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

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

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

## 2.6 Theorem 4.6

WTS. 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  $x_j \rightarrow x$ .

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  $x \in \text{acc}(A)$ , 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  $x \notin \text{acc}(A)$ , then fix any sequence  $\{x_j\} \subseteq A$ . We wish to show that  $x_j \not\rightarrow x$ .

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

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

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  $x_j \not\rightarrow x$  for any arbitrary sequence  $x_j$  in  $A$ .  $\square$

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

## 2.7 Theorem 4.7

WTS.  $X$  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 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  $T_1$ .  $\square$

## 2.8 Theorem 4.8

WTS. The map  $f : X \rightarrow Y$  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

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

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.  $\square$



## 2.9 Theorem 4.9

WTS. If  $\mathcal{E}_Y$  generates the topology on  $Y$ , and  $f$  is a mapping from  $X \rightarrow Y$ , then  $f : X \rightarrow Y$  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  $\Leftarrow$ , 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  $\Rightarrow$ , 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.  $\square$

## 2.10 Theorem 4.10

WTS. 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  $y \in \pi_\alpha^{-1}(V_y)$
- $\pi_\alpha^{-1}(V_x) \cap \pi_\alpha^{-1}(V_y) = \pi_\alpha^{-1}(V_x \cap V_y) = \emptyset$
- $\pi_\alpha^{-1}(V_x), \pi_\alpha^{-1}(V_y) \in \mathcal{T}_X$

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.  $\square$

## 2.11 Theorem 4.11

WTS. If  $X_\alpha$  and  $Y$  are topological spaces, and  $X = \prod_{\alpha \in A} X_\alpha$ , and  $f : Y \rightarrow X$  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.  $\square$

Remark. 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  $\alpha$ .

## 2.12 Theorem 4.12

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

Proof. Suppose that  $f_n \rightarrow f$  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  $\emptyset, X$  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  $f_n \rightarrow f$  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  $f_n \rightarrow f$  in the product topology.

Conversely, suppose that  $f_n \rightarrow f$  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.  $\square$

### 2.13 Theorem 4.13

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

Proof. Suppose that  $\{f_n\} \subseteq \mathbf{BC}(X)$  converges to some  $f$ . There are a couple things that we need to show prior to tackling the main proof.

- (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  $\{f_n\} \rightarrow f$  at worst, converges to  $f \in B(X)$ .

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 (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 a Cauchy, and it makes sense to call its limit  $f(x) = \lim f_n(x)$ . To show that for this  $f$ ,

- $f_n \rightarrow f$  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  $\lim_{n \rightarrow \infty} f_n(x) = f(x)$ , this means that

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

In the above we replaced the strict inequality with an inequality since the sequence may converge to its supremum. Since this holds for any  $x \in X$ , we have

$$\|f_m - f\|_u \leq \varepsilon$$

One can easily replace all the  $\varepsilon$  with  $\varepsilon/2$  to obtain strict inequalities, to finish the proof, simply send  $m \rightarrow \infty$  (since  $f_m \rightarrow f$  pointwise everywhere, the uniform norm goes to zero as well). This proves both bullet points.

Now we will prove Theorem 4.13, for any sequence  $\{f_n\} \subseteq \text{BC}(X)$ , if it does converge to some  $f$  uniformly, then we claim that  $f \in \text{BC}(X)$ . Note that  $f \in B(X)$ , so it suffices for us to show that  $f$  is continuous at every point  $x \in X$ .

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

- $\varepsilon/3 > 0$  induces some  $N$  such that for every  $n \geq N$ , at every point  $x \in X$

$$|f_n(x) - f(x)| \leq \|f_n - f\|_u < \varepsilon/3$$

- Another  $\varepsilon/3$  ball around  $f_n(x)$  (using the same point  $x \in X$ ), such that its inverse image is an open set  $U \in \mathcal{T}_X$ , because  $f_n \in \text{BC}(X)$

$$f_n^{-1}(V_{\varepsilon/3} f_n(x)) = U \in \mathcal{T}_X$$

- The last  $\varepsilon/3$  comes from the fact that  $y \in U \subseteq X$  so it satisfies

$$|f_n(y) - f(y)| \leq \|f_n - f\|_i < \varepsilon/3$$

Combining these three,

$$|f(y) - f(x)| \leq |f(y) - f_n(y)| + |f(x) - f_n(x)| + |f_n(x) - f_n(y)| < \varepsilon$$

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  $f \in \text{BC}(X)$ .  $\square$

## 2.14 Theorem 4.14

WTS. Suppose that  $A$  and  $B$  are disjoint closed subsets of the normal space  $X$ , and let  $\Delta = \{k2^{-n} : n \geq 1 \text{ and } 0 < k < 2^n\}$  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

$$H = \{(E_1, E_2) \in (\mathcal{T}_X \times \mathcal{T}_X) : \overline{E_1} \cap E_2^c = \emptyset\}$$



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

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

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

- $\overline{E_1} \subseteq G_1 \in \mathcal{T}_X$
- $E_2^c \subseteq G_2 \in \mathcal{T}_X$
- $G_1 \cap G_2 = \emptyset \implies G_1 \subseteq G_2^c \subseteq E_2$
- 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).

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

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

$$\bar{U}_0 = A, \quad \text{or alternatively, } U_0 = A^c$$

Then  $U_0 \in \mathcal{T}_X$ ,  $\bar{U}_0 = A \subseteq B^c$ . 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 satisfy

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

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

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

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. □

## 2.15 Theorem 4.15

WTS. 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  $f(x)$  cannot 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 union 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  $(\overline{U_s})^c$  is open in  $X$ . It immediately follows that

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

So  $f^{-1}((\alpha, +\infty))$  is a subset of  $\bigcup_{s > \alpha} (\overline{U_s})^c$ . To show the reverse, fix an element  $x$  in the union, then this induces some  $x \in (\overline{U_s})^c \subseteq (U_s)^c$ . 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.  $\square$

## 2.16 Theorem 4.16

WTS. 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 2.1. For every  $f \in C(A, [0, 1])$ , there exists a  $g \in C(X, [0, 1/3])$  such that

$$0 \leq f - g \leq 2/3 \quad \text{pointwise on } A \quad (4)$$

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  $g|_C = 1$ . Relabel  $g = g/3$  then  $g \in C(X, [0, 1/3])$  (multiplication is continuous).

To show that (4) 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

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

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

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 2.1 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 the Lemma 2.1, we get a function  $h \in C(X, [0, 1/3])$  such that, 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 4.9), since every  $g_j \in BC(X)$ . And

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

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.  $\square$

## 2.17 Theorem 4.17

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

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.  $\square$

## 2.18 Theorem 4.18

WTS. If  $X$  is a topological space, and  $E \subseteq X$  and  $x \in X$ , then  $x \in \text{acc } E \iff$  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  $x \in \text{acc } E$ , then for every neighbourhood  $U \in \mathcal{N}(x)$ ,  $E \cap U \setminus \{x\} \neq \emptyset$ , 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  $x_\alpha \rightarrow x$ , then every  $U \in \mathcal{N}(x)$  there exists a  $x_\alpha \in E \cap U \setminus \{x\}$  that makes

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

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

Now for the second part of the Theorem, suppose that  $x \in \overline{E}$ , if  $x \notin E$  then  $E = E \setminus \{x\}$  and  $x \in \text{acc } E$ , so there exists a net in  $E \setminus \{x\} \subseteq E$  such that  $x_\alpha \rightarrow x$ . 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

$$x_\alpha \rightarrow x \implies x \in \text{acc } E \subseteq \overline{E}$$

□



## 2.19 Theorem 4.19

WTS. Let  $X$  and  $Y$  be topological spaces, then every  $f : X \rightarrow Y$  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  $x_\alpha \rightarrow x$  and  $f(x_\alpha) \not\rightarrow f(x)$ .  $\square$

## 2.20 Theorem 4.20

WTS. 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  $x$ . □

## 2.21 Theorem 4.21

WTS. 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

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

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,

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

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

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

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 family 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. □

## 2.22 Theorem 4.22

WTS. 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.  $\square$

### 2.23 Theorem 4.23

WTS. 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  $T_2$ ).

