Prelude

My REU mentor recently bought me the book *Banach Algebra Techniques in Operator Theory*, so I'm going to be reading through it here. Astute readers may already know that I am also reading through the book *Quantum Theory for Mathematicians*, and may be wondering if this is going to crowd out that book. The answer is yes — but I don't really care that much. If I come out of the summer knowing more things than I knew entering, then I will have succeeded.

Prerequisite Notes

Since Douglas's book is very advanced, I'm going to end up going back and reading other important material in order to contextualize the parts of the book I don't fully understand.

Tychonoff's Theorem

I'm drawing information for this section from Volker Runde's book *A Taste of Topology*, specifically from Chapter 3.

Definition (Product Topology)**.** Let $\{(X_i, \tau_i)\}_i$ be a family of topological spaces, and $X = \prod_{i \in I} X_i$.

The product topology on X is the coarsest topology τ on X such that

$$\prod_i : X \to X_i; \quad f \mapsto f(i)$$

is continuous.

The product topology's open sets are of the form

$$\bigcap_{j=1}^{n} \pi_{i_j}(U_j),$$

where $i_j \in I$. The product topology is the topology of coordinatewise convergence.

Theorem (Tychonoff's)**.** *Let $\{(K_i, \tau_i)\}_{i \in I}$ be a nonempty family of compact topological spaces. Then, the product space $K = \prod_{i \in I} K_i$ is compact in the product topology.*

Proof. Let $\{f_\alpha\}_{\alpha \in A}$ be a net[i] in K. Let $J \subseteq I$ be nonempty, and let $f \in K$.

We call (J, f) a partial accumulation point of $\{f_\alpha\}_{\alpha \in A}$ if $f|_J$ is a accumulation point of $\{f_\alpha|_J\}_{\alpha \in A}$ in $\prod_{j \in J} K_j$. A partial accumulation point of $\{f_\alpha\}_{\alpha \in A}$ is a accumulation point of $\{f_\alpha\}_{\alpha \in A}$ if and only if $J = I$.

Let $\mathcal{P}$ be the set of partial accumulation points of $\{f_\alpha\}_{\alpha \in A}$ For any two $(J_f, f), (J_g, g) \in \mathcal{P}$, define the order $(J_f, f) \leq (J_g, g)$ if and only if $J_f \subseteq J_g$ and $g|_{J_f} = f$.

Since K_i is compact for each $i \in I$, the net $\{f_\alpha\}_\alpha$ has partial accumulation points $(\{i\}, f_i)$ for each $i \in I$ (since each K_i is compact, the net analogue to sequential compactness holds); in particular, $\mathcal{P}$ is nonempty.

Let $\mathcal{Q}$ be a totally ordered subset of $\mathcal{P}$, and $J_g = \bigcup \{J_f \mid (J_f, f) \in \mathbb{Q}\}$. Define g by letting $g(j) = f(j)$ for each $j \in J_f$ with $(J_f, f) \in \mathcal{Q}$, and arbitrarily on $I \setminus J_g$.

[i] See future definition of nets.

Since $\mathcal{Q}$ is totally ordered, g is well-defined. We claim that (J_g, g) is a partial accumulation point of $\{f_\alpha\}_\alpha$.

Let $N \subseteq \prod_{j \in J_g} K_j$ be a neighborhood of $g|_{J_g}$. We may suppose that

$$N = \pi_{j_1})^{-1}(U_{j_1}) \cap \cdots \cap \pi_{j_n}(U_{j_n}),$$

where $j_1, \dots, j_n \in J_g$, and $U_{j_i} \subseteq K_{j_i}$ are open.

Let $(J_h, h) \in \mathcal{Q}$ be such that $\{j_1, \dots, j_n\} \subseteq J_h$, which is possible since $\mathcal{Q}$ is totally ordered. Since (J_h, h) is a partial accumulation point of $\{f_\alpha\}_\alpha$, there is an index α and a $\beta \geq \alpha$, where

$$f_\beta(j_k) = \pi_{j_k}(f_\beta)\, U_{j_k},$$

so $f_\beta \in N$. Thus, (J_g, g) is a partial accumulation point of $\{f_\alpha\}_\alpha$, and is an element of $\mathcal{P}$.

By Zorn's lemma,[ii] $\mathcal{P}$ has a maximal element, $(J_{\max}, f_{\max})$.

Suppose toward contradiction that $J_{\max} \subset I$, meaning there is an $i_0 \in I \setminus J_{\max}$. Since $(J_{\max}, f_{\max})$ is a partial accumulation point of $\{f_\alpha\}_\alpha$, there is a subnet $\left\{f_{\alpha_\beta}\right\}_\beta$ such that $\pi_j\left(f_{\alpha_\beta}\right) \to \pi_j(f_{\max})$ for each $j \in J_{\max}$.

Since K_{i_0} is compact, we find a subnet $\left\{f_{\alpha_{\beta_\gamma}}\right\}_\gamma$ such that $\pi_{i_0}\left(f_{\alpha_{\beta_\gamma}}\right)_\gamma$ converges to x_{i_0} in K_{i_0}.

Define $\tilde{f} \in K$ by setting $\tilde{f}|_{J_{\max}} = f_{\max}$, and $\tilde{f}(i_0) = x_{i_0}$. Thus, $\left(J_{\max} \cup \{i_0\}, \tilde{f}\right)$ is a partial accumulation point, which contradicts the maximality of $(J_{\max}, f_{\max})$. $\square$

Banach Spaces

Let X be a compact Hausdorff space, and let $C(X)$ denote the set of continuous functions $f : X \to \mathbb{C}$. For $f_1, f_2 \in C(X)$ and $\lambda \in \mathbb{C}$, we define

(1) $(f_1 + f_2)(x) = f_1(x) + f_2(x)$

(2) $(\lambda f_1)(x) = \lambda f_1(x)$

(3) $(f_1 f_2)(x) = f_1(x) f_2(x)$

With these operations, $C(X)$ is a commutative algebra[iii] with identity over the field $\mathbb{C}$.

For each $f \in C(X)$, f is bounded (since X is compact and f is continuous); thus, $\sup|f| < \infty$. We call this the norm of f, and denote it

$$\|f\|_\infty = \sup\{|f(x)| \mid x \in X\}.$$

Proposition (Properties of the Norm on $C(X)$)**.**

(1) Positive Definiteness: $\|f\|_\infty = 0 \Leftrightarrow f = 0$

(2) Absolute Homogeneity: $\|\lambda f\|_\infty = |\lambda| \|f\|_\infty$

(3) Subadditivity (Triangle Inequality): $\|f + g\|_\infty \leq \|f\|_\infty + \|g\|_\infty$

(4) Submultiplicativity: $\|fg\|_\infty \leq \|f\|_\infty \|g\|_\infty$

[ii] In a partially ordered set, if every totally ordered subset contains an upper bound, the set contains a maximal element

[iii] A vector space with multiplication.

We define a metric ρ on $C(X)$ by $\rho(f,g) = \|f-g\|_\infty$.

Proposition (Properties of the Induced Metric on $C(X)$)**.**

(1) $\rho(f,g) = 0 \Leftrightarrow f = g$

(2) $\rho(f,g) = \rho(g,f)$

(3) $\rho(f,h) \leq \rho(f,g) + \rho(g,h)$

Proposition (Completeness of $C(X)$)**.** *If X is a compact Hausdorff space, then $C(X)$ is a complete metric space.*

Proof. Let $\{f_n\}_{n=1}^\infty$ be Cauchy. Then,

$$\begin{aligned} |f_n(x) - f_m(x)| &\leq \|f_n - f_m\|_\infty \\ &= \rho(f_n, f_m) \end{aligned}$$

for each $x \in X$. Thus, $\{f_n(x)\}_{n=1}^\infty$ is Cauchy for each $x \in X$. We define $f(x) = \lim_{n\to\infty} f_n(x)$. We will need to show that this implies $\lim_{n\to\infty} \|f_n - f\|_\infty = 0$.

Let $\varepsilon > 0$; choose N such that $n, m \geq N$ implies $\|f_n - f_m\|_\infty < \varepsilon$. For $x_0 \in X$, there exists a neighborhood U such that $|f_N(x_0) - f_N(x)| < \varepsilon$ for $x \in U$.[iv] Thus,

$$\begin{aligned} |f(x_0) - f(x)| &= |f_n(x_0) - f_N(x_0) + f_N(x_0) - f_N(x) + f_N(x) - f_n(x)| \\ &\leq |f_n(x_0) - f_N(x_0)| + |f_N(x_0) - f_N(x)| + |f_N(x) - f_n(x)| \\ &\leq 3\varepsilon. \end{aligned}$$

Thus, f is continuous. Additionally, for $n \geq N$ and $x \in X$, we have

$$\begin{aligned} |f_n(x) - f(x)| &= \lim_{m\to\infty} |f_n(x) - f_m(x)| \\ &\leq \lim_{m\to\infty} \|f_n - f_m\|_\infty \\ &\leq \varepsilon. \end{aligned}$$

Thus, $\lim_{n\to\infty} \|f_n - f\|_\infty = 0$, meaning $C(X)$ is complete. $\square$

Definition (Banach Space)**.** A Banach space is a vector space over $\mathbb{C}$ with a norm $\|\cdot\|$ is complete with respect to the induced metric.

