

# Functional Analysis

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# I. Analysis in Metric Spaces

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## II. Set Theory and Topology

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### 1 THE AXIOM OF CHOICE

**Definition.** Let  $S$  be a non-empty set. A **partial ordering** is a binary relation  $\leq$  on  $S$  which satisfies for  $s, t, u \in S$ ,

- (i) (*reflexivity*)  $s \leq s$
- (ii) (*transitivity*)  $s \leq t, t \leq u$  implies  $s \leq u$
- (iii) (*anti-symmetry*)  $s \leq t, t \leq s$  implies  $s = t$

We call the pair  $(S, \leq)$  a **partially ordered set**. We say that  $(S, \leq)$  is **totally ordered** if, given  $s, t \in S$ , at least one of  $s \leq t$  or  $t \leq s$  holds. We say that  $(S, \leq)$  is **well-ordered** if given any  $\emptyset \neq S_0 \subseteq S$ , there is some  $s_0 \in S_0$  such that  $s_0 \leq s$  for  $s \in S_0$ . A **chain** in a poset  $(S, \leq)$  is any  $\emptyset \neq C \subseteq S$  such that  $(S, \leq|_C)$  is totally ordered.

*Example.* (i)  $X \neq \emptyset, (\mathcal{P}(X), \subseteq)$  is a poset  
(ii)  $(\mathbb{R}, \leq)$  is a totally ordered set  
(iii)  $(\mathbb{N}, \leq), (\omega = \mathbb{N} \cup \{\infty\}, \leq)$ , are well-ordered sets.

**1.1 Theorem.** *The following are equivalent:*

- (i) (*Axiom of Choice 1*): For any  $x \neq \emptyset$ , there is a function  $\gamma : \mathcal{P}(X) \setminus \{\emptyset\} \rightarrow X$  such that  $\gamma(A) \in A$  for each  $A \in \mathcal{P}(X) \setminus \{\emptyset\}$ .
- (ii) (*Axiom of Choice 2*): Given any  $\{A_\lambda\}_{\lambda \in \Lambda}$  where  $A_\lambda \neq \emptyset$  for each  $\lambda$ ,

$$\prod_{\lambda \in \Lambda} A_\lambda = \{(a_\lambda)_{\lambda \in \Lambda} : a_\lambda \in A_\lambda \text{ for each } \lambda\} \neq \emptyset$$

- (iii) (*Zorn's Lemma*): In a poset  $(S, \leq)$ , if each chain  $C \subseteq S$  admits an upper bound in  $S$ , then  $(S, \leq)$  admits a maximal element.
- (iv) (*Well-ordering principle*): Any  $S \neq \emptyset$  admits a well-ordering

PROOF [TODO: Write up proof] ■

### 2 CARDINAL ARITHMETIC

[TODO: Write up]

### 3 TOPOLOGY

Let  $X$  denote a non-empty set, and  $\mathcal{P}(X)$  denote the power set of  $X$ .

**Definition.** A **topology** on a set  $X$  is a set  $\tau$  of subsets of  $X$  such that

- (i)  $\emptyset, X \in \tau$
- (ii) If  $U_\alpha \in \tau$  for all  $\alpha \in A$ , then  $\bigcup_{\alpha \in A} U_\alpha \in \tau$ .
- (iii) If  $n \in \mathbb{N}$  and  $U_i \in \tau$  for each  $1 \leq i \leq n$ , then  $\bigcap_{i=1}^n U_i \in \tau$ .

The sets  $U \in \tau$  are the **open sets** in  $X$ , and sets  $X \setminus U$  for some open set  $U$  are the **closed sets** in  $X$ . The pair  $(X, \tau)$  is called a **topological space**.

*Example.* (i) *Sorgenfrey line:* Set  $X = \mathbb{R}$ , and consider

$$\sigma = \{ V \subseteq \mathbb{R} \mid \text{for any } s \in V, \text{ there is } \delta = \delta(s) > 0 \text{ s.t. } [s, s + \delta) \subseteq V \}$$

It is a straightforward exercise to verify that  $\tau_{|\cdot|} \subsetneq \sigma$ . We say that  $\sigma$  is **finer** than  $\tau_{|\cdot|}$ .

(ii) *Relative or subset topology:* let  $(X, \tau)$  be a topological space and  $\emptyset \neq A \subseteq X$ . Then we can define a topology  $\tau|_A = \{U \cap A : U \in \tau\}$ .

### 3.1 METRIC TOPOLOGY

A metric space  $(X, d)$  is naturally a topological space, where the topology is given by

$$\tau_d = \{ U \subseteq X \mid \text{for each } x_0 \in U, \text{ there is } \delta = \delta(x_0) \text{ s.t. } B_\delta(x_0) \subseteq U \}.$$

Given two metrics  $d, \rho$  on  $X$ , we say that  $d \sim \rho$  are **equivalent** if and only if there are  $c, C > 0$  such that

$$cd(x, y) \leq \rho(x, y) \leq Cd(x, y) \text{ for any } x, y \in X$$

Note that  $d \sim \rho$  implies that  $\tau_d = \tau_\rho$ , but the reverse implication is not true. An example of this are the metrics on  $X = \mathbb{R}$  given by  $d(x, y)$  and  $\rho(x, y) = \frac{|x-y|}{1+|x-y|}$ . Then  $d \not\sim \rho$  but  $\tau_d = \tau_\rho$ . Let  $(X, d), (Y, \rho)$  be metric spaces. A map  $f : X \rightarrow Y$  is an **isometry** if for any  $x, y \in X$ ,  $d(x, y) = \rho(f(x), f(y))$ . By non-degeneracy,  $f$  is automatically injective. In particular, when  $(X, d)$  is complete, then  $(f(X), \rho|_{f(X)})$  is a complete metric space.

**Definition.** Let  $(X, \tau)$  and  $(Y, \sigma)$  be topological spaces, and  $f : X \rightarrow Y$ . We say that  $f$  is  **$(\tau - \sigma)$ -continuous at  $x_0$**  in  $X$  if for any  $V \in \sigma$  such that  $f(x_0) \in V$ , then there exists  $U \in \tau$  such that  $x_0 \in U$  and  $f(U) \subseteq V$ . We say that  $f$  is  **$(\tau - \sigma)$ -continuous** if it is continuous at each  $x_0$  in  $X$ .

An easy application of definitions yields the following:

**3.1 Proposition.** Let  $(X, \tau), (Y, \sigma)$  be topological spaces and  $f : X \rightarrow Y$ . Then  $f$  is continuous if and only if for any  $U \in \sigma$ ,  $f^{-1}(U) \in \tau$ .

**3.2 Lemma.** If  $x_0 \in X$  where  $(X, \tau)$  is a topological space, then

$$\mathcal{I}(x_0) = \{ f \in C_b(X) \mid f(x_0) = 0 \}$$

is closed, hence complete, subspace of  $C_b(X)$ .

**PROOF** If  $(f_n)_{n=1}^\infty \subseteq \mathcal{I}(x_0)$  and  $f = \lim_{n \rightarrow \infty} f_n$  with respect to  $\|\cdot\|_\infty$  in  $C_b(X)$ , then  $f(x_0) = \lim_{n \rightarrow \infty} f_n(x_0) = 0$ . Thus  $f \in \mathcal{I}(x_0)$ , and closed subsets of complete spaces are themselves complete. ■



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# III. Basic Elements of Functional Analysis

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## 4 BANACH SPACES

### 4.1 VECTOR SPACES

**Definition.** Let  $\mathbb{k}$  be a field. Then  $X$  is a **vector space** if  $X$  is a  $\mathbb{k}$ -module. If  $Y \subset X$  is a  $\mathbb{k}$ -vector space, we say that  $Y$  is a **subspace** of  $X$ .

Given a subset  $S \subset X$ , we write

$$\text{span } S = \{\alpha_1 v_1 + \cdots + \alpha_n v_n : \alpha \in \mathbb{k}, v_i \in S\}$$

to denote the smallest subspace of  $X$  containing  $S$ .

A basic property of vector spaces is that they have bases:

**Definition.** Let  $X$  be a vector space over  $\mathbb{k}$ . A subset  $S \subseteq X$  is called

- **linearly independent** if for any distinct  $x_1, \dots, x_n \in S$ , the equation  $0 = \alpha_1 x_1 + \cdots + \alpha_n x_n = 0$  where  $\alpha_i \in \mathbb{k}$  implies  $\alpha_1 = \cdots = \alpha_n = 0$ ,
- **spanning** if  $\text{span } S = X$ , and
- a **Hamel basis** if it is both linearly independent and spanning

As a basic consequence of Zorn's lemma, we have the following result:

**4.1 Lemma.** Suppose  $S \subset X$  is linearly independent. Then there exists a Hamel basis  $M$  containing  $S$ .

**PROOF** Let  $\mathcal{L} = \{S \subset L \subseteq X : L \text{ is linearly independent}\}$ . Then  $(\mathcal{L}, \subseteq)$  is a poset. If  $\mathcal{C} \subseteq \mathcal{L}$  is a chain, it is easy to verify that  $U = \bigcup_{L \in \mathcal{C}} L \in \mathcal{L}$  and is an upper bound for  $\mathcal{C}$ . Thus by Zorn's lemma,  $\mathcal{L}$  has some maximal element  $L$ ; by maximality,  $L$  is spanning for  $X$ . ■

**4.2 Proposition.** Let  $X$  be a vector space. Then  $X$  admits a Hamel basis  $M$ . Moreover, if  $M, M'$  are distinct Hamel bases, then  $|M| = |M'|$ .