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

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  $y \in H$ ,  $U_y \cap V_y = \emptyset$ , then  $U \cap V_y = U \cap V = \emptyset$ . This completes the proof.  $\square$

Remark. 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  $y \in V_r(y)$ .

## 2.24 Theorem 4.24

WTS. 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

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

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. □

## 2.25 Theorem 4.25

WTS. 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 a valid open cover for the compact set  $B$ , hence there exists a finite subcollection  $H \subseteq B$  such that

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

The second equality holds for every  $y \in H$  so that  $U_y \cap (\bigcup_{y \in H} V_y) = \emptyset$ . Define  $U = \bigcap_{y \in H} U_y$  and  $V = \bigcup_{y \in H} V_y$ , where both of these are disjoint open sets 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.  $\square$



## 2.26 Theorem 4.26

WTS. If  $X$  is compact, and  $f : X \rightarrow Y$  is continuous, then  $f(X)$  is compact.

A small lemma.

Lemma 2.2. 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.  $\square$

## 2.27 Theorem 4.27

WTS. 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  $f \in BC(X)$ .  $\square$

## 2.28 Theorem 4.28

WTS. If  $X$  is compact, and if  $Y$  is Hausdorff, then any continuous bijection  $f : X \rightarrow Y$  is a homeomorphism.

Proof. If  $E \subseteq X$  is closed, then since  $X$  is compact,  $E$  is compact as well. By continuity of  $f$ ,  $f(E)$  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  $f^{-1}$  have to be continuous),  $f$  is a homeomorphism.  $\square$

## 2.29 Theorem 4.29

WTS. 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

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

We wish to show that the arbitrary intersection of  $\bigcap_{\alpha \in A} \overline{E}_\alpha \neq \emptyset$ . 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  $\gamma \succeq \alpha$  and  $\gamma \succeq \beta$ , and

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

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

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

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  $U \in \mathcal{N}(x)$ ,  $U \cap E_\alpha \neq \emptyset$ . This is because if  $x \in E_\alpha$ , then  $U \cap E_\alpha$  contains at least  $\{x\}$ , if  $x \in \text{acc } E_\alpha$ , then by definition of an accumulation point,  $U \cap E_\alpha \setminus \{x\} \neq \emptyset$ , 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  $\gamma \succeq \alpha$ ,  $x_\gamma \in U \cap E_\alpha$ ,

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

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

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

### 2.30 Theorem 4.30

WTS. 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

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

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

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

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  $\partial E \cap E^\circ = \emptyset$ ,  $x \in E^\circ = E$  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.  $V' \cap W' = \emptyset$

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

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

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.  $V' \cap W' = \emptyset \implies V \cap W = \emptyset$

Furthermore,

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

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

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

Note that  $E^{\circ\circ} = (\overline{E})^c$ , since  $(E^c)^{\circ\circ} = \overline{(E^c)} = \overline{E}$  therefore  $\overline{E} \cap E^{\circ\circ} = \emptyset$ , hence

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

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

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

The subset relation  $V^\circ \subseteq \overline{V}^\circ$  comes from the fact that  $V^\circ$  is an open subset of  $\overline{V}$ , and hence is contained in  $(\overline{V})^\circ$  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.  $\square$

Remark. 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  $x \in E \subseteq U^\circ$ . This property is indeed a very strong one as it allows us to have effectively 'infinite' descending compact neighbourhoods of  $x$ .

### 2.31 Theorem 4.31

WTS.  $X$  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

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

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

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

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

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

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  $\bar{V}$  is also compact. Moreover

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

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.

□

## 2.32 Theorem 4.32

WTS. 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  $\bar{V} \subseteq U$

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

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

It follows that this  $(\bar{V}, \mathcal{T}_{\bar{V}})$  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  $\bar{V}$  in the form of

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

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

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

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

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

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:

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

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

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

We can write

$$f^{-1}(E) = f|_{\bar{V}}^{-1}(E)$$

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

For the case where  $0 \in E$ , note that

$$f^{-1}(E) = (f^{-1}(E) \cap \bar{V}) \cup (f^{-1}(E) \cap (\bar{V})^c) = (f|_{\bar{V}})^{-1}(E) \cup (f|_{\bar{V}^c})^{-1}(E)$$

The above equalities are messy in print. They are but a simple consequence of disjoint decomposition of the pre-images, since

$$\bar{V} \cap f^{-1}(E) = \{x \in \bar{V} : f(x) \in E\} = f|_{\bar{V}}^{-1}(E)$$

Back to our main discussion, recall that for every  $x \in \partial V$

$$f(x) = 0 \in f^{-1}(\{0\}) \subseteq f^{-1}|_{\bar{V}}(E)$$

Therefore  $\partial V \subseteq f^{-1}|_{\bar{V}}(E)$ , and  $(\bar{V})^c = f^{-1}|_{(\bar{V})^c}(E)$  gives us (since  $V^c$  is closed),

$$\begin{aligned} f^{-1}(E) &= f^{-1}|_{\bar{V}}(E) \cup \partial V \cup (\bar{V})^c \\ &= f^{-1}|_{\bar{V}}(E) \cup \overline{(V^c)} \cup (\bar{V})^c \\ &= f^{-1}|_{\bar{V}}(E) \cup (V^c \cup V^{co}) \\ &= f^{-1}|_{\bar{V}}(E) \cup V^c \end{aligned}$$

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

### 2.33 Theorem 4.33

WTS. 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.  $\square$

2.34 Theorem 4.34

WTS.

Proof.



### 2.35 Theorem 4.35

WTS. If  $X$  is a LCH space, we claim that

$$\overline{C_c(X)} = C_0(X)$$

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

$$C_c(X) \subseteq C_0(X) \subseteq BC(X)$$

Fix an  $f \in C_c(X)$ , 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  $\text{supp}(f)$ , 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  $\text{supp}(f)$  are also compact, we get  $f \in C_0(X)$ .

Next, we show that  $C_0(X) \subseteq BC(X)$ . Fix any element  $f$  of  $C_0(X)$  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  $f \in BC(X)$ .

Here I wish to offer an alternate proof for  $C_0(X) \subseteq BC(X)$ , we begin by constructing an open cover for  $\text{supp}(f)$  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  $x \in \text{supp}(f)$  we have  $|f(x)| < n$  and since  $n > 0$  this holds for every  $x \in X$  too. Therefore  $f \in BC(X)$ .

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

Fix a convergent sequence  $\{f_n\}_{n \geq 1} \subseteq \text{C}_c(X)$  that converges uniformly to some  $f \in \text{BC}(X)$  (since  $\text{BC}(X)$  is a closed subset of  $\text{C}(X)$  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  $(\text{supp}(f_n))^c \subseteq |f|^{-1}((-\infty, \varepsilon))$ , so fix any  $x \notin \text{supp}(f_n)$ , then

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

This establishes the estimate, and taking complements

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

Therefore for any arbitrary  $\varepsilon > 0$ ,  $\{x \in X, |f(x)| \geq \varepsilon\}$  is compact, and  $\overline{\text{C}_c(X)} \subseteq \text{C}_0(X)$ . Conversely, fix any  $f \in \text{C}_0(X)$ , 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  $f_n = g_n \cdot f \in \text{C}_c(X)$ . We wish to show that  $f_n \rightarrow f$  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

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

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

2.36 Theorem 4.36

WTS.

Proof.





### 2.37 Theorem 4.37

WTS. 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  $x \in (\overline{E} \setminus E) = \text{acc}(E) \cap E^c$ , 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  $x \in \text{acc}(E)$ , therefore

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

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.  $\square$

2.38 Theorem 4.38

WTS.

Proof.



2.39 Theorem 4.39

WTS.

Proof.



2.40 Theorem 4.40

WTS.

Proof.

□

2.41 Theorem 4.41

WTS.

Proof.



### 3 Chapter 6

#### 3.1 Theorem 6.15

WTS.

Proof. First suppose that  $(X, \mathcal{M}, \mu)$  is finite measure space. If  $\mu(X) < +\infty$ , then for every  $E \in \mathcal{M}$ , by monotonicity  $E \subseteq X$  yields  $\mu(E) \leq \mu(X) < +\infty$ . Next, for any  $p < +\infty$ ,  $\|\chi_E\|_p^p < +\infty$  and  $\|\chi_E\|_{+\infty} \leq 1 < +\infty$ . So all indicator functions are in  $L^p$ .