Proposition (Properties of the Banach Space Operations)**.** *Let $\mathcal{X}$ be a Banach space. The functions*

- $a : \mathcal{X} \times \mathcal{X} \to \mathcal{X}$; $a(f,g) = f + g$,
- $s : \mathbb{C} \times \mathcal{X} \to \mathcal{X}$; $s(\lambda, f) = \lambda f$,
- $n : \mathcal{X} \to \mathbb{R}^+$; $n(f) = \|f\|$

are continuous.

Definition (Directed Sets and Nets)**.** Let A be a partially ordered set with ordering $\leq$. We say A is directed if for each $\alpha, \beta \in A$, there exists a γ such that $\alpha \leq \gamma$ and $\beta \leq \gamma$.

A net is a map $\alpha \mapsto \lambda_\alpha$, where $\alpha \in A$ for some directed set A.

Definition (Convergence of Nets)**.** Let $\{\lambda_\alpha\}$ be a net in X. We say the net converges to $\lambda \in X$ if for every neighborhood U of λ, there exists α_U such that for $\alpha \geq \alpha_U$, every λ_α is contained in U.[v]

[iv] This is by the continuity of $\{f_n\}_n$.

[v] The net convergence generalizes sequence convergence in a metric space to the case where X does not have a metric.

Definition (Cauchy Nets in Banach Spaces)**.** A net $\{f_\alpha\}_\alpha$ in a Banach space $\mathcal{X}$ is said to be a Cauchy net if for every $\varepsilon > 0$, there exists α_0 in A such that $\alpha_1, \alpha_2 \geq \alpha_0$ implies $\|f_{\alpha_1} - f_{\alpha_2}\| < \varepsilon$.

Proposition (Convergence of Cauchy Nets in Banach Spaces)**.** *In a Banach space, every Cauchy net is convergent.*

Proof. Let $\{f_\alpha\}_\alpha$ be a Cauchy net in $\mathcal{X}$. Choose α_1 such that $\alpha \geq \alpha_1$ implies $\|f_\alpha - f_{\alpha_1}\| < 1$.

We iterate this process by choosing $\alpha_{n+1} \geq \alpha_n$ such that $\alpha \geq \alpha_{n+1}$ implies $\left\|f_\alpha - f_{\alpha_{n+1}}\right\| < \frac{1}{n+1}$.

The sequence $\{f_{\alpha_n}\}_{n=1}^\infty$ is Cauchy, and since $\mathcal{X}$ is complete, there exists $f \in \mathcal{X}$ such that $\lim_{n\to\infty} f_{\alpha_n} = f$.

We must now prove that $\lim_{\alpha\in A} f_\alpha = f$. Let $\varepsilon > 0$. Choose n such that $\frac{1}{n} < \frac{\varepsilon}{2}$, and $\|f_{\alpha_n} - f_\alpha\| < \frac{\varepsilon}{2}$. Then, for $\alpha \geq \alpha_n$, we have

$$\begin{aligned}
\|f_\alpha - f\| &\leq \|f_\alpha - f_{\alpha_n}\| + \|f_{\alpha_n} - f\| \\
&< \frac{1}{n} + \frac{\varepsilon}{2} \\
&< \varepsilon.
\end{aligned}$$

□

Definition (Convergence of Infinite Series)**.** Let $\{f_\alpha\}_\alpha$ be a set of vectors in $\mathcal{X}$. Let $\mathcal{F} = \{F \subseteq A \mid F \text{ finite}\}$.

Define the ordering $F_1 \leq F_2 \Leftrightarrow F_1 \subseteq F_2$.[vi] For each F, define

$$g_F = \sum_{\alpha\in F} f_\alpha.$$

If $\{g_F\}_{F\in\mathcal{F}}$ converges to some $g \in \mathcal{X}$, then

$$\sum_{\alpha\in A} f_\alpha$$

converges, and we write

$$g = \sum_{\alpha\in A} f_\alpha.$$

Proposition (Absolute Convergence of Series in Banach Space)**.** *Let $\{f_\alpha\}_\alpha$ be a set of vectors in the Banach space $\mathcal{X}$. Suppose $\sum\limits_{\alpha\in A} \|f_\alpha\|$ converges in $\mathbb{R}$. Then, $\sum_{\alpha\in A} f_\alpha$ converges in $\mathcal{X}$.*

Proof. All we need show is $\{g_F\}_{F\in\mathcal{F}}$ is Cauchy. Since $\sum\limits_{\alpha\in A} \|f_\alpha\|$ converges, there exists $F_0 \in \mathcal{F}$ such that $F \geq F_0$ implies

$$\sum_{\alpha\in F} \|f_\alpha\| - \sum_{\alpha\in F_0} \|f_\alpha\| < \varepsilon.$$

[vi] the inclusion ordering

Thus, for $F_1, F_2 \geq F_0$, we have

$$\begin{aligned}
\|g_{F_1} - g_{F_2}\| &= \left\|\sum_{\alpha\in F_1} f_\alpha - \sum_{\alpha\in F_2} f_\alpha\right\| \\
&= \left\|\sum_{\alpha\in F_1\setminus F_2} f_\alpha - \sum_{\alpha\in F_2\setminus F_1}\right\| \\
&\leq \sum_{\alpha\in F_1\setminus F_2} \|f_\alpha\| + \sum_{\alpha\in F_2\setminus F_1} \|f_\alpha\| \\
&\leq \sum_{\alpha\in F_1\cup F_2} \|f_\alpha\| - \sum_{\alpha\in F_0} \|f_\alpha\| \\
&< \varepsilon.
\end{aligned}$$

Thus, $\{g_F\}_{F\in\mathcal{F}}$ is Cauchy, and thus the series is convergent. □

Theorem (Absolute Convergence Criterion for Banach Spaces)**.** *Let $\mathcal{X}$ be a normed vector space. Then, $\mathcal{X}$ is a Banach space if and only if for every sequence $\{f_n\}_{n=1}^{\infty}$ of vectors in $\mathcal{X}$,*

$$\sum_{n=1}^{\infty} \|f_n\| < \infty \Rightarrow \sum_{n=1}^{\infty} f_n \text{ convergent.}$$

Proof. The forward direction follows from the previous proposition.

Let $\{g_n\}_{n=1}^{\infty}$ be a Cauchy sequence in a normed vector space where

$$\sum_{n=1}^{\infty} \|f_n\| < \infty \Rightarrow \sum_{n=1}^{\infty} f_n \text{ convergent.}$$

We select a subsequence $\{g_{n_k}\}_{k=1}^{\infty}$ as follows. Choose n_1 such that $i, j \geq n_1$ implies $\|g_i - g_j\| < 1$; recursively, we select n_{N+1} such that $\|g_{N+1} - g_N\| < 2^{-N}$. Then,

$$\sum_{k=1}^{\infty} \|g_{k+1} - g_k\| < \infty.$$

Set $f_k = g_{n_k} - g_{n_{k-1}}$ for $k > 1$, with $f_1 = g_{n_1}$. Then,

$$\sum_{k=1}^{\infty} \|f_k\| < \infty,$$

meaning $\displaystyle\sum_{k=1}^{\infty} f_k$ converges. Thus, $\{g_{n_k}\}_{k=1}^{\infty}$ converges, meaning $\{g_n\}_{n=1}^{\infty}$ converges in $\mathcal{X}$. □

Definition (Bounded Linear Functional)**.** Let $\mathcal{X}$ be a Banach space. A function $\varphi : \mathcal{X} \to \mathbb{C}$ is known as a bounded linear functional if

(1) $\varphi(\lambda_1 f_1 + \lambda_2 f_2) = \lambda_1\varphi(f_1) + \lambda_2\varphi(f_2)$ for each $\lambda_1, \lambda_2 \in \mathbb{C}$ and $f_1, f_2 \in \mathcal{X}$.

(2) There exists M such that $|\varphi(f)| \leq M\|f\|$ for each $f \in \mathcal{X}$.

Proposition (Equivalent Criteria for Bounded Linear Functionals)**.** *Let φ be a linear functional on $\mathcal{X}$. Then, the following conditions are equivalent:*

(1) φ is bounded;

(2) φ *is continuous;*

(3) φ *is continuous at* 0.

Proof. (1) $\Rightarrow$ (2): If $\{f_\alpha\}_{\alpha\in A}$ is a net in $\mathcal{X}$ converging to f, then $\lim_{\alpha\in A}\|f_\alpha - f\| = 0$. Thus,

$$\begin{aligned}\lim_{\alpha\in A}|\varphi(f_\alpha)-\varphi(f)| &= \lim_{\alpha\in A}|\varphi(f_\alpha - f)|\\ &\leq \lim_{\alpha\in F} M\|f_\alpha - f\|\\ &= 0\end{aligned}$$

(2) $\Rightarrow$ (3): Trivial.