**PROOF** Apply Lemma 4.1 to  $\emptyset \subset X$  to get some Hamel basis  $M = \{v_i : i \in I\}$ . For the second part, let  $\{w_j : j \in J\}$  be any spanning set: it suffices to show that  $|M| \leq |J|$ . If  $J$  is finite, this is a standard exercise in (finite dimensional) linear algebra.

Now suppose  $J$  is infinite and for any  $j \in J$ , write  $w_j = \sum_{i \in A_j \subset I} \lambda_{i,j} v_i$  where  $A_j \subset I$  is finite. Thus we have an injection  $\phi : \bigcup_{j \in J} \{j\} \times A_j \rightarrow M$ . But then since  $J$  is infinite,  $|J| = \left| \bigcup_{j \in J} A_j \right| \leq |M|$  as required. ■

The previous proposition implies that the following notion is well-defined:

**Definition.** The **dimension** of a vector space  $X$  is the cardinality of any Hamel basis for  $X$ .

An important feature of any category is to consider the set of maps between objects.

**Definition.** Given vector spaces  $X$  and  $Y$  over  $\mathbb{k}$ , let  $\mathcal{L}(X, Y)$  denote the set of all linear maps from  $X$  to  $Y$ . In particular, when  $Y = \mathbb{k}$ , we write  $\mathcal{L}(X, \mathbb{k}) = X'$  and call this the **algebraic dual** of  $X'$ .

Note that  $\mathcal{L}(X, Y)$  also has a natural vector space structure given by  $(\alpha S + T)(u) = \alpha S(u) + T(u)$ . We will discuss such spaces in more details later.

## 4.2 SEMINORMS AND NORMS

The remainder of the chapter will focus particularly on vector spaces  $\mathbb{F}$ , to denote either the field  $\mathbb{R}$  or the field  $\mathbb{C}$ . Note that if  $X$  is a  $\mathbb{C}$ -vector space, then  $X$  is naturally an  $\mathbb{R}$ -vector space by restriction of scalars, which we denote by  $X_{\mathbb{R}}$ . Moreover, if  $X$  is an  $\mathbb{R}$ -vector space, we can apply extension by scalars to define a  $\mathbb{C}$ -vector space structure on  $X$ , called the **complexification** of  $X$ .

We now focus on the essential additional structure we introduce in the study of normed vector spaces of Banach spaces:

**Definition.** Let  $X$  be a vector space over  $\mathbb{F}$ . A **seminorm** is a functional  $\|\cdot\| : X \rightarrow \mathbb{R}$  such that it is

- (non-negative)  $\|x\| \geq 0$  for any  $x \in X$
- (subadditive)  $\|x + y\| \leq \|x\| + \|y\|$  for  $x, y \in X$
- ( $|\cdot|$ -homogenous)  $\|\alpha x\| = |\alpha| \|x\|$  for  $\alpha \in \mathbb{F}$ ,  $x \in X$ .

If in addition,  $\|\cdot\|$  satisfies the added requirement

- (non-degenerate)  $\|x\| = 0$  if and only if  $x = 0$

we call  $\|\cdot\|$  a **norm** for  $X$ . In this case, the pair  $(X, \|\cdot\|)$  is a **normed vector space**. We say that  $(X, \|\cdot\|)$  is a **Banach space** provided that  $X$  is complete with respect to the metric  $\rho(x, y) = \|x - y\|$  induced by the norm.

*Example.* Here are some standard examples of Banach spaces:

(i)  $(\mathbb{F}, |\cdot|)$  is probably the simplest example of a Banach space.

(ii) *Finite-dimensional space:* denoted  $(\mathbb{F}^d, \|\cdot\|_p)$  with points  $x = (x_j)_{j=1}^d$  equipped with the  $p$ -norm

$$\|x\|_p = \begin{cases} \left( \sum_{j=1}^d |x_j|^p \right)^{1/p} & 1 \leq p < \infty \\ \max_{j=1, \dots, d} |x_j| & p = \infty \end{cases}$$

is a Banach space

(iii) If you have a background in basic measure theory, the space  $L_{p, \mathbb{F}}(\Omega)$ , where  $\Omega$  is a compact domain. For a concrete example, take for example

$$L^p \mathbb{F}([0, 1]) = \left\{ f : [0, 1] \rightarrow \mathbb{F} \mid f \text{ is Lebesgue measurable, } \left( \int_0^1 |f|^p \right)^{1/p} < \infty \right\} \Big/ \sim_{\text{a.e.}}$$

where  $1 \leq p < \infty$ . To enforce non-degeneracy, we must mod out by equivalence almost everywhere.

(iv) The space of essentially bounded functions,  $L_{\infty}^{\mathbb{F}}[0, 1]$ ,  $\|f\|_{\infty} = \text{ess sup}_{t \in [0, 1]} |f(t)|$ .

(v) *Function spaces*: let  $(X, d)$  be a metric space, and define

$$C_b(X, \mathbb{F}) = \{ f : X \rightarrow \mathbb{F} \mid f \text{ is continuous and bounded} \}, \quad \|f\|_\infty = \sup_{x \in X} |f(x)|.$$

Here, we define a more involved example.

*Example.* Let  $(X, d)$  be a metric space. We define the space of *Lipschitz functions*

$$\text{Lip}_{\mathbb{F}}(X, d) = \left\{ f : X \rightarrow \mathbb{F} \mid f \text{ is bounded, } L(f) = \sup_{\substack{x, y \in X \\ x \neq y}} \frac{|f(x) - f(y)|}{d(x, y)} < \infty \right\}$$

Note that for any  $f : X \rightarrow \mathbb{F}$ ,  $f \in \text{Lip}_{\mathbb{F}}(X, d)$  if and only if there is some  $L \geq 0$  such that  $|f(x) - f(y)| \leq Ld(x, y)$  for all  $x, y$  in  $X$ . One may verify that  $L(f)$  is the infimum over all values of  $L$  for which this inequality holds over  $X$ .

It is an easy exercise to see that  $\text{Lip}_{\mathbb{F}}(X, d)$  is a vector space and that  $L : \text{Lip}_{\mathbb{F}}(X, d) \rightarrow \mathbb{R}$  is a seminorm. However, we do not have non-degeneracy - for example, if  $f$  is constant, then  $L(f) = 0$ . To define a norm on the space of Lipschitz functions, we essentially force non-degeneracy by construction: we define the *Lipschitz norm*

$$\|f\|_{\text{Lip}} = \|f\|_\infty + L(f).$$

In this case, we do in fact have what we want:

**4.3 Proposition.**  $(\text{Lip}_{\mathbb{F}}(X, d), \|\cdot\|_{\text{Lip}})$  is a Banach space.

**PROOF** Let  $(f_n)_{n=1}^\infty$  be a Cauchy sequence in  $(\text{Lip}_{\mathbb{F}}(X, d), \|\cdot\|_{\text{Lip}})$ . Since  $\|\cdot\|_\infty \leq \|\cdot\|_{\text{Lip}}$  on  $\text{Lip}_{\mathbb{F}}(X, d)$ , this sequence is uniformly Cauchy and hence converges to some  $f \in C_b(X, \mathbb{F})$  with respect to the uniform norm. Moreover, if  $x, y \in X$ , then

$$\begin{aligned} |f(x) - f(y)| &= \lim_{n \rightarrow \infty} |f_n(x) - f_n(y)| \leq \sup_{n \in \mathbb{N}} |f_n(x) - f_n(y)| \\ &\leq \sup_{n \in \mathbb{N}} L(f_n) d(x, y) \leq \sup_{n \in \mathbb{N}} \|f_n\|_{\text{Lip}} d(x, y). \end{aligned}$$

Since Cauchy sequences are bounded in norm, we have that  $|f(x) - f(y)| \leq Ld(x, y)$  where  $L = \sup_{n \in \mathbb{N}} \|f_n\|_{\text{Lip}} < \infty$ , so in fact  $f \in \text{Lip}_{\mathbb{F}}(X, d)$ . It is easy to verify that  $\lim_{n \rightarrow \infty} \|f - f_n\|_{\text{Lip}} = 0$ .  $\blacksquare$

### 4.3 SEQUENCE SPACES

Since we do not assume the background of measure theory in this treatment, one of our main basic examples of Banach spaces will be the sequence spaces. Let  $\mathbb{F}^{\mathbb{N}}$  denote the set of all sequences in  $\mathbb{F}$ , and define

$$\ell^1 = \left\{ x = (x_j)_{j=1}^\infty \in \mathbb{F}^{\mathbb{N}} \mid \|x\|_1 = \sum_{j=1}^\infty |x_j| < \infty \right\}.$$

It is easy to see that  $(\ell^1, \|\cdot\|_1)$  is a normed vector space. Another common sequence space is the space

$$\ell^\infty = \left\{ x = (x_j)_{j=1}^\infty \in \mathbb{F}^{\mathbb{N}} \mid \|x\|_\infty = \sup_{n \in \mathbb{N}} |x_n| < \infty \right\}.$$

More generally, for  $1 < p < \infty$ , we may define

$$\ell^p = \left\{ x \in \mathbb{F}^{\mathbb{N}} \mid \|x\|_p = \left( \sum_{j=1}^{\infty} |x_j|^p \right)^{1/p} < \infty \right\}.$$

As always, it is easy to verify that the  $\ell^p$ -spaces, for  $1 \leq p < \infty$ , are in fact normed vector spaces. The interesting work is in proving that they are Banach spaces.