It follows that every simple function is also in  $L^p$ , since it is a finite linear combination of indicators. We now define  $\nu(E) = \phi(\chi_E)$ , we wish to show that  $\nu : \mathcal{M} \rightarrow \mathbb{C}$  is a complex measure which is absolutely continuous with respect to  $\mu$ .

To show  $\sigma$ -additivity, fix any disjoint sequence  $\{E_j\}_{j \geq 1} \subseteq \mathcal{M}$ . Where we also note that  $\mu(E) = \mu(\cup E_j) < +\infty$ . Now suppose that  $p < +\infty$ , then the following converges in the  $p$ -norm

$$\chi_E = \sum_{j \geq 1} \chi_{E_j}$$

We divert our attention to the following,

$$E \setminus \left( \bigcup_{j \leq n} E_j \right) = \left( \bigcup_{j \geq 1} E_j \right) \setminus \left( \bigcup_{j \leq n} E_j \right) = \bigcup_{j \geq n+1} E_j$$

and define  $F_{n+1}$  as the rightmost member above. Then  $\{F_{n \geq 1}\}$  is a decreasing sequence of sets. All sets are of finite measure, hence  $\mu(E) - \mu(\cup_{j \leq n} E_j) = \mu(F_{n+1}) \rightarrow 0$ .

Now, for any fixed  $n \geq 1$ ,

$$\left| \chi_E - \sum \chi_{E_j \leq n} \right| = \left| \sum \chi_{E_j \geq n+1} \right|$$

the above holds pointwise almost everywhere. Since the above function evaluates either to 0 or to 1, taking the  $p$ th power does not change pointwise, and

$$\left| \sum \chi_{E_j \geq n+1} \right|^p = \left| \sum \chi_{E_j \geq n+1} \right| = \sum \chi_{E_j \geq n+1}$$

Convergence in  $p$ -norm is given by

$$\left\| \chi_E - \sum \chi_{E_{j \leq n}} \right\| = \left\| \sum \chi_{E_{j \geq n+1}} \right\| = \mu(F_{n+1})^{1/p}$$

Applying continuity, and linearity to our  $\phi \in L^{p*}$

$$\begin{aligned} \nu(E) &= \phi(\chi_E) \\ &= \phi \left( \lim_{n \rightarrow \infty} \sum \chi_{E_{j \leq n}} \right) \\ &= \lim_{n \rightarrow \infty} \phi \left( \sum \chi_{E_{j \leq n}} \right) \\ &= \lim_{n \rightarrow \infty} \sum \phi \left( \chi_{E_{j \leq n}} \right) \\ &= \lim_{n \rightarrow \infty} \sum \nu(E_{j \leq n}) \end{aligned}$$

To show absolute convergence, recall that for any  $\phi(\chi_{E_j}) \in \mathbb{C}$ , define  $\beta_j = \frac{\phi(\chi_{E_j})}{\|\phi(\chi_{E_j})\|}$  then multiplication yields

$$\|\phi(\chi_{E_j})\| = \beta_j \phi(\chi_{E_j}) = \phi(\beta_j \chi_{E_j})$$

Then, the following series converges in the  $p$ -norm.

$$\left\| \sum_{j \geq 1} \beta_j \chi_{E_j} - \sum_{j \leq n} \beta_j \chi_{E_j} \right\|_p = \left\| \sum_{j \geq n+1} \beta_j \chi_{E_j} \right\|_p$$

And because  $\left| \sum_{j \geq n+1} \beta_j \chi_{E_j} \right|$  is pointwise equal to  $\left| \sum_{j \geq n+1} \chi_{E_j} \right|$ , since  $|\beta_j| = 1$  for every  $j \geq 1$ . We can reuse the same continuity and linearity argument. We also note that  $\sum_{j \geq 1} \beta_j \chi_{E_j} \in L^p$  since its  $p$ -norm is equal to  $\mu(E)^{1/p}$ .

$$\begin{aligned}
\sum_{j \geq 1} |\nu(E_j)| &= \sup_{n \geq 1} \sum_{j \leq n} \|\nu(E_{j \leq n})\| \\
&= \lim_{n \rightarrow \infty} \sum_{j \leq n} \|\phi(\chi_{E_j})\| \\
&= \lim_{n \rightarrow \infty} \sum_{j \leq n} \beta_j \phi(\chi_{E_j}) \\
&= \lim_{n \rightarrow \infty} \phi \left( \sum_{j \leq n} \beta_j \chi_{E_j} \right) \\
&= \phi \left( \lim_{n \rightarrow \infty} \sum_{j \leq n} \beta_j \chi_{E_j} \right) \\
&\leq \|\phi\| \left\| \sum_{j \geq 1} \beta_j \chi_{E_j} \right\|_p \\
&< +\infty
\end{aligned}$$

Assuming the above estimate holds, then we only need  $\nu(E) = \phi(\chi_E) = \mu(E) = 0$  ( $\nu$  is now a measure and  $\nu \ll \mu$ ), As the indicator of a null set is equal to the zero element in  $L^p$ . Then by Radon-Nikodym we can have some  $g \in L^1(\mu)$  such that

$$d\nu = g d\mu$$

We wish to satisfy the hypothesis of Theorem 6.14 for our function  $g$ . For every  $\chi_E$  measurable,  $\|\chi_E g\|_1 \leq \|g\|_1 < +\infty$ , by monotonicity of the integral in  $L^+$ . So any simple function,  $\alpha = \sum a_j \cdot \chi_{E_j}$  means that  $\alpha g$  is in  $L^1(\mu)$ , and

$$\phi(\alpha) = \int \alpha g d\mu$$

If  $\|\alpha\|_p = 1$ , then

$$\left| \int \alpha g \right| = |\phi(\alpha)| \leq \|\phi\| \cdot \|\alpha\|_p = \|\phi\| < +\infty$$

Then

$$M_q(g) = \sup \left\{ \left| \int \alpha \cdot g \right|, \|\alpha\|_p = 1, \text{ and } \alpha \text{ is simple, and vanishes out-} \right. \\ \left. \text{side a set of finite measure.} \right\} < \infty$$



Since  $S_g = \{x \in X, g(x) \neq 0\}$  is  $\sigma$ -finite, an application of Theorem 6.14 tells us that  $g \in L^q$ , and  $M_q(g) = \|g\|_q \leq \|\phi\| < +\infty$ . Now that we know  $g$  is in  $L^q$  we can use the density of  $\alpha$  in  $L^p$  to show, for every single  $f \in L^p$

$$\phi(f) = \int f g d\mu$$

Conjure a sequence of  $\alpha$ 's, and call them  $\{f_n\} \rightarrow f$  p.w.a.e, then each  $f_n \cdot g \in L^1$ . An application of the DCT and continuity gives us

$$\phi(\lim f_n) = \lim \phi(f_n) = \lim \int f_n g d\mu = \int f g d\mu = \phi(f)$$

This completes the proof for when  $\mu$  is finite.