(3) $\Rightarrow$ (1): If φ is continuous at 0, then there exists $\delta > 0$ such that $\|f\| < \delta \Rightarrow |\varphi(f)| < 1$. Thus, for any $g \in X$ nonzero, we have

$$\begin{aligned}|\varphi(g)| &= \frac{2\|g\|}{\delta}\left|\varphi\left(\frac{\delta}{2\|g\|}g\right)\right|\\ &< \frac{2}{\delta}\|g\|,\end{aligned}$$

meaning φ is bounded.

$\square$

Definition (Dual Space)**.** Let $\mathcal{X}^*$ be the set of bounded linear functionals on $\mathcal{X}$. For each $\varphi \in \mathcal{X}^*$, define

$$\|\varphi\| = \sup_{\|f\|=1}|\varphi(f)|.$$

We say $\mathcal{X}^*$ is the dual space of $\mathcal{X}$.

Proposition (Completeness of the Dual Space)**.** *For $\mathcal{X}$ a Banach space, $\mathcal{X}^*$ is a Banach space.*

Proof. Both positive definiteness and absolute homogeneity are apparent from the definition of the norm. We will now show the triangle inequality as follows. Let $\varphi_1, \varphi_2 \in \mathcal{X}^*$. Then,

$$\begin{aligned}\|\varphi_1+\varphi_2\| &= \sup_{\|f\|=1}|\varphi_1(f)+\varphi_2(f)|\\ &\leq \sup_{\|f\|=1}|\varphi_1(f)| + \sup_{\|f\|=1}|\varphi_2(f)|\\ &= \|\varphi_1\| + \|\varphi_2\|.\end{aligned}$$

We must now show completeness. Let $\{\varphi_n\}_n$ be a sequence in $\mathcal{X}^*$. Then, for every $f \in \mathcal{X}$, it is the case that

$$|\varphi_n(f)-\varphi_m(f)| \leq \|\varphi_n-\varphi_m\|\,\|f\|,$$

meaning $\{\varphi_n(f)\}_n$ is Cauchy for each f. Define $\varphi(f) = \lim_{n\to\infty}\varphi_n(f)$. It is clear that $\varphi(f)$ is linear, and for N such that $n, m \geq N \Rightarrow \|\varphi_n - \varphi_m\| < 1$,

$$\begin{aligned}|\varphi(f)| &\leq |\varphi(f)-\varphi_N(f)| + |\varphi_N(f)|\\ &\leq \lim_{n\to\infty}|\varphi_n(f)-\varphi_N(f)| + |\varphi_N(f)|\\ &\leq \left(\lim_{n\to\infty}\|\varphi_n-\varphi_N\| + \|\varphi_N\|\right)\|f\|\\ &\leq (1+\|\varphi_N\|)\|f\|,\end{aligned}$$

so φ is bounded. Thus, we must show that $\lim_{n\to\infty} \|\varphi_n - \varphi\| = 0$. Let $\varepsilon > 0$. Set N such that $n, m \geq N \Rightarrow \|\varphi_n - \varphi_m\| < \varepsilon$. Then, for $f \in \mathcal{X}$,

$$\begin{aligned} |\varphi(f) - \varphi_n(f)| &\leq |\varphi(f) - \varphi_m(f)| + |\varphi_m(f) - \varphi_n(f)| \\ &\leq |(\varphi - \varphi_m)(f)| + \varepsilon \|f\|. \end{aligned}$$

Since $\lim_{m\to\infty} |(\varphi - \varphi_m)(f)| = 0$, we have $\|\varphi - \varphi_m\| < \varepsilon$. □

Proposition (Banach Spaces and their Duals)**.**

(1) *The space ℓ^∞ consists of the set of bounded sequences. For $f \in \ell^\infty$, the norm on f is computed as $\|f\|_\infty = \sup_n |f(n)|$.*

(2) *The subspace $c_0 \subseteq \ell^\infty$ consists of all sequences that vanish at ∞. The norm on c_0 is inherited from the norm on ℓ_∞.*

(3) *The space ℓ^1 consists of the set of all absolutely summable sequences. For $f \in \ell^1$, the norm on f is computed as $\|f\| = \sum_{n=1}^{\infty} |f(n)|$.*

We claim that these are all Banach spaces.

We also claim that $c_0^* = \ell^1$, and $\left(\ell^1\right)^* = \ell^\infty$.

Proofs of Banach Space.

ℓ^∞:

Proof of Normed Vector Space: Let $a, b \in \ell^\infty$, and $\lambda \in \mathbb{C}$. Then,

$$\sup_n |a(n)| = 0$$

if and only if a is the zero sequence. Additionally, we have that

$$\begin{aligned} \|\lambda a\|_\infty &= \sup_n |\lambda a(n)| \\ &= |\lambda| sup_n |a(n)| \\ &= |\lambda| \|a\|_\infty, \end{aligned}$$

meaning $\|\cdot\|_\infty$ is absolutely homogeneous. Finally,

$$\begin{aligned} \|a + b\|_\infty &= \sup_n |a(n) + b(n)| \\ &\leq \sup_n |a(n)| + \sup_n |b(n)| \\ &= \|a\|_\infty + \|b\|_\infty. \end{aligned}$$

Proof of Completeness: Let $\{a_n\}_{n=1}^\infty$ be a Cauchy sequence of elements of ℓ^∞. Let $\varepsilon > 0$, and let N be such that $\|a_n - a_m\|_\infty < \varepsilon$ for $n, m \geq N$. Then, for each k,

$$\begin{aligned} |a_n(k) - a_m(k)| &= |(a_n - a_m)(k)| \\ &\leq \|a_n - a_m\| \\ &< \varepsilon, \end{aligned}$$

meaning that $a_n(k)$ is Cauchy in $\mathbb{C}$ for each k.

Set $a(k) = \lim_{n\to\infty} a_n(k)$. We must now show that $\lim_{n\to\infty} \|a - a_n\| = 0$. Let $\varepsilon > 0$, and set N such that for $n, m \geq N$, $\|a_m - a_n\| < \varepsilon$. Then,

$$\begin{aligned} |a(k) - a_n(k)| &\leq |a(k) - a_m(k)| + |a_m(k) - a_n(k)| \\ &\leq |a(k) - a_m(k)| + \|a_m - a_n\| \\ &< |a(k) - a_m(k)| + \varepsilon. \end{aligned}$$

Since $\lim_{m\to\infty} |a(k) - a_m(k)| = 0$, we have $\|a - a_n\| < \varepsilon$.[vii]

c_0:

Proof of Subspace: Let $a, b \in c_0$, and $\lambda \in \mathbb{C} \setminus \{0\}$. Let $\varepsilon > 0$. Set N_1 such that $|a(n)| < \frac{\varepsilon}{2|\lambda|}$ for all $n \geq N_1$, and set N_2 such that $|b(n)| < \frac{\varepsilon}{2}$ for all $n \geq N_2$.

Then, for all $n \geq \max\{N_1, N_2\}$,

$$\begin{aligned} |\lambda a(n) + b(n)| &\leq |\lambda||a(n)| + |b(n)| \\ &< |\lambda|\frac{\varepsilon}{2|\lambda|} + \frac{\varepsilon}{2} \\ &= \varepsilon. \end{aligned}$$

Proof of Completeness: In order to show completeness, we must show that c_0 is closed in ℓ^∞. Let $\{a_k\}_{k=1}^\infty$ be a sequence in c_0, with $a_k \to a$.

We will need to show that $a \in c_0$.[viii] Let $\varepsilon > 0$, and set K such that for all $k \geq K$, $\|a_k - a\| < \varepsilon/2$. For each k, choose N such that $|a_k(n)| < \varepsilon/2$ for all $n \geq N$. Then, for all $n \geq N$,

$$\begin{aligned} |a(n)| &\leq |a(n) - a_k(n)| + |a_k(n)| \\ &< \|a - a_k\| + |a_k(n)| \\ &< \varepsilon. \end{aligned}$$

Since c_0 is closed in ℓ^∞, it is thus complete.

ℓ^1:

Proof of Normed Vector Space: Let $a, b \in \ell^1$, and $\lambda \in \mathbb{C}$. Then,

$$\begin{aligned} \|\lambda a + b\| &= \sum_{k=1}^{\infty} |\lambda a(k) + b(k)| \\ &\leq \sum_{k=1}^{\infty} |\lambda a(k)| + \sum_{k=1}^{\infty} |b(k)| \\ &= |\lambda| \sum_{k=1}^{\infty} |a(k)| + \sum_{k=1}^{\infty} |b(k)| \\ &= |\lambda| \|a\| + \|b\|. \end{aligned}$$

Thus, $\lambda a + b \in \ell^1$. We have also shown both the triangle inequality and absolute homogeneity. We can also see that, if $\|a\| = 0$,

$$\begin{aligned} \|a\| &= \sum_{k=1}^{\infty} |a(k)| \\ &= 0, \end{aligned}$$

which is only true if $a(k) = 0$ for all k.

[vii] The reason we had to go about it like this was that we defined the sequence a pointwise; however, we need to show convergence *in norm*.

[viii] Sequential criterion for closure.

□

Example (Pointwise Convergence and Convergence in Norm). Consider a sequence $\{\varphi_n\}_n$ in $\mathcal{X}^*$. If the sequence converges in norm to φ, then it must also converge pointwise. However, the converse isn't true.