Let  $q = p/(p-1)$  so that  $1/p + 1/q = 1$ . Then  $q$  is called the **conjugate index** to  $p$ . We have a number of standard inequalities on  $\ell^p$ -spaces, the proofs of which can be found in general in [TODO: eventually link measure theory result].

**4.4 Proposition. (Inequalities in  $\ell^p$ -spaces)** Throughout, let  $1 < p, q < \infty$  be conjugate exponents.

- **Young's Inequality:** If  $a, b \geq 0$  in  $\mathbb{R}$ , then  $ab \leq \frac{a^p}{p} + \frac{b^q}{q}$ , with equality if and only if  $a^p = b^q$ .
- **Hölder's Inequality:** If  $x \in \ell^p$  and  $y \in \ell^q$ , then  $xy = (x_i y_i)_{i=1}^{\infty} \in \ell^1$ , with

$$\sum_{i=1}^{\infty} |x_i y_i| \leq \|x\|_p \|y\|_q.$$

Note that equality holds if and only if the following two conditions hold:

- (i)  $\text{sgn}(x_i y_i) = \text{sgn}(x_k y_k)$  for all  $j, k \in \mathbb{N}$  where  $x_i y_i \neq 0 \neq x_k y_k$ , and
  - (ii)  $|x|^p = (|x_j|^p)_{j=1}^{\infty}$  and  $|y|^q$  are linearly dependent in  $\ell^1$ .
- **Minkowski's Inequality:** If  $x, y \in \ell^p$ , then  $\|x + y\|_p \leq \|x\|_p + \|y\|_p$  with equality exactly when one of  $x$  or  $y$  is a non-negative scalar combination of the other.

In particular, Minkowski's Inequality [TODO: cite certain labels by name? and also link - would be nice]

We will also encounter the sequence spaces

$$\begin{aligned} \mathbf{c} &= \{(x_n)_{n=1}^{\infty} : \lim_{n \rightarrow \infty} x_n \text{ exists}\} \\ \mathbf{c}_0 &= \{(x_n)_{n=1}^{\infty} : \lim_{n \rightarrow \infty} x_n = 0\} \end{aligned}$$

where they are both equipped with  $\|\cdot\|_{\infty}$ . They are closed subspaces of  $\ell^{\infty}$ .

#### 4.4 BOUNDED CONTINUOUS FUNCTIONS INTO A NORMED SPACE

Let  $(Y, \|\cdot\|)$  be a normed space and  $\tau = \tau_{\|\cdot\|}$  the topology induced by  $\|\cdot\|$ . Let  $(X, \tau)$  be any topological space. We define the space

$$C_b(X, Y) = \left\{ f : X \rightarrow Y \mid f \text{ is bounded and } \tau - \tau_{\|\cdot\|} \text{ - continuous} \right\}$$

With pointwise operations, we see that  $C_b(X, Y)$  is a vector space. We also define for  $f \in C_b(X, Y)$ ,  $\|f\|_{\infty} = \sup\{\|f(x)\| : x \in X\}$ , making  $(C_b(X, Y), \|\cdot\|_{\infty})$  a normed vector space.

**4.5 Theorem.** If  $(Y, \|\cdot\|)$  is a Banach space, then  $(C_b(X, Y), \|\cdot\|_{\infty})$  is a Banach space.

**PROOF** Let  $(f_n)_{n=1}^\infty$  be a Cauchy sequence in  $(C_b(X, Y), \|\cdot\|_\infty)$ . Then for any  $x \in X$ , we have that  $(f_n(x))_{n=1}^\infty$  is Cauchy in  $(Y, \|\cdot\|)$  since  $\|f_n(x) - f_m(x)\| \leq \|f_n - f_m\|_\infty$ , and hence admits a limit  $f(x)$ . This defines a pointwise limit  $f : X \rightarrow Y$ . Fix  $x_0 \in X$ : we must show that  $f$  is continuous at  $x_0$ . Given  $\epsilon > 0$ , set

- $n_1$  so that whenever  $n, m \geq n_1$ ,  $\|f_n - f_m\|_\infty < \epsilon/4$ .
- $n_2$  so that whenever  $n \geq n_2$ ,  $\|f_n(x_0) - f(x_0)\| < \epsilon/4$ .
- $N = \max\{n_1, n_2\}$ .
- $U \in \tau$ ,  $x_0 \in U$  such that  $f_N(U) \subseteq B_{\epsilon/4}(f(x_0)) \subset Y$ .

Then for  $x \in U$ , we let  $n_x$  be so  $n_x \geq n_1$  and  $n \geq n_x$ , so that  $\|f_n(x) - f(x)\| < \epsilon/4$ . We then have

$$\begin{aligned} \|f(x) - f(x_0)\| &\leq \|f(x) - f_{n_x}(x)\| + \|f_{n_x}(x) - f_N(x)\| + \|f_N(x) - f_N(x_0)\| + \|f_N(x_0) - f(x_0)\| \\ &< \frac{\epsilon}{4} + \|f_{n_x} - f_N\|_\infty + \frac{\epsilon}{4} + \frac{\epsilon}{4} < \epsilon \end{aligned}$$

in other words that  $f(U) \subseteq B_\epsilon(f(x_0))$  so that  $f$  is continuous.

Now let us check that  $\|f\|_\infty < \infty$ . Since  $|\|f_n\|_\infty - \|f_m\|_\infty| \leq \|f_n - f_m\|_\infty$ ,  $(\|f_n\|_\infty)_{n=1}^\infty \subseteq \mathbb{R}$  is Cauchy, hence bounded. If  $x \in X$ , then

$$\|f(x)\| = \lim_{n \rightarrow \infty} \|f_n(x)\| \leq \sup_{n \in \mathbb{N}} \|f_n(x)\| \leq \sup_{n \in \mathbb{N}} \|f_n\|_\infty < \infty$$

so  $\|f\|_\infty = \sup_{x \in X} \|f(x)\| < \infty$ .

Finally, to show that the limit indeed converges appropriately, if  $\epsilon, n_1, x_0, N$  are as above, we have for  $n \geq n_1$

$$\|f_n(x_0) - f(x_0)\| \leq \|f_n(x_0) - f_N(x_0)\| + \|f_N(x_0) - f(x_0)\| < \frac{\epsilon}{2}$$

so  $\|f_n - f\|_\infty = \sup_{x_0 \in X} \|f_n(x_0) - f(x_0)\| \leq \epsilon/2 < \epsilon$ . The convergence is uniform since  $n_1$  is chosen uniformly in  $X$ . ■

**4.6 Corollary.**  $(C_b(X, \mathbb{F}), \|\cdot\|_\infty)$  is a Banach space.

*Example.* (i) Let  $T$  be a non-empty set and let

$$\ell^\infty(T) = \left\{ x = (x_t)_{t \in T} \in \mathbb{F}^T \mid \|x\|_\infty < \infty \right\}$$

With pointwise operations,  $(\ell^\infty, \|\cdot\|_\infty)$  is a normed space. In fact, it is a Banach space, since

$$f \mapsto (f(t))_{t \in T} : C_b(T, \mathcal{P}(T)) \rightarrow \ell^\infty(T)$$

is a surjective linear isometry, and the result follows.

(ii) Let  $c = \{x \in \ell^\infty \mid \lim_{n \rightarrow \infty} x_n \text{ exists}\}$ . Then  $(c, \|\cdot\|_\infty)$  is a Banach space. Consider the topological space given by  $\omega = \mathbb{N} \cup \{\infty\}$ , with topology

$$\tau_\omega = \mathcal{P}(\mathbb{N}) \cup \bigcup_{n \in \mathbb{N}} \{k \in \mathbb{N} : k \geq n\}$$

The map  $f \mapsto (f(n))_{n=1}^\infty : C_b(\omega) \rightarrow c$  is a linear surjective isometry.

- (iii) Recall that  $\mathcal{I}(\infty)$  is a closed, and hence complete, subspace of  $c$ . We may define  $c_0 = \left\{ x \in \mathbb{F}^{\mathbb{N}} \mid \lim_{n \rightarrow \infty} x_n = 0 \right\} \subseteq c \subseteq \ell^\infty$ . In this case,  $f \mapsto (f(n))_{n=1}^\infty : \mathcal{I}(\infty) \rightarrow c_0$  is a (linear) surjective isometry.
- (iv) Consider the Sorgenfrey line  $(\mathbb{R}, \sigma)$ . One may verify that

$$C_b((\mathbb{R}, \sigma), \mathbb{F}) = \left\{ f : \mathbb{R} \rightarrow \mathbb{F} \mid f \text{ is bounded and } \lim_{t \rightarrow t_0^+} f(t) = f(t_0) \text{ for } t \in \mathbb{R} \right\}$$

#### 4.5 LINEAR FUNCTIONALS AND OPERATORS

Suppose  $(X, \|\cdot\|)$  is a normed space. We denote

$$\begin{aligned} D(X) &= \{x \in X : \|x\| < 1\}, \\ S(X) &= \{x \in X : \|x\| = 1\}, \\ B(X) &= \{x \in X : \|x\| \leq 1\}. \end{aligned}$$

In general, if  $Z$  is any of the above sets, we may write  $x_0 + rZ = \{x_0 + rx : x \in Z\}$  to denote an open (open ball, sphere, closed ball) about  $x_0$  with radius  $r$ .