Let us upgrade our  $\mu$  into a  $\sigma$ -finite measure. Then there exists an increasing sequence  $\{E_n\} \nearrow X$  such that each  $E_n$  is of finite measure. Define

$$P_n = \{L^p, \forall f, |f| = |f| \cdot \chi_{E_n}\}$$

So every function in  $P_n$  vanishes outside a set of finite measure and is also in  $L^p$ . And  $Q_n$  is defined in a similar manner. Now, fix our  $\phi \in L^{p*}$ , and for each  $f \in P_n$ , there exists a corresponding  $g_n \in Q_n$ . Then  $p \in [1, +\infty)$  tells us that  $q \in (1, +\infty]$ , and the assumptions for Theorem 6.13 all hold. Therefore for each  $g_n \in Q_n$ , there is a corresponding bounded linear operator  $\phi_{g_n} \in (P_n)^*$  such that

$$\phi(f) = \phi|_{P_n}(f) = \int f g_n d\mu = \phi_{g_n}(f)$$

The remainder of the proof consists of taking the sequence of  $g_n$  towards some  $g \in L^q$ . We claim that this limit makes sense. As for any  $n < m$ , such that  $E_n \subseteq E_m$  then  $g_n = g_m$  on  $E_n$  pointwise. The proof is simple since each the restriction of our  $\phi \in L^{p*}$  onto  $E_n$  and  $E_m$  spawns two functions  $g_n$  and  $g_m \in L^1$ . To verify, take any subset  $Z \subseteq E_n$  then

$$\phi|_{P_n}(\chi_Z) = \int \chi_Z \cdot g_n = \int \chi_Z \cdot g_m = \phi|_{Q_n}(\chi_Z)$$

So  $g_n = g_m$  pointwise a.e on  $E_n$ . Now we define  $g$  measurable such that  $g|_{E_n} = g_n$  for every  $n$ . And

$$\begin{aligned}
|g_n| &= \chi_{E_n} \cdot |g_m| \implies \\
|g_n| &\leq |g_{n+1}| \implies \\
\|g_n\|_q &\leq \|g_{n+1}\|_q = \|\phi_{g_{n+1}}\|_{q^*} \leq \|\phi\|_{q^*} < +\infty
\end{aligned}$$

Where the second last estimate is from on the monotonicity of the supremum on subsets with  $(P_n \subseteq P_{n+1})$ . If  $q = +\infty$  then  $g \in L^\infty$  is trivial, but for any  $q < +\infty$ . We wish to show that  $g \in L^q$ . Since  $|g_n| \leq |g|$  pointwise for every  $n$ , and for each  $x \in X$ , there exists a  $N$ , where  $n \geq N$  implies  $|g(x)| = |g_n(x)|$ , so  $|g(x)|$  is an upperbound that is actually attained by the sequence  $|g_n(x)|$ . So,  $|g(x)| = \sup_{n \geq 1} \{|g_n(x)|\}$ .

Using the Monotone Convergence Theorem on  $|g_n|$ ,

$$\begin{aligned}
\int \lim_{n \rightarrow \infty} |g_n|^q d\mu &= \int \sup_{n \geq 1} |g_n|^q d\mu \\
&= \int |g|^q d\mu \\
&= \lim \int |g_n|^q d\mu
\end{aligned}$$

Which yields  $\|g\|_q^q = \lim \|g_n\|_q^q = \sup \|g_n\|_q^q \leq \|\phi\|_q^q < +\infty$ . It follows that  $g \in L^q$ .

Finally, we will show that  $\phi(f) = \int f g$  for every  $f \in L^p$ . Redefine  $f_n = f \cdot \chi_{E_n} \in P_n$  for every  $n \geq 1$ . We claim that  $f_n \rightarrow f$  in the  $p$ -norm.

$$\begin{aligned}
|f_n - f| &\leq |f_n| + |f| \\
&\leq |f| + |f| \\
&\leq 2|f|
\end{aligned}$$

And  $|f_n - f|^p \leq 2^p \cdot |f|^p \in L^+ \cap L^1$ . Now it is permissible to apply the Dominated Theorem, and we will do so.

$$\begin{aligned}
\lim \int |f_n - f|^p &= \int \lim |f_n - f|^p \\
\lim \|f_n - f\|_p^p &= \|\lim(|f_n - f|)\|_p^p \\
&= 0
\end{aligned}$$

And we have  $\phi(f) = \phi(\lim f_n) = \lim \phi(f_n)$

$$\begin{aligned}
\phi(f) &= \lim \phi|_{P_n}(f_n) \\
&= \lim \int f_n \cdot g_n \\
&= \lim \int f \cdot g \cdot \chi_{E_n} \\
&= \int \lim (fg \cdot \chi_{E_n}) \\
&= \int fg
\end{aligned}$$

Where we used the DCT again in the second last equality. The justification is a simple consequence of  $fg\chi_{E_n} \rightarrow fg$  pointwise and Holder's Inequality. This completes the proof for when  $\mu$  is of  $\sigma$ -finite measure, and  $p \in [1, +\infty)$ .

Suppose now  $\mu$  is arbitrary, and  $p \in (1, +\infty)$ , then  $q < +\infty$ . Now let us agree to define, for every  $\sigma$ -finite  $E \subseteq X$

$$P_E = \{L^p, |f| = |f| \cdot \chi_E\}$$

Where  $Q_E$  does not hold any surprises. Then for each  $E$  we have a  $\phi|_E$  which induces a  $g_E$  that vanishes outside  $E$ . We are ready for the final part of the proof.

First, if  $E \subseteq F$  and both  $E$  and  $F$  are  $\sigma$ -finite, then  $\|g_E\|_q \leq \|g_F\|_q$ . This is a simple consequence of monotonicity in  $L^+$  if we take  $|g_E|^q \leq |g_F|^q$ .

Second, we define

$$W = \{\|g_E\|_q, E \text{ is } \sigma\text{-finite, and } \phi|_{P_E} \text{ induces } g_E\}$$

Let  $M$  be the supremum of  $W$ , then there exists a sequence of  $\sigma$ -finite sets,  $\{E_n\}$  where  $\|g_{E_n}\|_q \rightarrow M \leq \|\phi\|_{p*}$ . Take a set  $F = \cup E_{n \geq 1}$ , which is also  $\sigma$ -finite, so that  $\|g_F\|_q = M$ . Now assume there exists another  $\sigma$ -finite superset of  $F$ , let us call it  $A$ . Then

$$\int |g_F|^q + \int |g_{A \setminus F}|^q = \int |g_A|^q \leq M^q = \|g_F\|_q^q$$

Everything is finite here so there is no need for caution, subtracting we have  $g_{A \setminus F} = 0$  pointwise a.e. For any  $f \in L^p$ , the spots where  $f$  does not vanish is  $\sigma$ -finite. This comes from  $\int |f|^p < +\infty$ . So it suffices to integrate over this  $\sigma$ -finite set. But we already know, even if this set  $A$  contains  $F$  as a subset,  $\int f g_F = \int f g_A$ .

We now define  $g = g_F$ , and the proof is complete. As for every  $\phi \in L^{p*}$ , there exists a  $g \in L^q$  such that the evaluation of any  $f \in L^p$  is given by integrating  $f$  with  $g$ .  $\square$

## 4 Chapter 7

### 4.1 Theorem 7.1

WTS. If  $I$  is a linear functional on  $C_c(X)$ , then for every compact  $K \subseteq X$ , there exists some  $C_K \geq 0$  with

$$|I(f)| \leq C_K \cdot \|f\|_u$$

Proof. Since  $\text{supp}(f)$  is compact, by Urysohn's Lemma (Theorem 4.32), there exists a  $\phi \in C_c(X, [0, 1])$  such that  $\phi = 1$  on  $K$  and vanishes outside some compact  $\bar{V} \subseteq X$ . Then at every  $x$ ,

$$-\|f\|_u \leq f(x) \leq +\|f\|_u$$

Implies that

$$(-\|f\|_u)\phi \leq f(x) \leq (+\|f\|_u)\phi$$

So that  $f + \|f\|_u\phi \geq 0$  and  $+\|f\|_u - f \geq 0$ , and by linearity,

$$(-\|f\|_u)I(\phi) \leq I(f) \leq (+\|f\|_u)I(\phi)$$

Therefore  $|I(f)| \leq I(\phi)\|f\|_u$ , and taking  $C_K = I(\phi)$  will suffice.  $\square$

## 4.2 Theorem 7.2

WTS. The Riesz-Markov-Kakutani Representation Theorem. If (for every)  $I$  is a positive linear functional on  $C_c(X)$ , then there exists a unique Radon measure  $\mu$  on  $X$ , such that

$$I(f) = \int f d\mu$$

for every  $f \in C_c(X)$ .  $\mu$  also satisfies, for every open  $U$ , and every compact  $K \subseteq X$

$$\mu(U) = \sup \{I(f), f \in C_c(X), f \prec U\} \quad (5)$$

$$\mu(K) = \inf \{I(f), f \in C_c(X), f \geq \chi_K\} \quad (6)$$

For the sake of completeness, we place the definitions for a Radon measure. Let  $X$  be a LCH space, and  $\mathbb{B}_{\mathcal{T}}$  be its usual  $\sigma$ -algebra, a measure  $\nu$  is a Radon measure iff

(i)  $\nu(K) < +\infty$  for every compact  $K$ .