For each k, define $L_k(f) = f(k)$, where $f \in \ell^1$. We can see that $L_k \in \left(\ell^1\right)^*$, and $\lim_{k\to\infty} L_k(f) = 0$ for each $f \in \ell^1$. The sequence of L_k thus converges to the zero functional pointwise, but since $\|L_k\| = 1$ always, it isn't the case that L_k converges to the zero functional in norm.

Definition (Weak Topology and w^*-Topology). Let X be a set, Y a topological space, and $\mathcal{F}$ be a family of functions from X to Y. The weak topology on X is the topology for which all functions in $\mathcal{F}$ are continuous.

For each f in $\mathcal{X}$, let $\hat{f} : \mathcal{X}^* \to \mathbb{C}$ be defined by $\hat{f}(\varphi) = \varphi(f)$. The w^*-topology on $\mathcal{X}^*$ is the weak topology on $\mathcal{X}^*$ defined by the family of functions $\left\{\hat{f} \mid f \in \mathcal{X}\right\}$.

If Y is Hausdorff and $\mathcal{F}$ separates the points of X, then the weak topology is Hausdorff.[ix]

Proposition (Hausdorff Property of w^*-Topology). *The w^*-topology on $\mathcal{X}^*$ is Hausdorff.*

Proof. If $\varphi_1 \neq \varphi_2$, then there exists at least one f such that $\varphi_1(f) \neq \varphi_2(f)$, meaning $\left\{\hat{f} \mid f \in \mathcal{X}\right\}$ separates the points of $\mathcal{X}^*$, so the w^*-topology is Hausdorff. □

Proposition (Convergence in the w^*-Topology). *A net $\{\varphi_\alpha\}_\alpha$ converges to $\varphi \in \mathcal{X}^*$ in the w^* topology if and only if $\lim_{\alpha\in A} \varphi_\alpha = \varphi$.*[x]

Proposition (Determination of the w^*-Topology). *Let $\mathcal{M}$ be a dense subset of $\mathcal{X}$, and let $\{\varphi_\alpha\}_{\alpha\in A}$ be a uniformly bounded net in $\mathcal{X}^*$, where $\lim_{\alpha\in A} \varphi_\alpha(f) = \varphi(f)$ for each $f \in \mathcal{M}$. Then, the net $\{\varphi_\alpha\}_{\alpha\in A}$ converges to φ in the w^* topology.*

Proof. Let $M = \sup_{\alpha\in A} \max\{\|\varphi_\alpha\|, \|\varphi\|\}$, and let $\varepsilon > 0$.

Given $g \in \mathcal{X}$, choose $f \in \mathcal{M}$ such that $\|f - g\| < \frac{\varepsilon}{3M}$. Let $\alpha_0 \in A$ such that $\alpha \geq \alpha_0$ implies $|\varphi_\alpha(f) - \varphi(f)| < \frac{\varepsilon}{3}$. Then, for all $\alpha \geq \alpha_0$,

$$\begin{aligned}
|\varphi_\alpha(g) - \varphi(g)| &\leq |\varphi_\alpha(g) - \varphi_\alpha(f)| + |\varphi_\alpha(f) - \varphi(f)| + |\varphi(f) - \varphi(g)| \\
&\leq \|\varphi_\alpha\| \|f - g\| + \frac{\varepsilon}{3} + \|\varphi\| \|f - g\| \\
&< \varepsilon.
\end{aligned}$$

□

Definition (Unit Ball). For $\mathcal{X}$ a Banach space, we denote the unit ball as $B_{\mathcal{X}} = \{f \in \mathcal{X} \mid \|f\| \leq 1\}$.[xi]

Theorem (Banach–Alaoglu). *The set $B_{\mathcal{X}^*}$ is compact in the w^*-topology.*

Proof. Let $f \in B_{\mathcal{X}}$. Let $\overline{\mathbb{D}}^f$ denote the f-labeled copy of the closed unit disc in $\mathbb{C}$. Set

$$P = \prod_{f\in B_{\mathcal{X}}} \overline{\mathbb{D}}^f.$$

Then, P is compact by Tychonoff's theorem.

[ix] I am trying to find a source to prove this, will include the proof of this implicit proposition hopefully.

[x] In the special case of Hilbert space $\mathcal{H}$, we know from the Riesz Representation Theorem that each $\varphi \in \mathcal{H}^*$ is represented by ψ such that $\varphi(f) = \langle f, \psi\rangle$.

[xi] The book uses a different notation, but I don't like that notation.

Define $\Lambda : B_{\mathcal{X}^*} \to P$ by $\Lambda(\varphi) = \varphi|_{B_{\mathcal{X}}}$. Notice that $\Lambda(\varphi_1) = \Lambda(\varphi_2)$ implies that $\varphi_1 = \varphi_2$ on $B_{\mathcal{X}}$, meaning $\varphi_1 = \varphi_2$. Therefore, Λ is injective.

Let $\{\varphi_\alpha\}_{\alpha\in A}$ be a net in $\mathcal{X}^*$ converging to φ in the w^*-topology. Then,

$$\begin{aligned}\lim_{\alpha\in A} \varphi_\alpha(f) = \varphi(f)\\ \lim_{\alpha\in A} \left(\Lambda\left(\varphi_\alpha\right)\right)(f) = \lim_{\alpha\in A} \left(\Lambda\left(\varphi\right)\right)(f),\end{aligned}$$

meaning

$$\lim_{\alpha\in A} \Lambda\left(\varphi_\alpha\right) = \Lambda\left(\varphi\right)$$

in P. Since Λ is one-to-one, we can see that $\Lambda : \mathcal{B}_{\mathcal{X}^*} \to \Lambda\left(B_{\mathcal{X}^*}\right) \subseteq P$ is a linear homeomorphism.

Let $\{\Lambda\left(\varphi_\alpha\right)\}_{\alpha\in A}$ be a net in $\Lambda\left(B_{\mathcal{X}^*}\right)$ converging in the product topology to ψ. Let $f, g \in B_{\mathcal{X}^*}$ and $\xi \in \mathbb{C}$ with $f + g \in B_{\mathcal{X}^*}$ and $\xi f \in B_{\mathcal{X}^*}$. Then,

$$\begin{aligned}\psi\left(f+g\right) &= \lim_{\alpha\in A}\left(\Lambda\left(\varphi_\alpha\right)\right)(f+g)\\ &= \lim_{\alpha\in A}\left(\Lambda\left(\varphi_\alpha\right)\right)(f) + \lim_{\alpha\in A}\left(\Lambda\left(\varphi_\alpha\right)\right)(g)\\ &= \psi(f) + \psi(g)\end{aligned}$$

and

$$\begin{aligned}\psi(\xi f) &= \lim_{\alpha\in A}\left(\Lambda\left(\varphi_\alpha\right)\right)(\xi f)\\ &= \lim_{\alpha\in A}\varphi_\alpha\left(\xi f\right)\\ &= \varphi\left(\xi f\right)\\ &= \xi\varphi\left(f\right)\\ &= \xi\left(\Lambda\left(\varphi\right)\right)(f)\\ &= \xi\psi(f).\end{aligned}$$

Thus, $\psi(f)$ determines $\tilde{\psi}(f) = \frac{1}{\|f\|}\psi\left(f\right)$ in $B_{\mathcal{X}^*}$ for all $f \in \mathcal{X} \setminus \{0\}$. If $f \in B_{\mathcal{X}}$, then $\tilde{\psi} \in \mathcal{B}_{\mathcal{X}^*}$ and $\Lambda(\tilde{\psi}) = \psi$.

Thus, $\Lambda\left(B_{\mathcal{X}^*}\right)$ is closed in P, meaning $B_{\mathcal{X}^*}$ is compact in the w^*-topology. □

We will be able to use the Banach–Alaoglu theorem to prove that every Banach space is isomorphic to a subspace of $C(X)$ for some compact Hausdorff space X. However, we will need some theorems and machinery to prove that

Definition (Sublinear Functionals)**.** Let $\mathcal{E}$ be a real linear space, and let p be a real-valued functional on $\mathcal{E}$. We say p is a sublinear functional if $p(f+g) \leq p(f) + p(g)$ for all $f, g \in \mathcal{E}$, and $p(\lambda f) = \lambda p(f)$.

Theorem (Hahn–Banach Dominated Extension)**.** *Let $\mathcal{E}$ be a real linear space, and p a (real-valued) sublinear functional on $\mathcal{E}$. Let $\mathcal{F} \subseteq \mathcal{E}$ be a subspace, and φ a real linear functional on $\mathcal{F}$ such that $\varphi(f) \leq p(f)$ for all $f \in \mathcal{F}$.*

Then, there exists a real linear functional Φ on $\mathcal{E}$ such that $\Phi(f) = \varphi(f)$ for $f \in \mathcal{F}$, and $\Phi(g) \leq p(g)$ for all $g \in \mathcal{E}$.

Proof. Let $\mathcal{F} \subseteq \mathcal{E}$ be a nonempty subspace, and let $f \notin \mathcal{F}$. Select $\mathcal{G} = \{g + \lambda f \mid g \in \mathcal{F},\ \lambda \in \mathbb{R}\}$.