**4.7 Proposition.** *If  $X, Y$  are normed spaces and  $S \in \mathcal{L}(X, Y)$ . Then the following are equivalent:*

- (i)  $S$  is continuous
- (ii)  $S$  is continuous at some  $x_0 \in X$
- (iii)  $\|S\| := \sup_{x \in D(X)} \|Sx\| < \infty$ .

Moreover, in this case, we have

$$\|S\| = \inf\{L > 0 : \|Sx\| \leq L\|x\| \text{ for } x \in X\} = \sup_{x \in S(X)} \|Sx\| = \sup_{x \in B(X)} \|Sx\|$$

**PROOF** ( $i \Rightarrow ii$ ) By definition.

( $ii \Rightarrow iii$ ) Since  $Sx_0 + D(Y)$  is a neighbourhood of  $Sx_0$ , get some  $\delta > 0$  so that

$$S(x_0 + \delta D(X)) \subseteq Sx_0 + D(Y)$$

and thus  $\delta S(D(X)) \subseteq D(Y)$ , or in other words that  $\|Sx\| \leq 1/\delta$  for  $x \in D(X)$ .

( $iii \Rightarrow i$ ) If  $x \in X$  and  $\epsilon > 0$ , then

$$\|Sx\| = (\|x\| + \epsilon) \left\| S \left( \frac{1}{\|x\| + \epsilon} \|x\| \right) \right\| \leq (\|x\| + \epsilon) \|S\|$$

so that  $\|Sx\| \leq \|S\| \|x\|$ . Thus if  $x, x' \in X$ , then  $\|Sx - Sx'\| \leq \|S\| \|x - x'\|$  so that  $S$  is Lipschitz, hence continuous.

To complete the proof, the content of (iii) implies (i) informs us that the Lipschitz constant  $L(S) \leq \|S\|$ . Furthermore, taking  $\|x\| = 1$ , the preceding proof gives us that  $\sup_{x \in S(X)} \|Sx\| \leq L(S)$ . Finally,

$$\|S\| = \sup_{x \in D(X) \setminus \{0\}} \|Sx\| = \sup_{x \in D(X) \setminus \{0\}} \|x\| \left\| S \left( \frac{1}{\|x\|} x \right) \right\| \leq \sup_{x \in S(X)} \|Sx\|$$

so that the three quantities are equal. The remaining equivalence is obvious. ■

We now let  $\mathcal{B}(X, Y) = \{S \in \mathcal{L}(X, Y) \mid S \text{ is bounded}\}$ . We will see that  $\|\cdot\|$ , above, defines a norm on  $\mathcal{B}(X, Y)$ .

**4.8 Theorem.** *Let  $X, Y, Z$  be normed spaces. Then*

- (i)  *$(\mathcal{B}(X, Y), \|\cdot\|)$  is a normed space under the operator norm.*
- (ii) *If  $S \in \mathcal{B}(X, Y)$  and  $T \in \mathcal{B}(Y, Z)$ , then  $T \circ S \in \mathcal{B}(X, Z)$  with  $\|T \circ S\| \leq \|T\| \cdot \|S\|$ .*
- (iii) *If  $Y$  is a Banach space, then so is  $(\mathcal{B}(X, Y), \|\cdot\|)$*

**PROOF** We have:

- (i) Define  $\Gamma : \mathcal{B}(X, Y) \rightarrow C_b(B(X), Y)$  by  $\Gamma(S) = S|_{B(X)}$ . By definition,  $\Gamma$  is linear and  $\|\Gamma(S)\|_\infty = \sup_{x \in B(X)} \|Sx\| = \|S\|$  so that  $\|\cdot\|$  is a norm and  $\Gamma : \mathcal{B}(X, Y) \rightarrow C_b(B(X), Y)$  is an isometry.
- (ii) Certainly  $T \circ S \in \mathcal{L}(X, Z)$ , so it suffices to show the bound on the norm. We have

$$\|T \circ S\| = \sup_{x \in X} \frac{\|T \circ S(x)\|}{\|x\|} = \sup_{\substack{x \in X \\ S(x) \neq 0}} \frac{\|T \circ S(x)\|}{\|S(x)\|} \cdot \frac{\|S(x)\|}{\|x\|} \leq \|T\| \cdot \|S\|$$

as required.

- (iii) Now suppose that  $Y$  is a Banach space. Since  $\Gamma$  is an isometry, by [Theorem 4.5](#), it suffices to show that  $\Gamma(\mathcal{B}(X, Y))$  is closed in the complete space  $C_b(B(X), Y)$ . Let  $(S_n)_{n=1}^\infty \subset \mathcal{B}(X, Y)$  be  $\|\cdot\|$ -Cauchy so there is some  $f \in C_b(B(X), Y)$  such that  $\lim_{n \rightarrow \infty} \|\Gamma(S_n) - f\|_\infty = 0$ . Let  $S : X \rightarrow Y$  be given by

$$Sx = \begin{cases} \|x\| f\left(\frac{x}{\|x\|}\right) & x \neq 0 \\ 0 & x = 0 \end{cases};$$

in other words, the linear extension of  $f$  to  $X$ ; we will show  $\lim_{n \rightarrow \infty} S_n = S$ . To see that this extension is indeed linear, let  $x, x' \in X$  and  $\alpha \in \mathbb{F}$  be such that  $x, x', x + \alpha x' \neq 0$ , then

$$\begin{aligned} S(x + \alpha x') &= \|x + \alpha x'\| f\left(\frac{1}{x + \alpha x'}(x + \alpha x')\right) \\ &= \|x + \alpha x'\| \lim_{n \rightarrow \infty} S_n\left(\frac{1}{x + \alpha x'}(x + \alpha x')\right) \\ &= \lim_{n \rightarrow \infty} (S_n x + \alpha S_n x') = \lim_{n \rightarrow \infty} \left[ \|x\| S_n\left(\frac{1}{\|x\|}x\right) + \alpha \|x'\| S_n\left(\frac{1}{\|x'\|}x'\right) \right] \\ &= \|x\| f\left(\frac{x}{\|x\|}\right) + \alpha \|x'\| f\left(\frac{x'}{\|x'\|}\right) \\ &= Sx + \alpha Sx'. \end{aligned}$$

The above computation is easier if any of  $x, x', x + \alpha x'$  are 0. It is immediate that  $S$  is continuous (say, at any point on  $S(X)$ ), so  $S \in \mathcal{B}(X, Y)$ . Finally, as  $S|_{B(X)} = f = \lim_{n \rightarrow \infty} S_n|_{B(X)}$  (with respect to the uniform norm), we have

$$\|S - S_n\| = \sup_{x \in B(X)} \|(S - S_n)x\| = \|f - \Gamma(S_n)\|_\infty \xrightarrow{n \rightarrow \infty} 0$$

as required. ■

## 4.6 DUAL SPACES

A natural way to study an object is to study functions defined on an object:

**Definition.** If  $X$  is a normed space, we let  $X^* = \mathcal{B}(X, \mathbb{F})$  denote the **(continuous) dual**.

When unspecified, we will always mean the dual space to denote the continuous dual space. When  $X$  is an infinite dimensional space, this distinction is important:

**4.9 Proposition.** *If  $X$  is an infinite dimensional normed space, then there exists  $f \in X' \setminus X^*$ .*

PROOF Let  $\{e_n\}_{n=1}^\infty \subset X$  be linearly independent; normalizing each element, we may assume that  $\|e_n\| = 1$  for each  $n \in \mathbb{N}$ . Let  $B$  be any Hamel basis containing  $\{e_n\}_{n=1}^\infty$ , and define  $f : X = \text{span } B \rightarrow \mathbb{F}$  by  $f(e_n) = n \cdot e_n$ , and  $f(e) = 0$  for  $e \in B \setminus \{e_n\}_{n=1}^\infty$  and extend by linearity. Notice that  $\|f\| \geq |f(e_n)| = n$  for any  $n \in \mathbb{N}$ , so  $f$  is unbounded. ■

In the following lemma, we discuss consequences of extension and restriction by scalars on dual spaces.