(ii)  $\nu$  is outer-regular on all Borel sets  $E$ ,

$$\nu(E) = \inf \{\nu(U), U \supseteq E, U \in \mathcal{T}\}$$

Intuition: approximation by open supersets.

(iii)  $\nu$  is inner-regular on all open sets  $U \in \mathcal{T}$ ,

$$\nu(U) = \sup \{\mu(K), K \subseteq U, K \text{ compact}\}$$

Intuition: approximation by compact subsets

The main proof is extremely long, so we will divide it into several parts. Following Folland's argumentation closely, we will prove (in order)

(a) If  $\mu_1, \mu_2$  are Radon measures on  $X$  such that for every  $f \in C_c(X)$

$$\int f d\mu_1 = I(f) = \int f d\mu_2$$

then  $\mu_1, \mu_2$  must satisfy (5), and  $\mu_1 = \mu_2$  on  $\mathbb{B}_{\mathcal{T}}$ .

- (b) If we define, for every open set  $U$ , define  $\mu : \mathcal{T} \rightarrow [0, +\infty]$  such that

$$\mu(U) = \sup \{I(f), f \in C_c(X), f \prec U\} \quad (7)$$

Then  $\mu$  is countably subadditive, meaning for every  $U \in \mathcal{T}$ ,  $\{U_{j \geq 1}\} \subseteq \mathcal{T}$

$$U = \bigcup U_{j \geq 1} \implies \mu(U) \leq \sum \mu(U_{j \geq 1})$$

- (c)  $\mu(\emptyset) = 0$ ,  $\{\emptyset, X\} \subseteq \mathcal{T}$ , so that by Theorem 1.10  $\mu$  induces an outer-measure  $\mu^*$

$$\mu^*(E) = \inf \left\{ \sum \mu(U_{j \geq 1}), U_j \in \mathcal{T}, E \subseteq \bigcup U_{j \geq 1} \right\} \quad (8)$$

- (d) If  $\mu^*$  is as described above, then if  $\mu$  is countably subadditive on  $\mathcal{T}$ , then

$$\mu^*(E) = \inf \{ \mu(U), U \supseteq E, U \in \mathcal{T} \} \quad (9)$$

Meaning the two definitions in (8) and (9) are equal.

- (e)  $\mu^*$  and  $\mu$  agree on all open sets, and  $\mu^*|_{\mathcal{T}} = \mu$ ,  
(f) Using again the definition in (8) and (9), we show that every open set  $U \in \mathcal{T}_X$  is  $\mu^*$ -measurable, meaning for every  $E \subseteq X$ ,

$$\mu^*(E) = \mu^*(E \cap U) + \mu^*(E \setminus U)$$

With this, since the set of all outer-measurable ( $\mu^*$ -measurable) sets,  $\mathcal{M}^*$  form a  $\sigma$ -algebra,

$$\mathcal{T} \subseteq \mathcal{M}^* \implies \mathbb{B}_{\mathcal{T}} \subseteq \mathcal{M}^*$$

By Theorem 1.1, and define

$$\mu = \mu^*|_{\mathbb{B}_{\mathcal{T}}} \quad (10)$$

is a Borel measure. And we note in passing that  $\mu$  is outer-regular on all  $E \in \mathbb{B}_{\mathcal{T}}$ ,

$$\mu(E) = \inf \{ \mu(U), U \supseteq E, U \in \mathcal{T} \} \quad (11)$$

(g) Using (10) for the definition of  $\mu$  on  $\mathbb{B}_{\mathcal{T}}$ , we prove that

- $\mu$  is outer-regular on all Borel sets, and
- $\mu$  satisfies Equation (5).

(h)  $\mu$  satisfies Equation (6)

(i)  $\mu$  is finite on all compact sets.

(j)  $\mu$  is inner-regular on all open sets.

(k) For every  $f \in C_c(X, [0, 1])$ ,

$$I(f) = \int f d\mu \quad (12)$$

(l) For every  $f \in C_c(X)$ ,

$$I(f) = \int f d\mu \quad (13)$$

A small lemma needs to be made before proceeding, that concerns the 'monotonicity' of  $I$  on  $C_c X$ .

Lemma 4.1. Suppose that  $f, g \in C_c(X)$ , and  $f \geq g \geq 0$  for every  $X$ , then  $f - g \in C_c(X)$  and  $I(f) \geq I(g)$

Proof. Suppose that  $x \in X$  where  $f(x) = 0$ , then

$$f(x) - g(x) = -g(x) \geq 0 \implies g(x) = 0 \implies f - g = 0$$

Hence

$$\begin{aligned} \{x, f(x) = 0\} &\subseteq \{x, f(x) - g(x) = 0\} \implies \{x, f(x) - g(x) \neq 0\} \subseteq \{x, f(x) \neq 0\} \\ &\implies \text{supp}(f - g) \subseteq \text{supp}(f) \end{aligned}$$

Since  $\text{supp}(f)$  is compact, and  $\text{supp}(f - g)$  is a closed subset of  $\text{supp}(f)$ , yields  $f - g \in C_c(X)$ . And if  $I$  is any positive linear functional on  $C_c(X)$ , then

$$\begin{aligned} f - g \geq 0 &\implies I(f - g) \geq 0 \\ &\implies I(f) \geq I(g) \geq 0 \end{aligned}$$

□



Remark. If  $f \prec U$  and  $g \prec U$  for some open subset  $U \subseteq X$ , then clearly  $\text{supp}(f - g) \subseteq \text{supp}(f) \subseteq U$ , and  $1 \geq f \geq f - g \geq 0$  means that  $f - g \prec U$  as well.

#### 4.2.1 Part a

Proof. Suppose that  $\mu_1$  and  $\mu_2$  are Radon measures on  $X$ , and for every  $f \in C_c(X)$ ,

$$\int f d\mu_1 = I(f) = \int f d\mu_2$$

We first prove (5). Without loss of generality, by monotonicity of  $L^+$ , if  $f \prec U$  for some open  $U$ , then  $0 \leq f \leq \|f\|_u \chi_U = \chi_U$  for all  $x$  and

$$\int f d\mu_1 \leq \int \|f\|_u \chi_U d\mu_1 \leq \mu_1(U)$$

Therefore  $\mu_1(U)$  (resp.  $\mu_2(U)$ ) is an upper-bound for the set

$$\{I(f), f \in C_c(X), f \prec U\}$$

Since  $\mu_1$  is inner-regular on  $U \in \mathcal{T}$ , for every  $\varepsilon > 0$  we can find some compact  $K \subseteq U$  where

$$\mu_1(U) - \varepsilon < \mu_1(K)$$

By Urysohn's Lemma (Theorem 4.32), there exists some  $g \in C_c(X)$  with

- $g \in C_c(X, [0, 1])$ ,
- $g = 1$  on  $K \subseteq U$ ,
- $g = 0$  outside some  $\bar{V} \subseteq U$ , and
- $g \prec U$ .

Hence for every  $x \in K$ ,  $g \geq \chi_K$ . If  $x \notin K$  then  $g \geq 0 = \chi_K$ ; so  $g - \chi_K \geq 0$  for every  $x \in X$ . Since  $\chi_K \prec U$ , using Lemma 4.1, we get

$$\mu_1(K) \leq \int \chi_K d\mu_1 = I(\chi_K) \leq I(g)$$

So for every  $\varepsilon > 0$ , there exists a  $g \in C_c(X)$ , and  $g \prec U$  where

$$\mu_1(U) - \varepsilon < \mu_1(K) \leq I(g)$$

Therefore  $\mu_1(U) = \sup \{I(f), f \in C_c(X), f \prec U\}$ , and the first claim in (a) is proven. To show that  $\mu$  is indeed unique, since for every open set  $U$ , we must have  $\mu_1(U) = \mu_2(U)$ , and if  $E \in \mathbb{B}_{\mathcal{T}}$  is any Borel set, and by outer-regularity,

$$\mu_1(E) = \inf \{\mu_1(U), U \supseteq E, U \in \mathcal{T}\} = \inf \{\mu_2(U), U \supseteq E, U \in \mathcal{T}\} = \mu_2(E)$$

Therefore this measure is unique.  $\square$

#### 4.2.2 Part b

Proof. To show countable subadditivity for  $\mu$  with equation (7), fix any  $U \in \mathcal{T}$  and a sequence  $\{U_{j \geq 1}\} \subseteq \mathcal{T}$  with  $U = \bigcup U_{j \geq 1}$ . It suffices to show that the partial sum of  $\sum \mu(U_{j \leq n})$  is greater than  $I(f)$  for any  $f \in C_c(X)$ ,  $f \prec U$  (hence it is an upper bound).