We will extend φ to $\Phi_{\mathcal{G}}$ by taking $\Phi(g+\lambda f) \leq p(g+\lambda f)$. Dividing by $|\lambda|$, we find that, for all $h \in \mathcal{F}$

$$\Phi(f-h) \leq p(f-h)$$

and

$$-p\left(h-f\right) \leq \Phi\left(h-f\right).$$

Thus, recalling that $\Phi(h) = \varphi(h)$ for $h \in \mathcal{F}$,

$$-p\left(h-f\right) + \varphi(h) \leq \Phi\left(f\right) \leq p(f-h) + \varphi(h).$$

The desired Φ only has this property if

$$\sup_{h\in\mathcal{F}}\left\{\varphi(h) - p(h-f)\right\} \leq \inf_{k\in\mathcal{F}}\left\{\varphi(k) + p(f-k)\right\}.$$

However, we also have

$$\begin{aligned}\varphi(h) - \varphi(k) &= \varphi(h-k)\\ &\leq p(h-k)\\ &\leq p(f-k) + p(h-f),\end{aligned}$$

meaning

$$\varphi(h) - p(h-f) \leq \varphi(k) + p(f-k).$$

Therefore, we can thus extend φ on $\mathcal{F}$ to Φ on $\mathcal{G}$, where $\Phi(h) \leq p(h)$. We label this as $\Phi_{\mathcal{G}}$.

Let $\mathcal{P} = \{(\mathcal{G}_\delta, \Phi_{\mathcal{G}_\delta})\}_{\delta\in D}$ denote the class of extensions of φ such that $\Phi_{\mathcal{G}_\delta}(h) \leq p(h)$ for all $h \in \mathcal{G}_\delta$.

An element of $\mathcal{P}$ contains $\mathcal{G}$ such that $\mathcal{F} \subseteq \mathcal{G} \subseteq \mathcal{E}$, where $\Phi_{\mathcal{G}}$ extends φ, meaning $\mathcal{P}$ is nonempty.

The partial order on $\mathcal{P}$ can be set by $(\mathcal{G}_1, \Phi_{\mathcal{G}_2}) \leq (\mathcal{G}_2, \Phi_{\mathcal{G}_2})$ if $G_1 \subseteq G_2$ and $\Phi_{\mathcal{G}_1}(f) = \Phi_{\mathcal{G}_2}(f)$ for all $f \in \mathcal{G}_1$.

Consider a chain[xii] $\{(\mathcal{G}_\alpha, \Phi_{\mathcal{G}_\alpha})\}_{\alpha\in A}$. To find an upper bound, consider

$$\mathcal{G} = \bigcup_{\alpha\in A}\mathcal{G}_\alpha,$$

where $\Phi_{\mathcal{G}}(f) = \Phi_{\mathcal{G}_\alpha}(f)$ for every $f \in \mathcal{G}_\alpha$. Then, $\Phi_{\mathcal{G}}$ is a linear functional that satisfies the given properties,[xiii] and $(\mathcal{G}, \Phi_{\mathcal{G}})$ is an upper bound for $\{(\mathcal{G}_\alpha, \Phi_{\mathcal{G}_\alpha})\}$.

Thus, by Zorn's Lemma, there is a maximal element of $\mathcal{P}$, $(\mathcal{G}_{\max}, \Phi_{\mathcal{G}_{\max}})$. If $\mathcal{G}_0 \neq \mathcal{E}$, then we can find a $f \notin \mathcal{G}_0$ and repeat the process performed at the beginning of the proof, which would contradict maximality.

Thus, we have constructed a linear functional Φ such that $\Phi(f) \leq p(f)$ for all $f \in \mathcal{E}$ that extends φ. $\square$

Theorem (Hahn–Banach Continuous Extension)**.** *Let $\mathcal{M}$ be a subspace of the Banach space $\mathcal{X}$. If φ is a bounded linear functional on $\mathcal{M}$, then there exists Φ on $\mathcal{X}^*$ such that $\Phi(f) = \varphi(f)$ for all $f \in \mathcal{M}$ and $\|\Phi\| = \|\varphi\|$.*

[xii] totally ordered subset

[xiii] I am too lazy to prove this.

Proof. Consider $\tilde{\mathcal{X}}$ as the real linear space on which $\|\cdot\|$ is the sublinear functional. Set $\psi = \operatorname{Re}(\varphi)$ on $\mathcal{M}$.

We can see that, since $\operatorname{Re}(\varphi(f)) \leq |\varphi(f)|$, $\|\psi\| \leq \|\varphi\|$.

Set $p(f) = \|\varphi\| \|f\|$. Since $\psi(f) \leq p(f)$ for all $f \in \mathcal{X}$, by the dominated extension theorem, there exists Ψ defined on $\tilde{\mathcal{X}}$ that extends ψ. In particular, we can see that $\Psi(f) \leq \|\varphi\| \|f\|$.

Define Φ on $\mathcal{X}$ by $\Phi(f) = \Psi(f) - i\Psi(if)$ for any $f \in \mathcal{X}$. We will show that Φ is a complex bounded linear functional that extends φ and has norm $\|\varphi\|$. We can see that

$$\begin{aligned}\Phi(f+g) &= \Psi(f+g) - i\Psi(i(f+g))\\ &= \Psi(f) - i\Psi(if) + \Psi(g) - i\Psi(ig)\\ &= \Phi(f) + \Phi(g),\end{aligned}$$

and for $\lambda_1, \lambda_2 \in \mathbb{R}$,[xiv]

$$\Phi((\lambda_1 + i\lambda_2) f) = \Phi(\lambda_1 f) + \Phi(i\lambda_2 f) \qquad = (\lambda_1 + i\lambda_2)\Phi(f).$$

To verify that $\Phi(f)$ extends $\varphi(f)$, let $f \in \mathcal{M}$, and we can see that

$$\begin{aligned}\Phi(f) &= \Psi(f) - i\Psi(if)\\ &= \psi(f) - i\psi(if)\\ &= \operatorname{Re}(\varphi(f)) - i\operatorname{Re}(\varphi(if))\\ &= \operatorname{Re}(\varphi(f)) - i(-\operatorname{Im}(\varphi(f)))\\ &= \varphi(f).\end{aligned}$$

Finally, to verify that $\|\Phi\| = \|\varphi\|$, all we need show is that $\|\Phi\| \leq \|\Psi\|$. Let $\Phi(f) = re^{i\theta}$. Then,

$$\begin{aligned}|\Phi(f)| &= r\\ &= e^{-i\theta}\Phi(f)\\ &= \Phi\left(e^{-i\theta} f\right)\\ &= \Psi\left(e^{-i\theta} f\right)\\ &\leq \left|\Psi\left(e^{-i\theta} f\right)\right|\\ &\leq \|\Psi\| \|f\|,\end{aligned}$$

meaning

$$\|\Phi\| \|f\| \leq \|\Psi\| \|f\|.$$

$\square$

Corollary (Norming Functional). *If $f \in \mathcal{X}$, then there exists $\varphi \in \mathcal{X}^*$ such that $\|\varphi\| = 1$ and $\varphi(f) = \|f\|$.*

Proof. Assume $f \neq 0$. Let $\mathcal{M} = \{\lambda f \mid \lambda \in \mathbb{C}\}$, and define ψ on $\mathcal{M}$ by $\psi(\lambda f) = \lambda \|f\|$. Then, $\|\psi\| = 1$ and an extension of ψ to $\mathcal{X}$ has the desired properties. $\square$

Theorem (Banach). *Let $\mathcal{X}$ be any Banach space. Then, $\mathcal{X}$ is isometrically isomorphic to some closed subspace of $C(X)$ for compact Hausdorff X.*

[xiv] Notice that $\Phi(if) = \Psi(if) - i\Psi(-f) = i\Psi(f) + \Psi(if) = i\Phi(f)$

Proof. Set $X = B_{\mathcal{X}^*}$ in the w^*-topology, which by Banach–Alaoglu, is compact.

Set $\beta : \mathcal{X} \to C(X)$ by $\beta(f)(\varphi) = \varphi(f)$. Then, for $\lambda_1, \lambda_2 \in \mathbb{C}$, $f_1, f_2 \in \mathcal{X}$,

$$\begin{aligned}\beta\left(\lambda_1 f_1 + \lambda_2 f_2\right)(\varphi) &= \varphi\left(\lambda_1 f_1 + \lambda_2 f_2\right)\\ &= \lambda_1 \varphi(f_1) + \lambda_2 \varphi\left(f_2\right)\\ &= \left(\lambda_1 \beta\left(f_1\right) + \lambda_2 \beta\left(f_2\right)\right)(\varphi).\end{aligned}$$

Let $f \in \mathcal{X}$. Then,

$$\begin{aligned}\|\beta(f)\|_\infty &= \sup_{\varphi \in B_{\mathcal{X}^*}} |\beta(f)(\varphi)|\\ &= \sup_{\varphi \in B_{\mathcal{X}^*}} |\varphi(f)|\\ &\leq \sup_{\varphi \in B_{\mathcal{X}^*}} \|\varphi\| \|f\|\\ &\leq \|f\|.\end{aligned}$$

Additionally, since there exists a norming functional in $B_{\mathcal{X}^*}$, we have that $\|\beta(f)\|_\infty = \|f\|$, meaning β is an isometric isomorphism. □

Note: The preceding construction cannot yield an isometric isomorphism to $C\left(B_{\mathcal{X}^*}\right)$ itself, even if $\mathcal{X} = C(Y)$ for some Y.