**4.10 Lemma.** *Let  $X$  be a  $\mathbb{C}$ -vector space.*

- (i) *If  $f \in X'_\mathbb{R}$  into  $\mathbb{R}$ , then  $f_\mathbb{C}$  given by  $f_\mathbb{C}(x) = f(x) - if(ix)$  defines an element of  $X'$ .*
- (ii) *If  $g \in X'$ , then  $f = \text{Re } g$  in  $X'_\mathbb{R}$  satisfies  $g = f_\mathbb{C}$ .*
- (iii) *If  $X$  is a normed  $\mathbb{C}$ -vector space, then for  $f \in X'_\mathbb{R}$ ,  $f \in X'_\mathbb{R}$  if and only if  $f_\mathbb{C} \in X^*$ . Moreover,  $\|f\| = \|f_\mathbb{C}\|$ .*

PROOF (i) and (ii) are straightforward and left as exercises; let's see (iii). Let  $x \in X$  be arbitrary and set  $z = \text{sgn } f_\mathbb{C}(x)$ . Then

$$\begin{aligned} |f_\mathbb{C}(x)| &= \bar{z}f_\mathbb{C}(x) = f_\mathbb{C}(\bar{z}x) = \text{Re } f_\mathbb{C}(\bar{z}x) = f(\bar{z}x) = |f(\bar{z}x)| \\ &\leq \|f\| \|\bar{z}x\| = \|f\| \|x\| \end{aligned}$$

so we see that  $\|f_\mathbb{C}\| \leq \|f\|$ . Conversely,  $|f(x)| = |\text{Re } f_\mathbb{C}(x)| \leq |f_\mathbb{C}(x)| \leq \|f_\mathbb{C}\| \|x\|$  so that  $\|f\| \leq \|f_\mathbb{C}\|$ . ■

Since  $\mathbb{F}$  is complete, we have the following corollary of [Theorem 4.8](#):

**4.11 Corollary.** *If  $X$  is a normed spaces, then  $X^*$  is always a Banach space.*

Here is an example computation of the dual space of a Banach space:

**4.12 Proposition.** *Let for  $x \in \ell^1$ ,  $f_x : \mathbf{c}_0 \rightarrow \mathbb{F}$  be given by  $f_x(y) = \sum_{j=1}^\infty x_j y_j$ . Then  $x \mapsto f_x : \ell^1 \rightarrow \mathbf{c}_0^*$  is a surjective isometry.*

PROOF If  $x \in \ell^1$  and  $y \in \mathbf{c}_0 \subseteq \ell^\infty$ , then

$$\sum_{j=1}^\infty |x_j y_j| \leq \sum_{j=1}^\infty |x_j| \|y\|_\infty = \|x\|_1 \|y\|_\infty < \infty$$

so  $f_x(y) = \sum_{j=1}^\infty x_j y_j$  is well-defined and  $\|f_x\| \leq \|x\|_1$ . It is obvious that  $f_x$  is linear. To show that the norms are equal, let  $y^n = (\overline{\text{sgn } x_1}, \dots, \overline{\text{sgn } x_n}, 0, \dots) \in \mathbf{c}_0$  where  $\|y^n\| = 1$ . Then

$$\|f_x\| \geq |f_x(y^n)| = \sum_{j=1}^n x_j \overline{\text{sgn } x_j} = \sum_{j=1}^n |x_j| \quad (4.1)$$



so that  $\|f_x\| \geq \|x\|_1$  and we have equality, so the map is a surjective linear isometry.

Now let  $f \in \mathbf{c}_0^*$ ,  $e_n = (0, \dots, 0, 1, 0, 0, \dots) \in \mathbf{c}_0$ , and let  $x_n = f(e_n)$ . Suppose  $y \in \mathbf{c}_0$  is arbitrary and set  $y^n = (y_1, \dots, y_n, 0, 0, \dots)$ , so that  $\lim_{n \rightarrow \infty} y^n = y$  uniformly. Since  $f$  is continuous, we have

$$f(y) = \lim_{n \rightarrow \infty} f(y^n) = \lim_{n \rightarrow \infty} \sum_{j=1}^n y_j x_j = \sum_{j=1}^{\infty} x_j y_j = f_x(y)$$

and moreover taking the sequence  $(y_n)_{n=1}^{\infty}$  from (4.1) we have that

$$\sum_{j=1}^n |x_j| = |f(y^n)| \leq \|f\| < \infty$$

so  $x \in \ell^1$  and  $f = f_x$ , as required. ■

**4.13 Corollary.**  $\ell^1 \cong \mathbf{c}^*$  isometrically isomorphically.

**PROOF** For  $y \in \mathbf{c}$ , let  $L(y) = \lim_{n \rightarrow \infty} y_n$  and  $y^n = (y_1, \dots, y_n, L(y), L(y), \dots) \in \mathbf{c}$ . As before,  $\lim_{n \rightarrow \infty} y^n = y$  uniformly. Let  $f \in \mathbf{c}^*$  be arbitrary so that  $f|_{\mathbf{c}_0} = f_x$  for some  $x \in \ell^1$ .

Let  $\mathbf{1} = (1, 1, \dots)$ , and  $\mathbf{1}_n = (0, \dots, 0, 1, 1, \dots)$ . Note that  $f(\mathbf{1}_n)_{n=1}^{\infty}$  is Cauchy in  $\mathbb{F}$  for if  $m < n$  is arbitrary, since  $\mathbf{1}_m - \mathbf{1}_n \in \mathbf{c}_0$ ,

$$|f(\mathbf{1}_n) - f(\mathbf{1}_m)| = |f(\mathbf{1}_n - \mathbf{1}_m)| \leq \sum_{j=m+1}^n |x_j|$$

which can be made arbitrarily small for sufficiently large  $m$ .

Thus we may set  $x_0 = \lim_{n \rightarrow \infty} f(\mathbf{1}_n)$  and  $\tilde{x} = (x_0, x_1, \dots) \in \ell^1$  where  $x_j = f(e_j)$ . Then

$$f(y) = \lim_{n \rightarrow \infty} f(y^n) = \sum_{j=1}^{\infty} x_j y_j + x_0 L(y)$$

so we may consider the map  $x \mapsto f_x : \ell^1 \rightarrow \mathbf{c}$  where  $x = (x_n)_{n=0}^{\infty}$  given by  $f_x(y) = \sum_{j=1}^{\infty} x_j y_j + x_0 L(y)$ . Similarly to before, we may show that  $\|f_x\| = \|x\|_1$ . ■

Again appealing to Theorem 4.5, we have:

**4.14 Corollary.**  $(\ell_1, \|\cdot\|_1)$  is complete.

## 5 FUNDAMENTAL RESULTS IN BANACH SPACE THEORY

### 5.1 THE HAHN-BANACH THEOREM

The Hahn-Banach theorem is a fundamental constructive result in Banach space theory which implies that linear functionals exist in abundance.

**Definition.** Let  $X$  be a  $\mathbb{R}$ -vector space. A **sublinear functional** is any  $\rho : X \rightarrow \mathbb{R}$  that satisfies

- (non-negative homogeneity)  $\rho(tx) = t\rho(x)$  for  $t \geq 0$ ,  $x \in X$ .

- (subadditivity)  $\rho(x + y) \leq \rho(x) + \rho(y)$  for  $x, y \in X$ .

**5.1 Theorem. (Hahn-Banach)** Let  $X$  be a  $\mathbb{R}$ -vector space,  $\rho : X \rightarrow \mathbb{R}$  a sublinear functional,  $Y \subseteq X$  a subspace and  $f \in Y'$  such that  $f \leq \rho|_Y$ . Then there exists  $F \in X'$  such that  $F|_Y = f$  and  $F \leq \rho$  on  $X$ .

PROOF The technique for this proof is to first do it by extensions by a single point  $x \in X \setminus Y$ , then to appeal to Zorn's lemma to extend the result to  $X$ . To extend the definition of  $f$  along the subspace  $\text{span}\{x\} \cup Y$ , it suffices find  $c \in \mathbb{R}$  such that

$$f(y) + \alpha c \leq \rho(y + \alpha x) \quad (5.1)$$

for  $y \in Y$  and  $\alpha \in \mathbb{R}$ . Assuming we have such a  $c$ , we may set  $F : \text{span } Y \cup \{x\} \rightarrow \mathbb{R}$  by  $F(y + \alpha x) = f(y) + \alpha c$ . Then it is clear that  $F$  is linear and satisfies  $F \leq \rho$  on  $\text{span } Y \cup \{x\}$ .