Fix any  $f$ , then denote  $K = \text{supp}(f) \subseteq U$ , and since  $\{U_{j \geq 1}\}$  is an open cover for  $K$ , there exists a finite subcollection,  $B \subseteq \mathbb{N}^+$  such that

$$K \subseteq \bigcup_{j \in B} U_j$$

Using Theorem 4.41 on this finite cover of  $K$ , there exists a partition of unity in  $\{g_{j \leq n}\}$  where

- $g_j \in C_c(X, [0, 1])$ ,
- $g_j \prec U_j \subseteq U$  for every  $j \leq n$ , and
- $\sum g_j = 1$  on  $K$ ,

And notice for every  $j \leq n$ ,

$$\begin{aligned} \{f = 0\} \cup \{g_j = 0\} &\subseteq \{f \cdot g_j = 0\} \implies \{f \cdot g_j \neq 0\} \subseteq \{f \neq 0\} \cap \{g_j \neq 0\} \\ &\implies \text{supp}(f \cdot g_j) \subseteq \text{supp}(f) \cap \text{supp}(g_j) \\ &\implies \text{supp}(f \cdot g_j) \subseteq U_j \subseteq U \end{aligned}$$

Hence  $f \cdot g_j \prec U$  and  $f \cdot g_j \in C_c(X, [0, 1])$  for every  $1 \leq j \leq n$ . Moreover, if we take the sum over a finite  $n$ , we obtain  $f = \sum f \cdot g_{j \leq n}$ , this is because for every  $x \in X$ , so we have

$$\sum_{j \leq n} f(x) \cdot g_j(x) = f(x) \cdot \sum_{j \leq n} g_j(x) = f(x)$$

Then  $I(f) = I(\sum f \cdot g_j) = \sum I(f \cdot g_j)$ . And by definition of  $\mu(U_j)$ , since it is the supremum over all  $I(h_j)$ , where  $h_j \in C_c(X, [0, 1])$  and  $h_j \prec U_j$

$$I(f \cdot g_j) \leq \mu(U_j), \quad \forall j \leq n$$

Hence

$$I(f) \leq \sum_{j \leq n} \mu(U_j) \leq \sum_{j \geq 1} \mu(U_j)$$

Where for the last estimate we used the fact that  $\mu$  is non-negative, and since this holds for any  $f$ , we can conclude that  $\mu(U) \leq \sum_{j \geq 1} \mu(U_j)$ .  $\square$

#### 4.2.3 Part c

Proof. By definition of a topology,  $\{\emptyset, X\} \subseteq \mathcal{T}$ , and  $\mu(\emptyset) = \sup\{I(f), f \in C_c(X), f \prec \emptyset\}$ , so  $\text{supp}(f) = \emptyset$ , and  $\{x, f(x) \neq 0\} \subseteq \emptyset$ , so the set contains one element, namely  $I(0) = 0$  by linearity. So  $\mu(\emptyset) = 0$ . The assumptions for Theorem 1.10 are satisfied and (8) is indeed an outer-measure.  $\square$

#### 4.2.4 Part d

Proof. Denote the right members of (8) and (9) by  $W_1$  and  $W_2$ , we wish to show that  $\inf W_1 = \inf W_2$ . Clearly  $\inf W_1 \leq \inf W_2$ , since  $W_2 \subseteq W_1$ . Now, if  $\mu$  is countably additive, then for every  $\omega \in W_1$  induces a sequence of open sets  $\{U_{j \geq 1}\}$  such that  $E \subseteq \bigcup U_{j \geq 1}$ . Denote the union over  $\{U_{j \geq 1}\}$  by  $U$ , which is also another open set,

$$\inf W_2 \leq \mu(U) \leq \sum \mu(U_{j \geq 1}) = \omega$$

Since  $\omega$  is arbitrary, we conclude that  $\inf W_2 = \inf W_1$ , and this proves (d).  $\square$

#### 4.2.5 Part e

Proof. If  $U$  and  $V$  are open subsets of  $X$ , and if  $U \subseteq V$ , then

$$\begin{aligned} U \subseteq V &\implies \{f \in C_c(X), f \prec U\} \subseteq \{f \in C_c(X), f \prec V\} \\ &\implies \{I(f), f \in C_c(X), f \prec U\} \subseteq \{I(f), f \in C_c(X), f \prec V\} \end{aligned}$$

Hence  $\mu(U) \leq \mu(V)$ . Now by equation (9),  $\mu^*(U) \leq \mu(U)$ . To show the reverse inequality, suppose by contradiction that  $\mu^*(U) < \mu(U)$ .

Since  $\mu^*(U)$  is an infimum, then for every  $\varepsilon > 0$  there exists some  $V \supseteq U$  where if we write  $\mu^*(U) + \varepsilon = \mu(U)$

$$\mu(V) < \mu^*(U) + \varepsilon = \mu(U) \implies \mu(V) < \mu(U), U \subseteq V$$

This contradicts what we have just proven, and therefore  $\mu^*(U) = \mu(U)$  for every open set  $U$ .  $\square$

#### 4.2.6 Part f

Proof. We wish to show that every open set  $U$  is  $\mu^*$ -measurable. By Theorem 1.10, it suffices to show that for every  $E \subseteq X$

$$\mu^*(E) \geq \mu^*(E \cap U) + \mu^*(E \setminus U) \quad (14)$$

because the reverse inequality is given by subadditivity of  $\mu^*$ , and we can also assume that  $\mu^*(E) < +\infty$ . Let us assume that  $E$  is open, we wish to find some function  $h \in C_c(X)$ ,  $h \prec E$  with

$$I(h) > \mu^*(E \cap U) + \mu^*(E \setminus U) - 2\varepsilon$$

The above formula is fussy, but the liberty is taken to show it beforehand to avoid any potential confusion that follows. Since  $E \cap U$  is an open subset of  $X$ , the definition of  $\mu(E \cap U) = \mu^*(E \cap U)$  in (7) tells us that every  $\varepsilon > 0$  induces some  $f \in C_c(X)$ ,  $f \prec E \cap U$  where

$$I(f) > \mu(E \cap U) - \varepsilon = \mu^*(E \cap U) - \varepsilon \quad (15)$$

Also,  $\text{supp}(f)$  is a closed set (compact subsets of Hausdorff spaces are closed), therefore  $E \setminus \text{supp}(f)$  is an open set. We make a small diversion from the current part of the proof and turn out attention to the fact that

$$\begin{aligned} \text{supp}(f) \subseteq U &\implies U^c \subseteq (\text{supp}(f))^c \\ &\implies E \setminus U \subseteq E \setminus \text{supp}(f) \end{aligned}$$

And because the outer-measure  $\mu^*$  is monotone,

$$\mu^*(U) \leq \mu^*(E \setminus \text{supp}(f)) \quad (16)$$

Now, using the definition of  $\mu(E \setminus \text{supp}(f))$  (recall that  $E \setminus \text{supp}(f)$  is an open set), for every  $\varepsilon > 0$ , there exists some  $g \in C_c(X)$ ,  $g \prec E \setminus \text{supp}(f)$  with

$$I(g) > \mu(E \setminus \text{supp}(f)) - \varepsilon = \mu^*(E \setminus \text{supp}(f)) - \varepsilon \quad (17)$$

It is at this part of the proof where we wish to define  $h = f + g$ , but first we must verify

- $f + g \in C_c(X, [0, 1])$ ,
- $f + g \prec E$

The sum of two non-negative functions is non-negative, and for every  $x \in \text{supp}(f)$ ,  $f \leq 1$ . Also

$$\begin{aligned} \text{supp}(g) \subseteq (\text{supp}(f))^c &\implies \text{supp}(f) \subseteq (\text{supp}(g))^c \\ &\implies \text{supp}(f) \subseteq \{g = 0\} \end{aligned}$$

The last implication comes from taking complements on both sides of  $\{g \neq 0\} \subseteq \text{supp}(g)$ . So  $x \in \text{supp}(f) \implies f + g \leq 1$ . Now if  $x \notin \text{supp}(f)$ , then  $f + g = g \leq 1$ . Furthermore,  $\text{supp}(f + g)$  is a closed subset of compact  $\text{supp}(f) \cup \text{supp}(g)$ . This is because  $\{f + g \neq 0\} \subseteq \{f \neq 0\} \cup \{g \neq 0\}$ , and the finite union of two compact sets is again compact.