It can be shown via topological arguments that if $\mathcal{X}$ is separable, we can take X to be the interval $[0, 1]$.

Now, we turn to finding the dual space of $C([0, 1])$. In particular, we will soon find out that $C([0, 1]) = \mathrm{BV}([0, 1])$, which is the space of all functions of bounded variation.

Definition (Bounded Variation)**.** If φ is a complex function with domain $[0, 1]$, φ is said to be of bounded variation if for every partition $0 = t_0 < t_1 < \cdots < t_n < t_{n+1} = 1$, it is the case that

$$\sum_{i=0}^{n} \left|\varphi\left(t_{n+1}\right) - \varphi\left(t_n\right)\right| \leq M.$$

The infimum of all such values of M is denoted $\|\varphi\|_{\mathrm{BV}}$.[xv] Henceforth, all functions of bounded variation will be referred to as BV functions.

Proposition (Limits of BV Functions)**.** *A BV function possesses a limit from the left and right at each end-point.*

Proof. Let $\varphi : [0, 1] \to \mathbb{C}$ not have a limit from the left at some point $t \in (0, 1]$.

Then, for any $\delta > 0$, there exist s_1, s_2 such that $t - \delta < s_1 < s_2 < t$ and $|\varphi(s_2) - \varphi(s_1)| \geq \varepsilon$. Selecting $\delta_2 = t - s_2$, we inductively create a sequence $\{s_n\}_{n=1}^{\infty}$ where $0 < s_1 < s_2 < \cdots < s_n < \cdots < t$.

Consider a partition $t_0 = 0$, and $t_k = s_k$ for $k = 1, 2, \ldots, N$, and $t_{N+1} = 1$, we have

$$\begin{aligned}\sum_{k=0}^{N} |\varphi(t_{k+1}) - \varphi(t_k)| &\geq \sum_{k=1}^{N} |\varphi(s_{k+1}) - \varphi(s_k)|\\ &\geq N\varepsilon.\end{aligned}$$

Thus, φ is not a BV function. □

[xv] The book uses $\|\varphi\|_\nu$, but I think that's more confusing than BV.

Corollary (Discontinuities of a BV Function)**.** *Let $\varphi : [0, 1] \to \mathbb{C}$ be a BV function. Then, φ has countably many discontinuities.*

Proof. Notice that φ is discontinuous at a point t if and only if $\varphi(t) \neq \varphi(t^+)$ or $\varphi(t) \neq \varphi(t^-)$.

If $t_0, t_1, \dots, t_n$ are distinct points of $[0, 1]$, then

$$\sum_{i=0}^{N} \left|\varphi(t) - \varphi(t^+)\right| + \sum_{i=0}^{N} \left|\varphi(t) - \varphi(t^-)\right| \leq \|\varphi\|_{\text{BV}}.$$

Thus, for every $\varepsilon > 0$, there exist at most finitely many t such that $|\varphi(t) - \varphi(t^+)| + |\varphi(t) - \varphi(t^-)| \geq \varepsilon$, meaning there can be at most countably many discontinuities. □

Definition (Riemann–Stieltjes Integral)**.** Let $f \in C([0, 1])$, and let $\varphi \in \text{BV}([0, 1])$. Then, we denote the Riemann–Stieltjes integral

$$\int_0^1 f \, d\varphi = \sum_{i=0}^{n} f(t_i') \left[\varphi(t_{i+1}) - \varphi(t_i)\right],$$

where $\{t_i\}$ is a partition and $t_i' \in [t_i, t_{i+1}]$.

Proposition (Essential properties of the Riemann–Stieltjes Integral)**.** *If $f \in C([0, 1])$ and $\varphi \in BV([0, 1])$, then*

(1) $\displaystyle\int_0^1 f \, d\varphi$ *exists;*

(2) $\displaystyle\int_0^1 (\lambda_1 f_1 + \lambda_2 f_2) \, d\varphi = \lambda_1 \int_0^1 f_1 \, d\varphi + \lambda_2 \int_0^1 f_2 \, d\varphi$ *for* $\lambda_1, \lambda_2 \in \mathbb{C}$ *and* $f_1, f_2 \in C([0, 1])$*;*

(3) $\displaystyle\int_0^1 f \, d(\lambda_1 \varphi_1 + \lambda_2 \varphi_2) = \lambda_1 \int_0^1 f_1 \, d\varphi_1 + \lambda_2 \int_0^1 f_2 \, d\varphi_2$ *for* $\lambda_1, \lambda_2 \in \mathbb{C}$ *and* $\varphi_1, \varphi_2 \in BV([0, 1])$*;*

(4) $\displaystyle\left|\int_0^1 f \, d\varphi\right| \leq \|f\|_\infty \|\varphi\|_{BV}$ *for* $f \in C([0, 1])$ *and* $\varphi \in BV([0, 1])$*.*

Proposition (BV Function Limits and Riemann–Stieltjes Integrals)**.** *Let $\varphi \in BV([0, 1])$ and ψ be defined by $\psi(t) = \varphi(t^-)$ for $t \in (0, 1)$, where $\psi(0) = \varphi(0)$ and $\psi(1) = \varphi(1)$.*

Then, $\psi \in BV([0, 1])$, $\|\psi\|_{BV} \leq \|\varphi\|_{BV}$, and

$$\int_0^1 f \, d\varphi = \int_0^1 f \, d\psi$$

for $f \in C([0, 1])$.

Proof. We list the set $\{s_i\}_{i \geq 1}$ the points where φ is discontinuous from the left. By the definition of ψ, we have $\psi(t) = \varphi(t)$ for $t \notin \{s_i\}_{i \geq 1}$.

Let $0 = t_0 < t_1 < \cdots < t_n < t_{n+1} = 1$ be a partition where if $t_i \in \{s_i\}_{i \geq 1}$, then neither t_{i-1} nor t_{i+1} is. To show that ψ is BV, then we must show

$$\sum_{i=0}^{n} \left|\psi(t_{i+1}) - \psi(t_i)\right| \leq \|\varphi\|_{\text{BV}}.$$

Set $\varepsilon > 0$. If $t_i \notin \{s_i\}_{i\geq 1}$, $i = 0$, or $i = n+1$, then set $t_i' = t_i$. If $t_i \in \{s_i\}_{i\geq 1}$ and $i \neq 0, n+1$, choose $t_i' \in (t_{i-1}, t_i)$ such that $\left|\varphi\left(t_i^-\right) - \varphi\left(t_i'\right)\right| < \frac{\varepsilon}{2n}$. Then, $0 = t_0' < t_1' < \cdots < t_n' < t_{n+1}' = 1$ is a partition of $0, 1$ with

$$\begin{aligned}\sum_{i=0}^{n} \left|\psi\left(t_{i+1}\right) - \psi\left(t_i\right)\right| &= \sum_{i=0}^{n} \left|\varphi\left(t_{i+1}^-\right) - \varphi_{t_i^-}\right| \\ &\leq \sum_{i=0}^{n} \left|\varphi\left(t_{i+1}^-\right) - \varphi\left(t_{i+1}'\right)\right| + \sum_{i=0}^{n} \left|\varphi\left(t_{i+1}'\right) - \varphi(t_i')\right| + \sum_{i=0}^{n} \left|\varphi\left(t_i'\right) - \varphi\left(t_i^-\right)\right| \\ &\leq \frac{\varepsilon}{2} + \|\varphi\|_{\mathrm{BV}} + \frac{\varepsilon}{2}\end{aligned}$$

Since ε was arbitrary, $\psi \in \mathrm{BV}([0,1])$, with $\|\psi\|_{\mathrm{BV}} \leq \|\varphi\|_{\mathrm{BV}}$.