To do this, let  $y^+, y^- \in Y$  be arbitrary and observe that by subadditivity

$$f(y^+) + f(y^-) = f(y^+ + y^-) \leq \rho(y^+ + y^-) \leq \rho(y^+ + x) + \rho(y^- - x)$$

so that  $f(y^-) - \rho(y^- - x) \leq \rho(y^+ + x) - f(y^+)$ . Since  $y^-, y^+$  were arbitrary, there is some  $c \in \mathbb{R}$  such that

$$\sup\{f(y) - \rho(y - x) : y \in Y\} \leq c \leq \inf\{\rho(y + x) - f(y) : y \in Y\}$$

Now if  $t > 0$  is arbitrary, for  $y \in Y$ , since  $c \leq \rho(\frac{1}{t}y + x) - f(\frac{1}{t}y)$ , by non-negative homogeneity  $tx \leq \rho(y + tx)$ ;  $f(y)$  so that  $f(y) + tc \leq \rho(y + tx)$ . In the exact same way, if  $s > 0$ , for  $y \in Y$ , we have  $f(y) - sc \leq \rho(y - sx)$ . It is clear that  $f(y) + 0 \leq \rho(y + 0x)$ . Thus we have our desired inequality in (5.1)

We now use Zorn's lemma to extend this result to the whole space. Consider the set of  $\rho$ -extensions of  $f$ ,

$$\mathcal{E} = \left\{ (\mathcal{M}, \psi) : Y \subseteq \mathcal{M} \subseteq X, \mathcal{M} \text{ is a subspace, } \psi \in \mathcal{M}', \psi|_Y = f, \psi \leq \rho|_{\mathcal{M}} \right\}$$

equipped with the partial order where  $(\mathcal{M}, \psi) \leq (\mathcal{N}, \phi)$  if and only if  $\mathcal{M} \subseteq \mathcal{N}$  and  $\phi|_{\mathcal{M}} = \psi$ . Suppose  $\mathcal{C} \subseteq \mathcal{E}$  is a chain with respect to  $\leq$ , and let

- $\mathcal{U} = \bigcup_{(\mathcal{M}, \psi) \in \mathcal{C}} \mathcal{M}$ , and
- $\phi : \mathcal{U} \rightarrow \mathbb{R}$  by  $\phi(x) = \psi(x)$  whenever  $x \in \mathcal{M}$

where it is easily verified that  $\mathcal{U}$  is a subspace and  $\phi$  is well-defined since  $\mathcal{C}$  is a chain. Moreover, we have that  $\phi \in \mathcal{U}'$ , since if  $x, y \in \mathcal{U}$ , get  $x \in \mathcal{M}$ ,  $y \in \mathcal{N}$  for some  $(\mathcal{M}, \psi) \leq (\mathcal{N}, \psi') \in \mathcal{C}$ , so  $\phi(\alpha x + y) = \psi'(\alpha x + y) = \alpha \psi'(x) + \psi'(y) = \alpha \phi(x) + \phi(y)$ . In the same way, we have  $\psi \leq \rho|_{\mathcal{U}}$ . Thus  $(\mathcal{U}, \phi) \in \mathcal{E}$  and is indeed an upper bound for  $\mathcal{C}$ .

Thus by Zorn's lemma,  $\mathcal{E}$  has some maximal element  $(\mathcal{M}, F)$ . In particular, we must have  $\mathcal{M} = X$ , for if not, get  $x \in X \setminus \mathcal{M}$  and apply the single point extension result to  $\text{span } \mathcal{M} \cup \{x\}$  to get some strictly larger element  $(\text{span}\{x\} \cup \mathcal{M}, F')$ , violating maximality. ■

To put Hahn-Banach into a more useful form and define it for any normed vector space over  $\mathbb{R}$  or  $\mathbb{C}$ , we have the following result:

**5.2 Theorem. (Continuous Hahn-Banach)** Let  $X$  be a normed space.

- If  $Y \subseteq X$  a subspace and  $f \in Y^*$ , then there exists  $F \in X^*$  such that  $F|_Y = f$  and  $\|F\| = \|f\|$ .
- If  $x \in X$ , then there is  $f \in X^*$  such that  $f(x) = \|x\|$  and  $\|f\| = 1$ .

**PROOF** We appeal to [Lemma 4.10](#). We have:

- (i) Define  $\rho : X \rightarrow \mathbb{R}$  be given by  $\rho(x) = \|f\| \cdot \|x\|$ , so  $\rho$  is sublinear and  $\operatorname{Re} f \leq \rho|_Y$ . Apply Hahn-Banach and get  $\tilde{F} \in X_{\mathbb{R}}^*$  such that  $\tilde{F}|_Y = \operatorname{Re} f$  and  $\tilde{F} \leq \rho$ . By [Lemma 4.10](#),  $F = \tilde{F}_{\mathbb{C}}$  satisfies the required properties.
- (ii) If  $x = 0$ , this is trivial, so suppose not. Let  $f_0 : \operatorname{span}\{x\} \rightarrow \mathbb{F}$  be given by  $f_0(\alpha x) = \alpha \|x\|$ . If  $x \neq 0$ , we have immediately that  $\|f_0\| = 1$ ; apply (i) above. ■

As a nice application of Hahn-Banach, we get the following embedding result. Let  $X$  be a normed space and  $X^{**}$  denote the bidual, and for  $x \in X$ , define  $\hat{x} : X^* \rightarrow \mathbb{F}$  by  $\hat{x}(f) = f(x)$ .

**5.3 Theorem.** *The map  $\phi : X \rightarrow X^{**}$  given by  $\phi(x) = \hat{x}$  is a linear isometry.*

**PROOF** Linearity is immediate. Notice that  $|\hat{x}(f)| = |f(x)| \leq \|f\| \|x\|$  so  $\|\hat{x}\| \leq \|x\|$ . Moreover, [Theorem 5.2](#) provides for each  $x \in X$  some  $f_x \in S(X^*)$  with  $|f_x(x)| = \|x\|$ , so that  $\|\hat{x}\| = \|x\|$ . ■

This method gives a nice way to define the completion of a normed space. Naturally, we may do this construction for any metric space, but it is nicer for Banach space. Since  $X^{**}$  is a dual space, it is complete, so that  $\hat{X} = \{\hat{x} : x \in X\}$  has  $\overline{\hat{X}} \subseteq X^{**}$  is complete. But then  $\overline{\hat{X}}$  is Banach space containing a dense isometric copy of  $X$ , and since the completion of a metric space is unique (up to surjective isometry), this is the completion of  $X$ ,  $\overline{X}$ .

## 5.2 HYPERPLANE SEPARATION

An important application of Hahn-Banach is the Hyperplane Separation Theorem, also known as the Geometric Hahn-Banach Theorem. If  $A, B \subset X$  with  $A \cap B = \emptyset$  along with some other suitable assumptions, we will find a  $\mathbb{R}$ -hyperplane between  $A$  and  $B$ .

**Definition.** In a vector space, a **hyperplane** is any set of the form  $x_0 + \ker f$  with  $x_0 \in X$  and  $f \in X'$ . Then a  **$\mathbb{R}$ -hyperplane** is any set of the form  $x_0 + \ker \operatorname{Re} f$ .

**5.4 Proposition.** *Let  $X$  be a normed space.*

- (i) *If  $f \in X^* \setminus \{0\}$ , then  $\overline{\ker f}$  is closed and nowhere dense.*
- (ii) *if  $f \in X' \setminus X^*$ , then  $\overline{\ker f} = X$ .*

*Thus a hyperplane in  $X$  is either closed and nowhere dense, or it is dense.*

**PROOF** To see (i),  $\ker f = f^{-1}(\{0\})$  is a closed set since  $f$  is continuous. Since  $f$  is not the zero map,  $\ker f$  is a proper closed subspace. In general, if  $Y \subsetneq X$  is a proper closed subspace, then it is nowhere dense. If not, then there would exist  $y_0 \in Y$  and  $\delta > 0$  such that  $y_0 + \delta D(X) \subseteq Y$ . But then  $D(X) \subseteq \frac{1}{\delta}(Y - y_0) = Y$ , so  $X = \operatorname{span} D(X) \subseteq Y$ , a contradiction.

To see (ii), suppose that  $\ker f$  is not dense in  $X$ . Then there would be  $x_0 \in X$  and  $\delta > 0$  such that  $(x_0 + \delta D(X)) \cap \ker f = \emptyset$ , so

$$0 \notin f(x_0 + \delta D(X)) = f(x_0) + \delta f(D(X)) \implies \frac{1}{\delta} f(x_0) \notin -f(D(X)) = f(D(X)) \quad (5.2)$$

But then  $\|f\| \leq \frac{1}{\delta} f(x_0)$ , for if  $\|f\| > \frac{1}{\delta} f(x_0)$ , there would be  $x \in D(X)$  such that  $|f(x)| > \frac{1}{\delta} |f(x_0)|$ . Thus

$$\left| \frac{f(x_0)}{\delta f(x)} \right| < 1 \implies \frac{f(x_0)}{\delta f(x)} = \frac{1}{\delta} f(x)$$

contradicting the statement in [\(5.2\)](#). ■

**Definition.** Let  $\emptyset \neq A \subseteq X$ . We say that  $A$  is

- **convex** if for  $a, b \in A$  and  $0 < \lambda < 1$ ,  $(1 - \lambda)a + \lambda b \in A$ .
- **absorbing** at  $a_0 \in A$  if for any  $x \in X$ , there is  $\epsilon(a_0, x) > 0$  such that  $a_0 + tx \in A$  for  $0 \leq t < \epsilon$ .

For example, if  $X$  is a normed space, then any open set is absorbing around any of its points.

**5.5 Lemma. (Minkowski Functional)** Let  $A \subset X$  be a convex set containing 0 and absorbing at 0. Define  $p : X \rightarrow \mathbb{R}$  by  $p(x) = \inf\{t > 0 : x \in tA\}$ . Then  $p$  is a sublinear functional. Moreover, we have that

- (i)  $\{x \in X : p(x) < 1\} \subseteq A \subseteq \{x \in X : p(x) \leq 1\}$ ; and
- (ii) if  $X$  is normed and  $A$  is a neighbourhood of 0, then there is  $N > 0$  such that  $p(x) \leq N \|x\|$  for  $x \in X$ .

**PROOF** First note, for any  $x \in X$ , if  $A$  is absorbing at 0, there is  $s > 0$  such that  $sx \in A$ , so  $x \in \frac{1}{s}A$  and hence  $0 \leq p(x) < \infty$ .