A moment's thought should yield the fact that the last estimate should be an equality, but it is a needless distraction. Therefore  $\text{supp}(f + g)$  is compact and  $f + g \in C_c(X, [0, 1])$ .

Now both bullet points are satisfied, and we can set  $h = f + g$ . Adding equation (17) with (15) gives us

$$I(h) = I(f) + I(g) > \mu^*(E \cap U) + \mu^*(E \setminus \text{supp}(f)) - 2\varepsilon$$

Upon applying (16) to the right member of the above estimate, we have

$$I(h) > \mu^*(E \cap U) + \mu^*(E \setminus U) - 2\varepsilon$$

But this particular  $h \in C_c(X) \cap \{f \prec E\}$ , therefore

$$\mu^*(E) \geq I(h) > \mu^*(E \cap U) + \mu^*(E \setminus U) - 2\varepsilon$$

Since  $\varepsilon > 0$  is arbitrary, equation (14) holds for every open  $E$ . Now for any general  $E \subseteq X$ , fix any  $\varepsilon > 0$  and by how we defined  $\mu^*(E)$ , there exists some open  $V \supseteq E$  —recall that  $\mu^*(E)$  is the infimum over the set of  $\mu(V)$  where  $V$  is an open superset of  $E$  — hence

$$\mu^*(E) + \varepsilon > \mu(V) \geq \mu^*(V \cap U) + \mu^*(V \setminus U)$$

By monotonicity (twice) of the outer-measure  $\mu^*$ , we have

$$\mu^*(E) + \varepsilon > \mu^*(E \cap U) + \mu^*E \setminus U$$

Let  $\varepsilon \rightarrow 0$ , and we get

$$\mu^*(E) \geq \mu^*(E \cap U) + \mu^*(E \setminus U)$$

Therefore every open  $U \subseteq X$  is  $\mu^*$ -measurable. So  $\mu = \mu^*|_{\mathbb{B}_{\mathcal{T}}}$  is a Borel measure on  $X$ .  $\square$

#### 4.2.7 Part g

Proof. To show outer-regularity, fix any  $E \in \mathbb{B}_{\mathcal{T}}$ , then by definition,

$$\mu(E) = \mu^*(E) = \inf \{\mu(U), U \supseteq E, U \in \mathcal{T}\}$$

And for every open  $U$ , (5) follows from Equation (7).  $\square$

#### 4.2.8 Part h

Proof. We want to show that for every compact  $K$ , Equation (6) holds. To reduce the notational baggage that follows, we agree to define

$$\{I(f), f \in C_c(X), f \prec U\} = \{I(f), f \prec U\}$$

Similarly for  $\{I(f), f \geq \chi_K\}$ . If  $\mu(K) = 0$ , then  $\mu(K)$  is obviously a lower bound, since  $f \geq \chi_K \geq 0$  means that  $I(f) \geq 0$ , for every  $f \geq \chi_K$ . So we can suppose  $\mu(K) > 0$ .

Fix an arbitrary  $f \geq \chi_K$ , then this particular  $f$  induces an open set  $U_\alpha = \{f > 1 - \alpha\}$ , where  $\alpha > 0$ . Notice also that

$$K \subseteq \{f \geq 1\} \subseteq \{f > 1 - \alpha\} = U_\alpha$$

Since  $U_\alpha$  is an open superset of  $K$ , by Equation (11),  $\mu(K) \leq \mu(U_\alpha)$ , but  $\mu(U_\alpha)$  is simply the supremum of  $\{I(g), g \prec U_\alpha\}$ . If we wish to show that  $\mu(K) \leq \mu(U_\alpha) \leq I(f)$ , it suffices to show that  $I(f)$  is an upper-bound for  $\{I(g), g \prec U_\alpha\}$ .

Fix any  $I(g) \in \{I(g), g \prec U_\alpha\}$ , note that  $1 - \alpha \neq 0$  for any  $\alpha$  small enough, then

- $f/(1 - \alpha) > 1$  on  $U_\alpha$ ,
- $1 \geq g \geq 0$  on  $U_\alpha$ , in particular,  $f/(1 - \alpha) - g \geq 0$  on  $U_\alpha$ ,
- If  $x \notin U_\alpha$ , then  $f/(1 - \alpha) - g = f(1 - \alpha) \geq 0$ .
- Therefore  $f/(1 - \alpha) - g \geq 0$  for any  $x$ , and by Lemma 4.1,

$$I(f/(1 - \alpha)) \geq I(g) \quad \forall g \prec U_\alpha$$

Combining the above estimate with  $\mu(K) \leq \mu(U_\alpha)$  gives us

$$\mu(K) \leq \frac{1}{1 - \alpha} I(f)$$

Now write  $\varepsilon = \alpha/\mu(K) > 0$  and for every  $\varepsilon > 0$  we get

$$\mu(K) - I(f) \leq \alpha\mu(K) = \varepsilon$$

Send  $\varepsilon \rightarrow 0$  and  $\mu(K) \leq I(f)$  for every  $f \geq \chi_K$ .

To show that  $\mu(K)$  is indeed the infimum for  $\{I(f), f \geq \chi_K\}$ , notice that for every  $\varepsilon > 0$  we can obtain some open superset  $U \supseteq K$  (by outer-regularity) where  $\mu(U) < \mu(K) + \varepsilon$ . By Urysohn's Lemma, there exists some  $g \prec U$ ,  $g(x) = 1$  for every  $x \in K$ .

$$g \in \{I(f), f \prec U\} \cap \{I(f), f \geq \chi_K\}$$

Therefore  $I(g) \leq \mu(U) < \mu(K) + \varepsilon$  as desired, and Equation (6) holds.  $\square$

#### 4.2.9 Part i

Proof.  $\mu(K) < +\infty$  for every compact  $K$ . Indeed, since  $I(\chi_K) \in \{I(f), f \geq \chi_K\}$ , then by Theorem 7.1, there exists a constant  $C_K \geq 0$  that bounds

$$\mu(K) \leq |I(\chi_K)| = I(\chi_K) \leq C_K \cdot \|\chi_K\| = C_K < +\infty$$

$\square$

#### 4.2.10 Part j

Proof. Fix any open set  $U$ , then for every  $\varepsilon > 0$ , there exists some  $f \prec U$  with  $\mu(U) - \varepsilon < I(f)$ . Then denote  $K = \text{supp}(f) \subseteq U$ . If we take any  $I(h) \in \{I(h), h \geq \chi_K\}$ , then  $h \geq f$  gives us  $I(h) \geq I(f)$  by Lemma 4.1. So  $I(f)$  is a lower bound of  $\{I(h), h \geq \chi_K\}$ , therefore

$$\mu(U) - \varepsilon \leq I(f) \leq \mu(K)$$

Since  $\text{supp}(f) = K \subseteq U$ , this proves inner-regularity of  $\mu$  on open sets.  $\square$

#### 4.2.11 Part k

Proof. Suppose  $f \in C_c(X, [0, 1])$ , we first show that Equation (12) holds. We divide the interval  $[0, 1]$  into  $N \geq 1$  chunks by writing

$$K_j = \{f \geq j/N\}$$

for every  $1 \geq j \geq N$ . And define  $K_0 = \text{supp}(f)$ . Each  $K_j$  is a closed subset of  $\text{supp}(f)$ , and therefore compact. More is true,