For N any arbitrary integer, define $\eta_N(t) = 0$ for t not in $\{s_1, s_2, \dots, s_N\}$, and $\eta_N(s_i) = \varphi(s_i) - \psi(s_i)$. Then, we can see that $\|\varphi - (\psi + \eta_N)\|_{\mathrm{BV}} = 0$, with $\int_0^1 f\, d\eta_N = 0$. Thus,

$$\begin{aligned}\int_0^1 f\, d\varphi &= \int_0^1 f\, d\psi + \lim_{N\to\infty} \int_0^1 f\, d\eta_N \\ &= \int_0^1 f\, d\psi.\end{aligned}$$

□

We let $\mathrm{BV}([0,1])$ be the space of all BV functions with pointwise addition and scalar multiplication, with norm $\|\cdot\|_{\mathrm{BV}}$.[xvi]

Theorem. *$BV([0,1])$ is a Banach space.*

Proof. Suppose $\{\varphi_n\}_{n=1}^{\infty}$ is a sequence in $\mathrm{BV}([0,1])$ such that

$$\sum_{n=1}^{\infty} \|\varphi_n\|_{\mathrm{BV}} < \infty.$$

Additionally,

$$\begin{aligned}|\varphi_n(t)| &\leq |\varphi_n(t) - \varphi_n(0)| + |\varphi_n(1) - \varphi_n(t)| \\ &\leq \|\varphi_n\|_{\mathrm{BV}}\end{aligned}$$

for $t \in [0,1]$, meaning

$$\sum_{n=1}^{\infty} \varphi_n(t)$$

converges uniformly and absolutely to a function φ defined on $[0,1]$. We can see that $\varphi(0) = 0$ and φ is continuous from the left on $(0,1)$. We must now show that φ is of bounded variation and

$$\lim_{N\to\infty} \left\|\varphi - \sum_{n=1}^{N} \varphi_n\right\| = 0.$$

[xvi] Yes, technically before now I was engaging in a gross abuse of notation.

To start, let $0 = t_0 < t_1 < \cdots < t_k < t_{k+1} = 1$ be a partition of $[0,1]$. Then,

$$\begin{aligned}\sum_{i=0}^{k} |\varphi(t_{i+1}) - \varphi(t_i)| &= \sum_{i=0}^{k} \left|\sum_{n=1}^{\infty} \varphi_n(t_{i+1}) - \sum_{n=1}^{\infty} \varphi_n(t_i)\right| \\ &\leq \sum_{n=1}^{\infty}\left(\sum_{i=0}^{k} |\varphi_n(t_{i+1}) - \varphi_n(t_i)|\right) \\ &\leq \sum_{n=1}^{\infty} \|\varphi_n\|_{\text{BV}}.\end{aligned}$$

Thus, $\varphi \in \text{BV}([0,1])$. Additionally,

$$\begin{aligned}\sum_{i=0}^{k}\left|\left(\varphi - \sum_{n=1}^{N}\varphi_n\right)(t_{i+1}) - \left(\varphi - \sum_{n=1}^{N}\varphi_n\right)(t_i)\right| &= \sum_{i=0}^{k}\left|\sum_{n=N+1}^{\infty}\varphi_n(t_{i+1}) - \sum_{n=N+1}^{\infty}\varphi_n(t_i)\right| \\ &\leq \sum_{i=0}^{k}\sum_{n=N+1}^{\infty} |\varphi_n(t_{i+1}) - \varphi_n(t_i)| \\ &\leq \sum_{n=N+1}^{\infty} \|\varphi_n\|_{\text{BV}},\end{aligned}$$

meaning $\varphi = \sum_{n=1}^{\infty} \varphi_n$ in the BV norm. □

Theorem (Riesz)**.** *Let $\hat{\varphi}(f) = \int_0^1 f\, d\varphi$. Then, $\varphi \to \hat{\varphi}$ is an isometric isomorphism between $(C([0,1]))^*$ and $BV([0,1])$.*

Proof. We must show that the map $\varphi \mapsto \hat{\varphi}$ is an isometric isomorphism.

We can see that, to start, $\hat{\varphi} \in (C([0,1]))^*$, with $\|\hat{\varphi}\| \leq \|\varphi\|_{\text{BV}}$.

We must now show that for $L \in (C([0,1]))^*$, there exists $\psi \in \text{BV}([0,1])$ such that $\hat{\psi} = L$, $\left\|\hat{\psi}\right\|_{\text{BV}} \leq \|L\|$, and ψ is unique.

Let $B([0,1])$ be the space of all *bounded* functions on $[0,1]$. It is readily apparent that $C([0,1]) \subseteq B([0,1])$,[xvii] and we can see $B([0,1])$ is a Banach space with pointwise addition and scalar multiplication under the norm $\|f\|_u = \sup_{t\in[0,1]} |f(t)|$.[xviii] For $E \subseteq [0,1]$, define I_E to be the indicator function on E. The indicator function is always bounded.[xix]

Since L is a bounded linear functional on $C([0,1])$, the Hahn–Banach continuous extension theorem allows us to create a (not necessarily unique) bounded linear functional L' on $B([0,1])$ with $\|L'\| = \|L\|$.

In particular, we can choose L' such that $L'\left(I_{\{0\}}\right) = 0$, by extending L to the linear span of $I_{\{0\}}$ and $C([0,1])$:

$$\begin{aligned}\left|L'\left(f + \lambda I_{\{0\}}\right)\right| &= |L(f)| \\ &\leq \|L\|\,\|f\|_\infty \\ &\leq \|L\|\left\|f + \lambda I_{\{0\}}\right\|_u\end{aligned}$$

[xvii] Extreme Value Theorem

[xviii] Obviously $B([0,1])$ is a normed vector space. For a Cauchy sequence of functions $(f_n)_n \in B([0,1])$, completeness has pointwise convergence to f. Boundedness and convergence follows from the properties of the supremum.

[xix] I am using I_E instead of $\mathbb{1}_E$ since it's easier for me to type that faster.

for all $f \in C([0,1])$ and $\lambda \in \mathbb{C}$.

FOr $0 < t \leq 1$, let $\varphi(t) = L\left(I_{(t,t+1]}\right)$, with $\varphi(0) = 0$. We aim to show that $\varphi \in \mathrm{BV}([0,1])$ and $\|\varphi\|_{\mathrm{BV}} \leq \|L\|$.

Select a partition $0 = t_0 < t_1 < \cdots < t_n < t_{n+1} = 1$, and set

$$\lambda_k = \frac{\varphi(t_{k+1}) - \varphi(t_k)}{|\varphi(t_{k+1}) - \varphi(t_k)|}$$

for $\varphi(t_{k+1}) \neq \varphi(t_k)$, and $\lambda_k = 0$ otherwise. Then,

$$f = \sum_{k=0}^{n} \lambda_k I_{(t_k, t_{k+1}]} \in B([0,1])$$

with $\|f\|_u \leq 1$, and

$$\begin{aligned}\sum_{k=0}^{n} |\varphi(t_{k+1}) - \varphi(t_k)| &= \sum_{k=0}^{n} \lambda_k (\varphi(t_{k+1} - t_k)) \\ &= \sum_{k=0}^{n} L'\left(I_{(t_k - t_{k+1}]}\right) \\ &= L'(f) \\ &\leq \|L'\| = \|L\|.\end{aligned}$$

Thus, $\|\varphi\|_{\mathrm{BV}} \leq \|L\|$.

Now, we need to show that $L(g) = \int_0^1 g\, d\varphi$ for every $g \in C([0,1])$.

Let $g \in C([0,1])$. For $\varepsilon > 0$, set $0 = t_0 < t_1 < \cdots < t_n < t_{n+1} = 1$ a partition such that

$$|g(s) - g(s')| < \frac{\varepsilon}{2\|L'\|}$$

for every $s, s' \in (t_k, t_{k+1}]$, and

$$\left| \int_0^1 g\, d\varphi - \sum_{k=0}^{n} g(t_k)(\varphi(t_{k+1}) - \varphi(t_k)) \right| < \frac{\varepsilon}{2}.$$

Thus, for $f = \sum_{k=0}^{n} g(t_k) I_{(t_k, t_{k+1}]} + g(0) I_{\{0\}}$, we have

$$\begin{aligned}\left| L(g) - \int_0^1 g\, d\varphi \right| &\leq |L(g) - L'(f)| + \left| L'(f) - \int_0^1 g\, d\varphi \right| \\ &\leq \|L'\| \|g - f\|_u + \left| \sum_{k=0}^{n} g(t_k)(\varphi(t_{k+1}) - \varphi(t_k)) - \int_0^1 g\, d\varphi \right| \\ &\leq \frac{\varepsilon}{2} + \frac{\varepsilon}{2} \\ &= \varepsilon.\end{aligned}$$

Thus, $L(g) = \int_0^1 g\, d\varphi$.

We obtain $\psi \in \mathrm{BV}([0,1])$ with $\|\psi\|_{\mathrm{BV}} \leq \|\varphi\|_{\mathrm{BV}} \leq \|L\|$ (see function limits), and

$$\begin{aligned}\hat{\psi}(g) &= \int_0^1 g\, d\psi \\ &= \int_0^1 g\, d\varphi \\ &= L(g).\end{aligned}$$

Now, we must show that the mapping $\varphi \mapsto \hat{\varphi}$ is injective.

Let $\varphi \in \mathrm{BV}([0,1])$. Fix $0 < t_0 \leq 1$, and let f_n be a sequence of functions in $C([0,1])$ defined by

$$f_n(t) = \begin{cases} 1 & 0 \leq t \leq \frac{n-1}{n} t_0 \\ n\left(1 - \frac{t}{t_0}\right) & \frac{n-1}{n} t_0 < t \leq t_0 \\ 0 & t_0 < t \leq 1 \end{cases}.$$

The function $I_{(0,t_0]} - f_n$ is zero outside the open interval $\left(\frac{n-1}{n} t_0, t_0\right)$. If we define

$$\varphi_n(t) = \begin{cases} \varphi\left(\frac{n-1}{n} t_0\right) & 0 \leq t \leq \frac{n-1}{n} t_0 \\ \varphi(t) & \frac{n-1}{n} t_0 < t \leq t_0 \\ \varphi(t_0) & t_0 < t \leq 1 \end{cases},$$

then

$$\begin{aligned}\left|\int_0^1 \left(I_{(0,t_0]} - f_n\right)\, d\varphi\right| &= \left|\int_0^1 \left(I_{(0,t_0]} - f_n\right)\, d\varphi_n\right| \\ &\leq \|\varphi_n\|_{\mathrm{BV}}.\end{aligned}$$

We claim that $\lim_{n\to\infty} \|\varphi\|_{\mathrm{BV}} = 0$.