Let's see non-negative homogeneity. Clearly  $p(0) = 0$ . If  $s > 0$  and  $x \in X$ , then

$$p(sx) = \inf\{t > 0 : sx \in tA\} = \inf\left\{t > 0 : x \in \frac{t}{s}A\right\} = s \cdot \inf\left\{\frac{t}{s} > 0 : x \in \frac{t}{s}A\right\} = sp(x)$$

We also have subadditivity. First, note that if  $s, t > 0$  and  $a, b \in A$ , then

$$sa + tb = (s + t)\left(\frac{s}{s + t}a + \frac{t}{s + t}b\right) \in (s + t)A \implies sA + tA \subseteq (s + t)A$$

by convexity, and also  $(s + t)A = \{(s + t)a : a \in A\} \subseteq \{sa + tb : a, b \in A\} = sA + tA$ . Thus  $sA + tA = (s + t)A$ . Now for  $x, y \in X$ , we have

$$\begin{aligned} p(x) + p(y) &= \inf\{s > 0 : x \in sA\} + \inf\{t > 0 : y \in tA\} \\ &= \inf\{s + t : s > 0, t > 0, x \in sA, y \in tA\} \\ &\geq \inf\{s + t : s > 0, t > 0, x + y \in sA + tA = (s + t)A\} \\ &= \inf\{r > 0 : x + y \in rA\} = p(x + y) \end{aligned}$$

so that  $p$  is a sublinear functional. Then

- (i) If  $p(x) < 1$ , then there is  $0 < t < 1$  so  $x \in tA$ ; i.e.  $\frac{1}{t}x \in A$  and  $x = (1 - t) \cdot 0 + t \cdot \frac{1}{t}x \in A$ . The second inclusion is obvious.
- (ii) The assumptions provide  $\delta > 0$  so  $\delta D(X) \subseteq A$ . Then for  $x \in X$  and  $\epsilon > 0$ ,

$$x \in (\|x\| + \epsilon)D(X) = \frac{\|x\| + \epsilon}{\delta} \delta D(X) \subseteq \frac{\|x\| + \epsilon}{\delta} A$$

so  $p(x) \leq \frac{\|x\| + \epsilon}{\delta}$  so  $p(x) \leq \frac{1}{\delta} \|x\|$ ; the result follows with  $N = 1/\delta$ . ■

**5.6 Theorem. (Hyperplane Separation)** Let  $X$  be an  $\mathbb{F}$ -vector space,  $A, B \subset X$  be convex with  $A \cap B = \emptyset$  and  $A$  absorbing at some  $a_0$ . Then there are  $f \in X'$  and  $\alpha \in \mathbb{R}$  such that

$$\operatorname{Re} f(a) \geq \alpha \geq \operatorname{Re} f(b)$$

for  $a \in A$  and  $b \in B$ . Moreover, if  $X$  is normed, then

- If  $A$  is a neighbourhood of  $a_0$ , we have  $f \in X^*$ ; and
- if  $A$  is absorbing around each of its points (for example if  $A$  is open), then we have  $\operatorname{Re} f(a) > \alpha \geq \operatorname{Re} f(b)$ .

PROOF We first re-centre at 0. Let  $A - B = \{a - b : a \in A, b \in B\}$ . Then it is easy to verify that

- (i)  $A - B$  is absorbing at any  $a_0 - b, b \in B$
- (ii)  $A - B$  is convex
- (iii) if  $X$  is normed and  $A$  a neighbourhood of  $a_0$ , then  $A - B$  is a neighbourhood of each  $a_0 - b, b \in B$ ; and if  $A$  is absorbing around any of its points (resp. open), then  $A - B$  is absorbing around any of its points (resp. open).

Let  $x_0 = a_0 - b_0$  for some  $b_0 \in B$ , and set  $C = x_0 - (A - B)$ , so we have  $0 = x_0 - x_0 \in C$ . Then by the above points,  $C$  is absorbing at 0, convex, and if  $X$  is normed and  $A$  a neighbourhood of  $a_0$ , then  $C$  is a neighbourhood of 0; and if  $A$  is absorbing at any of its points (resp.  $A$  is open), then  $C$  is absorbing at each of its points (resp. open).

Let  $p$  be the Minkowski functional of  $C$ . Notice that since  $A \cap B = \emptyset, 0 \notin A - B$  so  $x_0 \notin C$ . Thus by (i) of the lemma,  $p(x_0) > 1$ .

Let us find  $f$  and  $\alpha$ . Let  $f_0 : \mathbb{R}x_0 \rightarrow \mathbb{R}$ , by  $f_0(sx) = sp(x_0)$ . Hence  $f_0$  is linear and  $f_0 \leq p|_{\mathbb{R}x_0}$ , so by Hahn-Banach, get  $f \in X'_\mathbb{R}$  such that  $f \leq p$  on  $X$ . If  $a \in A$  and  $b \in B$ , then  $x_0 - (a - b) \in C$ , so by (i) of the lemma, since  $p(x_0) \geq 1$ , we have  $f(x_0 - (a - b)) \leq p(x_0 - (a - b)) \leq 1$ . Thus  $f(x_0) + f(b) \leq 1 + f(a)$  so in fact  $f(b) \leq f(a)$ . Thus there exists some  $\alpha \in \mathbb{R}$  such that

$$\sup\{f(b) : b \in B\} \leq \alpha \leq \inf\{f(a) : a \in A\}$$

If  $\mathbb{F} = \mathbb{R}$ , we are done; otherwise, we shall replace  $f$  by  $f_\mathbb{C}$

For the remainder of the proof, we suppose  $X$  is a normed space, and  $A$  is a neighbourhood of  $a_0$ . Then part (ii) of the lemma provides  $N > 0$  so that  $p(x) \leq N\|x\|$ . Then for  $x \in X$ ,  $f(x) \leq p(x) \leq N\|x\|$  and  $-f(x) = p(-x) \leq N\|-x\| = N\|x\|$  so  $|f(x)| \leq N\|x\|$ , in other words that  $\|f\| \leq N$  and  $f \in X^*$ . If  $A$  is absorbing around any of its points, then  $f(a) > \alpha$  for any  $a \in A$ . Indeed, suppose  $f(a) = \alpha$ . Then there would be  $t > 0$  so  $a + t(-x_0) \in A$ . But then  $\alpha \leq f(a - tx_0) = f(a) - tf(x_0) < \alpha$ , a contradiction. ■

**Definition.** If  $\emptyset \neq S \subset X$ , then its **convex hull** is given by

$$\operatorname{conv}(S) = \left\{ \sum_{j=1}^n \lambda_j x_j : n \in \mathbb{N}, x_1, \dots, x_n \in S \text{ and } \lambda_1, \dots, \lambda_n \geq 0 \text{ with } \sum_{j=1}^n \lambda_j = 1 \right\}$$

One can verify that  $\operatorname{conv}(S)$  is in fact convex, and is the smallest convex set containing  $S$ , i.e.

$$\operatorname{conv}(S) = \bigcap \{C : S \subseteq C \subseteq X, C \text{ convex}\}$$

If  $X$  is normed, we let  $\overline{\operatorname{conv}}(S)$  denote the **closed convex hull**, i.e. the closure of the convex hull.

**Definition.** A **half-space** of  $X$  is any set of the form  $H = \{x \in X : \operatorname{Re} f(x) \leq \alpha\}$  for some  $f \in X', \alpha \in \mathbb{R}$ .

If  $X$  is normed, then the last proposition shows  $H$  is closed if and only if  $f$  is bounded.

**5.7 Theorem.** If  $X$  is a normed vector space and  $\emptyset \neq S \subset X$ , then  $\overline{\operatorname{conv}}(S) = \bigcap \{H : S \subseteq H \subset X, H \text{ a closed half space}\}.$

**PROOF** It is immediate that  $\overline{\text{conv}}(S) \subseteq \cap\{H : S \subseteq H \subset X, H \text{ a closed half-space}\}$ . Thus suppose  $x_0 \notin \overline{\text{conv}}(S)$ . Then there is  $\delta > 0$  such that  $(x_0 + \delta D(X)) \cap \overline{\text{conv}}(S) = \emptyset$ . Since  $x_0 + \delta D(X)$  is open and convex, hyperplane separation gives provides  $f \in X^*$  and  $\alpha \in \mathbb{R}$  so  $\text{Re } f(a) > \alpha \geq \text{Re } f(b)$  for  $a \in x_0 + \delta D(X)$  and  $b \in \overline{\text{conv}}(S)$ . Then  $S \subset H = \{y \in X : \text{Re } f(y) \leq \alpha\}$  but  $x_0 \notin H$ . ■

## 6 SOME APPLICATIONS OF BAIRE CATEGORY THEOREM

**6.1 Theorem. (Baire Category I)** *If  $(X, d)$  is a complete metric space and  $\{U_n\}_{n=1}^\infty$  is a countable collection of dense, open subsets, then  $\bigcap_{n=1}^\infty U_n$  is dense in  $X$ .*

**Definition.** Let  $(X, d)$  be a metric space. A subset  $F \subset X$  is **nowhere dense** if  $X \setminus F$  is dense in  $X$ ; equivalently,  $\overline{F}$  contains no non-trivial open subsets. We say that a subset  $M \subseteq X$  is **meagre** (1st category) if  $M = \bigcup_{n=1}^\infty F_n$  and each  $F_n$  is nowhere dense; and a set is **non-meagre** (2nd category) otherwise.