- $K_{j-1} \supseteq K_j$  for every  $1 \leq j \leq N$ .
- $x \in K_j$  iff  $f(x) \in [\frac{j}{N}, 1]$ ,
- $x \notin K_j$  iff  $f(x) \in [0, \frac{j}{N})$ , and
- $x \in (K_{j-1} \setminus K_j)$  iff  $f(x) \in [\frac{j-1}{N}, \frac{j}{N})$

Folland constructs a finite sequence of compactly supported functions,  $\{f_j\}$ , where  $1 \leq j \leq N$  such that

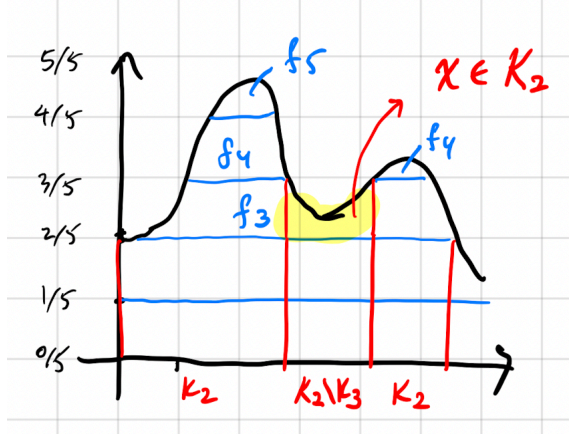
- Each  $0 \leq f_j \leq 1/N$ ,
- If  $x \in (K_m \setminus K_{m+1})$  iff  $f(x) \in [\frac{m}{N}, \frac{m+1}{N})$  means that  $f_j = 1$  for all  $1 \leq j \leq m$ , and
- $f_{m+1} = f - m/N$  on  $K_m$ , such that

$$f(x) = \left(\sum f_{j \leq m}(x)\right) + \left(f(x) - \frac{m}{N}\right) = \frac{m}{N} + \left(f(x) - \frac{m}{N}\right)$$



- And for every  $m < j \leq N$ ,  $f_j = 0$ .
- If  $x \notin K_m$  iff  $f(x) \in [0, \frac{m}{N})$  then for every  $m + 1 \leq j \leq N$ ,  $f_j = 0$ .

The illustration for when  $N = 5$  below should make things clearer.



It is also trivial to verify that

- For every  $x \in K_j$ ,  $f_j = N^{-1}$ , and

$$\chi_{K_j} N^{-1} \leq f_j \quad (18)$$

Also, if  $x \notin K_j$  then  $f_j \geq 0$ , therefore  $f_j \geq \chi_{K_j} N^{-1}$  at every  $x$ .

- If  $x \notin K_{j-1}$  then  $f_j = 0 \leq \chi_{K_{j-1}} \cdot N^{-1}$ . If  $x$  is in  $K_{j-1}$  then  $f_j \leq N^{-1}$  by construction and therefore

$$f_j \leq \chi_{K_{j-1}} N^{-1} \quad (19)$$

for all  $x$ .

- $f_j \in C_c(X)$ , since  $\text{supp}(f_j) \subseteq \text{supp}(f)$ .

Combining Equations (18) with (19), and by monotonicity in  $L^+(X, \mathbb{B}_{\mathcal{T}}, \mu)$ , since  $f_j \in L^+$

$$\int \frac{1}{N} \chi_{K_j} d\mu \leq \int f_j d\mu \leq \int \frac{1}{N} \chi_{K_{j-1}} d\mu$$

And for every  $1 \leq j \leq N$ ,

$$\frac{1}{N} \mu(K_j) \leq \int f_j d\mu \leq \frac{1}{N} \mu(K_{j-1}) \quad (20)$$

Furthermore, from Equation (18), since  $Nf_j \geq \chi_{K_j}$  then by Equation (6),

$$\mu(K_j) \leq I(Nf_j) \implies \frac{1}{N}\mu(K_j) \leq I(f_j)$$

Now for any arbitrary  $I(h) \in \{I(h), h \geq \chi_{K_{j-1}}\}$ , since

$$h \geq \chi_{K_{j-1}} \geq Nf_j \implies I(h) \geq I(Nf_j)$$

So  $NI(f_j)$  is a lower bound for  $\{I(h), h \geq \chi_{K_{j-1}}\}$  and

$$I(f_j) \leq \frac{1}{N}\mu(K_{j-1})$$

Combining the last two results, with  $I(f_j)$ , we get

$$\frac{1}{N}\mu(K_j) \leq I(f_j) \leq \frac{1}{N}\mu(K_{j-1}) \quad (21)$$

Taking the sum over  $1 \leq j \leq N$  for Equations (20) and (21). Define  $A = N^{-1} \sum_0^{N-1} \mu(K_j)$ , and  $B = N^{-1} \sum_1^N \mu(K_j)$

$$B \leq \int f d\mu \leq A$$

And also

$$B \leq I(f) \leq A$$

This is because of finite additivity of both  $I$  and the integral, and  $f = \sum f_j$  on  $K_0 = \text{supp}(f)$ . Subtracting the two equations (keeping in mind that  $\mu(K_j) < +\infty$  for any compact  $K_j$ ), we get

$$(-1)(A - B) \leq \left( \int f d\mu - I(f) \right) \leq A - B \implies \left| \int f d\mu - I(f) \right| \leq A - B$$

It is trivial to verify that

$$0 \leq A - B = N^{-1}(\mu(K_0) - \mu(K_N)) \leq N^{-1}\mu(K_0)$$

as  $K_N \subseteq K_0$ . Let  $N \rightarrow \infty$  and

$$\int f d\mu = I(f)$$

Equation (12) holds as desired.  $\square$

#### 4.2.12 Part I

Proof. Now for any general  $f \in C_c(X)$ ,  $f$  must be bounded on the plane since  $C_c(X) \subseteq BC(X)$ , and  $|f| \leq M_0$  for some  $M_0 \geq 0$ . Since  $\text{supp}(f)$  is compact, we know that

$$\int |f| d\mu \leq \int M_0 \chi_{\text{supp}(f)} d\mu \leq M_0 \mu(\text{supp}(f)) < +\infty$$

And  $C_c(X) \subseteq L^1(\mu)$ . Furthermore,

$$\frac{1}{2}(|\text{Re } f| + |\text{Im } f|) \leq |f| \leq M_0$$

So that  $\text{Re } f$  and  $\text{Im } f$  are in  $C_c(X)$ . Without loss of generality, we may assume that  $f$  is real. Define  $f_1 = \text{Re } f^+/M_0$  and  $f_2 = \text{Re } f^-/M_0$  and it immediately follows that  $f_1, f_2 \in C_c(X, [0, 1])$ .

By linearity of  $I$  on  $C_c(X)$  and the integral in  $L^1(\mu)$ ,

$$I(f_1 - f_2) = I(f) = \int f d\mu = \int f_1 d\mu - \int f_2 d\mu$$

Then we may apply the above to the real and imaginary parts of a general  $f \in C_c(X)$ , and this completes the proof.  $\square$

### 4.3 Theorem 7.3

WTS. See Theorem 7.2

Proof. □

### 4.4 Theorem 7.4

WTS. See Theorem 7.2

Proof. □

4.5 Theorem 7.5

WTS.

Proof.



4.6 Theorem 7.6

WTS.

Proof.



4.7 Theorem 7.7

WTS.

Proof.

□

4.8 Theorem 7.8

WTS.

Proof.





#### 4.9 Theorem 7.9

WTS. If  $\mu$  is a Radon measure on  $X$ , then  $C_c(X)$  is dense in  $L^p(\mu)$  for  $1 \leq p < +\infty$ .

Proof. Theorem 6.7 tells us that the set of  $L^p$  simple functions (as Folland calls them), which are

$$\Lambda = \left\{ f, f = \sum_{j \leq n} a_j \chi_{E_j}, a_j \in \mathbb{C}, \mu(E_j) < +\infty \right\}$$

So for every  $f \in L^p$ , there exists a sequence  $\{f_n\} \subseteq \Lambda$  with  $f_n \rightarrow f$  pointwise and  $f_n \rightarrow f$  in  $L^p$ .  $\square$

4.10 Theorem 7.10

WTS.

Proof.

□

## 5 Chapter 8

### 5.1 Theorem 8.1

WTS.

Proof.

□

5.2 Theorem 8.2

WTS.

Proof.

□