Since φ is left continuous at t_0, there exists $\delta > 0$ such that $0 < t_0 - t < \delta$ implies $|\varphi(t_0 - t)| < \frac{\varepsilon}{2}$. Let $0 = t_0 < t_1 < \cdots < t_{k+1} = 1$ be a partition of $[0,1]$, where

$$\left| \|\varphi\|_{[}\mathrm{BV}] - \left(\sum_{i=0}^{k} |\varphi(t_{i+1}) - \varphi(t_i)|\right)\right| < \frac{\varepsilon}{2}.$$

Let $t_0 = t_{i_0}$ for some i_0, where $t_{i_0} - t_{i_0 - 1} < \delta$. Then,

$$|\varphi(t_{i_0}) - \varphi(t_{i_0-1})| < \frac{\varepsilon}{2},$$

and $\mathrm{Var}(\varphi)_{\left[t_{i_0-1}, t_{i_0}\right]} < \varepsilon$. Therefore,

$$\begin{aligned}\varphi(t_0) &= \int_0^1 I_{(0,t_0]}\, d\varphi \\ &= \lim_{n\to\infty} \int_0^1 f\, d\varphi,\end{aligned}$$

with $\hat{\varphi} = 0$ implying $\varphi = 0$. Thus, $(C([0,1]))^* = \mathrm{BV}([0,1])$. $\square$

Example (Conjugate Space of $C(X)$)**.** If X is any compact Hausdorff space, rather than merely $[0,1]$, it makes no sense to talk about bounded variation (since X may not have an ordering on it), so to find $(C(X))^*$ would require some extra work.

Every countably additive measure on $\mathcal{B}_X$ gives rise to a bounded linear functional on $C(X)$. Using the Hahn–Banach continuous extension theorem, we can extend this to the Banach space of bounded Borel functions, and obtain a Borel measure by evaluating the extended linear functional on the indicator functions of Borel subsets of X.

If we restrict our attention to regular measures[xx], the extended functional *is* unique, and we can identify $(C(X))^*$ to be $M(X)$, which is the set of complex regular Borel measures on X.

This result is known as the Riesz–Markov–Kakutani Representation Theorem.

Example (Quotient Spaces of Banach Spaces)**.** Let $\mathcal{X}$ be a Banach space, and $\mathcal{M}$ be a closed subspace of $\mathcal{X}$. We will try to find a norm on $\mathcal{X}/\mathcal{M}$.

The space $\mathcal{X}/\mathcal{M}$ is the set of equivalence classes of $f \in \mathcal{X}$ where $[f] = \{f + g \mid g \in \mathcal{M}\}$. The norm can be defined by

$$\|[f]\| = \inf_{g\in\mathcal{M}} \|f - g\|.$$

If $\|[f]\| = 0$, then there is a sequence g_n such that $\lim_{n\to\infty} \|f - g_n\| = 0$,[xxi] meaning $g_n \to f$; since $\mathcal{M}$ is closed, this implies that $[f] = [0]$. In the converse direction, if $[f] = [0]$, then $0 \leq \|[f]\| \leq \|f - f\| = 0$. Thus, $\|[f]\|$ is positive definite.

To show homogeneity, let $f \in \mathcal{X}$ and $\lambda \in \mathbb{C}$. Then,

$$\begin{aligned}\|\lambda[f]\| &= \inf_{g\in\mathcal{M}} \|\lambda f - g\| \\ &= \inf_{h\in\mathcal{M}} \|\lambda(f - h)\| \\ &= |\lambda| \inf_{h\in\mathcal{M}} \|f - h\| \\ &= |\lambda| \, \|[f]\|.\end{aligned}$$

Finally, to show the triangle inequality, let $f_1, f_2 \in \mathcal{X}$. Then,

$$\begin{aligned}\|[f_1] + [f_2]\| &= \|[f_1 + f_2]\| \\ &= \inf_{g\in\mathcal{M}} \|(f_1 + f_2) - g\| \\ &= \inf_{g_1,g_2\in\mathcal{M}} \|(f_1 - g_1) + (f_2 - g_2)\| \\ &\leq \inf_{g_1\in\mathcal{M}} \|f_1 - g_1\| + \inf_{g_2\in\mathcal{M}} \|f_2 - g_2\| \\ &= \|[f_1]\| + \|[f_2]\|.\end{aligned}$$

Finally, to show completeness, we let $\{[f_n]\}_{n=1}^{\infty}$ be a Cauchy sequence in $\mathcal{X}/\mathcal{M}$. Then, there exists a subsequence $\{[f_{n_k}]\}_{k=1}^{\infty}$ such that $\left\|\left[f_{n_{k+1}}\right] - [f_{n_k}]\right\| < \frac{1}{2^k}$.

Select $h_k \in \left[f_{n_{k+1}} - f_{n_k}\right]$ such that $\|h_k\| < \frac{1}{2^k}$. Then, $\sum_{k=1}^{\infty} \|h_k\| < 1 < \infty$, meaning $\sum_{k=1}^{\infty} h_k = h$ for some h.

[xx] Inner regular means the measure of a set can be approximated by compact subsets, outer regular means the measure of a set can be approximated by open supersets, and regular means both inner and outer regular.

[xxi] I am using $\|[f]\| = \inf_{g\in\mathcal{M}} \|f - g\|$ instead since that is what my professor uses.

Since

$$\begin{aligned}[f_{n_k} - f_{n_1}] &= \sum_{i=1}^{k-1} \left[f_{n_{i+1}} - f_{n_i}\right] \\ &= \sum_{i=1}^{k-1} [h_i]\,,\end{aligned}$$

we must have $\lim_{k\to\infty} [f_{n_k} - f_{n_1}] = [h]$, meaning $\lim_{k\to\infty} [f_{n_k}] = [h + f_{n_1}]$.

We can see that there is a natural (projection) map $\pi : \mathcal{X} \to \mathcal{X}/\mathcal{M}$, defined by $\pi(f) = [f]$. This is a contraction and a surjective (which we will later see to be the same as open) map.

Definition (Bounded Linear Transformation)**.** Let $\mathcal{X}, \mathcal{Y}$ be Banach spaces. The linear transformation $T : \mathcal{X} \to \mathcal{Y}$ is bounded if

$$\begin{aligned}\|T\|_{\text{op}} &= \sup_{\|f\|=1} \|T(f)\| \\ &< \infty\end{aligned}$$

The set of all bounded linear transformations from $\mathcal{X}$ to $\mathcal{Y}$ is denoted $\mathcal{L}(\mathcal{X}, \mathcal{Y})$. We have proven earlier that a linear transformation is bounded if and only if it is continuous.[xxii]

Proposition (Properties of $\mathcal{L}(\mathcal{X}, \mathcal{Y})$)**.** *The space $\mathcal{L}(\mathcal{X}, \mathcal{Y})$ is a Banach space.*

Proof. It is readily apparent that $\mathcal{L}(\mathcal{X}, \mathcal{Y})$ is a normed vector space under pointwise addition and scalar multiplication. All we need to show now is completeness.

Let $(T_n)_n$ be a Cauchy sequence of elements of $\mathcal{L}(\mathcal{X}, \mathcal{Y})$. Then, for $\varepsilon > 0$, there exists N such that for $m, n > N$,

$$\|T_m - T_n\|_{\text{op}} < \varepsilon.$$

This means that for any $f \in \mathcal{X}$, there exists N_f such that for $m, n > N_f$,

$$\begin{aligned}\|(T_m - T_n)(f)\| &\leq \|f\| \, \|T_m - T_n\|_{\text{op}} \\ &< \frac{\varepsilon}{\|f\|} \|f\| \\ &= \varepsilon.\end{aligned}$$

Since for each f, $(T_n(f))_n$ is Cauchy, and $\mathcal{Y}$ is complete, we define T to be the pointwise limit of $(T_n)_n$.

Thus, since

$$\begin{aligned}\lim_{m\to\infty} \|T_m - T_n\|_{\text{op}} &= \|T - T_n\|_{\text{op}} \\ &< \varepsilon,\end{aligned}$$

we have that $\mathcal{L}(\mathcal{X}, \mathcal{Y})$ is complete. □

Theorem (Open Mapping)**.** *Let $\mathcal{X}$, $\mathcal{Y}$ be Banach spaces, and let $T \in \mathcal{L}(\mathcal{X}, \mathcal{Y})$ be surjective. Then, T is an open map.*

[xxii] This holds in all normed vector spaces, not just Banach spaces.