

Folland Reading

me

September 20, 2022

Contents

1	Chapter 1	2
2	Chapter 2	2
3	Chapter 3	2
4	Chapter 4	3
4.1	Theorem 4.1	3
4.2	Theorem 4.2	4
4.3	Theorem 4.3	5
4.4	Theorem 4.4	6
4.5	Theorem 4.5	7
4.6	Theorem 4.6	8
4.7	Theorem 4.7	9
4.8	Theorem 4.8	10
4.9	Theorem 4.9	11
4.10	Theorem 4.10	12
4.11	Theorem 4.11	13
4.12	Theorem 4.12	14
4.13	Theorem 4.13	15
4.14	Theorem 4.14	16
4.15	Theorem 4.15	17
4.16	Theorem 4.16	19
4.17	Theorem 4.17	21
4.18	Theorem 4.18	22

4.19	Theorem 4.19	23
4.20	Theorem 4.20	24
4.21	Theorem 4.21	26
4.22	Theorem 4.22	27
4.23	Theorem 4.23	28
4.24	Theorem 4.24	29
4.25	Theorem 4.25	30
4.26	Theorem 4.26	31
4.27	Theorem 4.27	32
4.28	Theorem 4.28	33
4.29	Theorem 4.29	34
5	Chapter 5	36
6	Chapter 6	37
6.1	Theorem 6.15	37
1	Chapter 1	
2	Chapter 2	
3	Chapter 3	

4 Chapter 4

4.1 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*

$$\overline{A} = A \cup \text{acc } (A) \tag{1}$$

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

Proof.

□

4.2 Theorem 4.2

WTS.

4.3 Theorem 4.3

WTS.

Proof.



4.4 Theorem 4.4

WTS.

4.5 Theorem 4.5

WTS.

4.6 Theorem 4.6

WTS.

4.7 Theorem 4.7

WTS.

4.8 Theorem 4.8

WTS.

4.9 Theorem 4.9

WTS.

4.10 Theorem 4.10

WTS.

4.11 Theorem 4.11

WTS.

4.12 Theorem 4.12

WTS.

4.13 Theorem 4.13

WTS.

4.14 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 $r \in \Delta$ and
2. $\overline{U_r} \subseteq U_s$ for $r < s$.

Proof.

□

4.15 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 ε 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 ε 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 Δ , there exists an r , $f(x) < r < \alpha$ such that $x \in U_r$ such that $x \in \bigcup_{r < \alpha} U_r$. So $f^{-1}((-\infty, \alpha)) \subseteq \bigcup_{r < \alpha} U_r$.

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

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

4.16 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 4.1. *For every $f \in C(A, [0, 1])$, there exists a $g \in C(X, [0, 1/3])$ such that*

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

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 (2) 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 4.1 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 4.1, 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

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

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

4.17 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 $B = X \setminus G^{-1}((-1, +1))$ 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. $\operatorname{Re}(f) = f_1 \in C(A, \mathbb{R})$
2. $\operatorname{Im}(f) = f_2 \in C(A, \mathbb{R})$

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

4.18 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

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

□

4.19 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 exists an α_0 such that for every $\alpha \succ \alpha_0$ implies that $x_\alpha \in f^{-1}(V)$. Hence

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

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

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

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 $\alpha \in A$

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

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

4.20 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 β_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 α_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_β 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 . □

4.21 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. □

4.22 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

4.23 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 $y \in V_r(y)$.*

4.24 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. □

4.25 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 $U_y \cap (\bigcup V_{y \in H}) = \emptyset$. Define $U = \bigcap U_{y \in H}$ and $V = \bigcup V_{y \in H}$, 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

4.26 Theorem 4.26

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

A small lemma.

Lemma 4.2. *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

4.27 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

4.28 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 $E \subset X$ 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

4.29 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 α 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_α , 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 $x_B \in \left(\bigcup_{\alpha \in B} U_\alpha\right)^c$. 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_β with $\beta \in A$ such that U_β 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

5 Chapter 5

6 Chapter 6

6.1 Theorem 6.15

WTS.

First suppose that (X, \mathcal{M}, μ) 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 μ .

To show σ -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,

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

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 $\mu(E) - \mu(\cup E_{j \leq n}) = \mu(F_{n+1}) \rightarrow 0$.

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 $\phi \in L^{p*}$

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

To show absolute convergence, recall that for any $\phi(\chi_{E_j}) \in \mathbb{C}$, define $\beta_j = \frac{\phi(\chi_{E_j})}{\overline{\text{sgn}(\|\phi(\chi_{E_j})\|)}}$ 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 $\nu(E) = \phi(\chi_E) = \mu(E) = 0$ (ν 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 χ_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 αg 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

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

Since $S_g = \{x \in X, g(x) \neq 0\}$ is σ -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 α in L^p to show, for every single $f \in L^p$

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

Conjure a sequence of ' α '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 μ is finite.

Let us upgrade our μ into a σ -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 $\phi(f) = \int fg$ 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 μ is of σ -finite measure, and $p \in [1, +\infty)$.

Suppose now μ is arbitrary, and $p \in (1, +\infty)$, then $q < +\infty$. Now let us agree to define, for every σ -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 σ -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 σ -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 σ -finite, so that $\|g_F\|_q = M$. Now assume there exists another σ -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 σ -finite. This comes from $\int |f|^p < +\infty$. So it suffices to integrate over this σ -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 . ■