**6.2 Theorem. (Baire Category II)** *Let  $(X, d)$  be a complete metric space. Then a non-empty open  $U \subseteq X$  is non-meagre.*

**PROOF** Suppose not, so  $U = \bigcup_{n=1}^\infty F_n \subseteq \bigcup_{n=1}^\infty \overline{F_n}$ , each  $F_n$  (hence  $\overline{F_n}$ ) nowhere dense. Then each  $V_n = X \setminus \overline{F_n}$  is open and dense, and hence by BCT I,  $G = \bigcap_{n=1}^\infty V_n$  is dense in  $X$ , and hence  $U \cap G \neq \emptyset$ , violating assumption ■

**6.3 Theorem. (Banach-Steinhaus)** *Let  $X, Y$  be normed spaces,  $U \subseteq X$  be non-meagre, and  $\mathcal{F} \subset \mathcal{B}(X, Y)$  be such that for each  $x \in U$ ,  $\sup\{\|Tx\| : T \in \mathcal{F}\} < \infty$  (pointwise bounded). Then  $\mathcal{F}$  is uniformly bounded, i.e.  $\sup\{\|T\| : T \in \mathcal{F}\} < \infty$ .*

**PROOF** Let for each  $n \in \mathbb{N}$

$$F_n = \bigcap_{T \in \mathcal{F}} T^{-1}(nB(Y)) = \{x \in X : \|Tx\| \leq n \text{ for all } T \in \mathcal{F}\}$$

so each  $F_n$  is closed and, by the pointwise boundedness assumption,  $U \subseteq \bigcup_{n=1}^\infty F_n$ . By assumption of non-meagreness of  $U$ , at least one  $F_{n_0}$  admits an interior point: there is  $x_0 \in F_{n_0}$  and  $\delta > 0$  such that  $x_0 + \delta D(X) \subseteq F_{n_0}$ . Then if  $x \in D(X)$ , we have

$$Tx = \frac{1}{\delta} \left[ T \left( x_0 + \frac{\delta}{2} x \right) - T \left( x_0 - \frac{\delta}{2} x \right) \right]$$

so  $\|Tx\| \leq \frac{2}{\delta} n_0$ , in other words

$$\|T\| = \sup_{x \in D(x)} \|Tx\| \leq \frac{2n_0}{\delta} < \infty$$

where the bound is independent of  $T$ . ■

**6.4 Theorem. (Open Mapping)** *Let  $X, Y$  be Banach spaces, and  $T \in \mathcal{B}(X, Y)$  surjective. Then  $T$  is an open map; i.e.  $T(U)$  is open in  $Y$  whenever  $U$  is open in  $X$ .*

*Remark.* Given  $x \in X$  and  $\alpha \in \mathbb{F} \setminus \{0\}$ , non-empty  $A \subset X$ , we have that  $\overline{x + \alpha A} = x + \alpha \overline{A}$ . Indeed, note that for  $(a_k)_{k=1}^\infty \subset A$ , we have

$$a_k \rightarrow a \in \overline{A} \text{ if and only if } x + \alpha a_k \rightarrow x + \alpha a \in x + \alpha \overline{A}$$

**6.5 Lemma.** *With the assumptions as above, we have that if  $\overline{T(D(X))} \supset rB(Y)$  for some  $r > 0$ , then  $T(D(X)) \supseteq rD(Y)$ .*

**PROOF** Let  $z \in rD(Y)$  and let  $0 < \delta < 1$  be so  $\|z\| < r(1 - \delta) < r$ . Set  $y = z/(1 - \delta)$  so  $\|y\| < r/(1 - \delta)$ . It suffices to show that  $y \in \frac{1}{1-\delta}T(D(X))$ . To begin, let  $A = T(D(X)) \cap rB(Y)$ , so  $\overline{A} = rB(Y)$ . Indeed, if  $y \in rB(Y) \subseteq \overline{T(D(X))}$ , then there is  $(y_k)_{k=1}^\infty \subset \overline{T(D(X))}$ , so  $y = \lim y_k$ . But then there is  $x_k \in D(X)$  so each  $\|y_k - T(x_k)\| < 1/k$  so  $y = \lim T(x_k)$  with each  $x_k \in D(X)$ .

Now we inductively build a sequence  $(y_n)_{n=1}^\infty$  as follows.

- Since  $y \in rD(Y) \subseteq \overline{A}$ , there is  $y_1 \in A \cap (y + \delta rD(Y))$
- $y \in y_1 + \delta rD(Y) \subseteq y_1 + \delta \overline{A} = y_1 + \delta \overline{A}$ , so there is  $y_2 \in (y_1 + \delta A) \cap (y + \delta^2 rD(Y))$
- $y \in y_n + \delta^n rD(Y) \subseteq y_n + \delta^n \overline{A}$ , so there is  $y_{n+1} \in (y_n + \delta^n A) \cap (y + \delta^{n+1} rD(Y))$

By construction,  $y_{n+1} - y_n \in \delta^n A$ , so  $\|y_{n+1} - y_n\| \leq \delta^n r$  and there is  $x_n \in \delta^n D(X)$  such that  $y_{n+1} - y_n = T x_n$ . Likewise,  $y_1 \in A \subseteq T(D(X))$  so  $y = T(x_0)$  for some  $x_0 \in D(X)$ . Notice that each  $y_n \in y + \delta^n r \in D(Y)$ , so  $\|y_n - y\| \leq \delta^n r \rightarrow 0$ . Since  $X$  is complete, we let  $x = \sum_{n=0}^\infty x_n$ , and by construction

$$\|x\| \leq \sum_{n=0}^\infty \|x_n\| < \sum_{n=0}^\infty \delta^n = \frac{1}{1 - \delta}$$

Then by linearity and continuity of  $T$ , we have

$$Tx = \sum_{n=0}^\infty T x_n = y_1 + \sum_{n=1}^\infty (y_{n+1} - y_n) = y_N + \sum_{n=N}^\infty (y_{n+1} - y_n) \rightarrow y$$

so that indeed  $T(x) = y$ , as required. ■

*Remark.* So far, we've only used completeness of  $X$  and continuity and linearity of  $T$ .

We now proceed with the proof of the open mapping theorem.

**PROOF** It suffices to see that  $T(D(X))$  contains a neighbourhood of 0 in  $Y$ . Indeed, if  $\emptyset \neq U \subseteq X$  is open,  $x \in U$ , then there is  $\delta > 0$  such that  $x + \delta D(X) \subseteq U$ , so  $U - x \supseteq \delta D(X)$ . If  $T(D(X)) \supseteq rD(Y)$ , then  $T(U - x) \supseteq \delta T(D(X)) \supseteq r\delta D(Y)$  so that  $Tx + r\delta D(Y) \subseteq T(U)$ . In other words,  $T(U)$  is a neighbourhood of any of its points, and thus open.

Now write  $X = \bigcup_{n=1}^\infty nD(X)$ , and we assume that  $T(X) = Y$ . Hence  $Y = \bigcup_{n=1}^\infty nT(D(X))$ , so  $Y = \bigcup_{n=1}^\infty n\overline{T(D(X))}$ . But  $Y$  is complete, so by Baire category theorem, there is some  $n$  so that  $n\overline{T(D(X))}$  has non-empty interior. Since  $nT(D(X))$  is convex and symmetric, and hence  $n\overline{T(D(X))}$  is convex and symmetric as well. Thus if  $y \in D(Y)$ , then  $y_0 \pm \epsilon \in y_0 + \epsilon D(Y)$  so

$$\epsilon y = \frac{1}{2} [y_0 + \epsilon y - (y_0 - \epsilon y)] \in n\overline{T(D(X))}$$

and  $\frac{\epsilon}{n}y \in \overline{T(D(X))}$ , i.e.  $\frac{\epsilon}{n}D(Y) \subseteq \overline{T(D(X))}$ . Thus applying the main lemma,  $\frac{\epsilon}{n}D(Y) \subseteq T(D(X))$ . ■

**6.6 Theorem. (Inverse Mapping)** *If  $X, Y$  are Banach spaces and  $T \in \mathcal{B}(X, Y)$  is invertible,  $T^{-1} \in \mathcal{B}(Y, X)$*

PROOF Direct application of the open mapping theorem. ■

Let  $X, Y$  be normed spaces. Then we define for  $(x, y) \in X \oplus Y$ , and we let  $\|(x, y)\|_1 = \|x\| + \|y\|$ . It is easy to check that  $\|\cdot\|_1$  is a norm on  $X \oplus Y$ , and if  $X, Y$  are Banach, then so is  $(X \oplus Y, \|\cdot\|_1)$ . In this case, we write  $X \oplus_1 Y$ .

**6.7 Theorem. (Closed Graph)** *Let  $X, Y$  be Banach spaces and  $T \in \mathcal{L}(X, Y)$ . Then  $T \in \mathcal{B}(X, Y)$  if and only if  $\Gamma(T) = \{(x, Tx) : x \in X\}$  is closed in  $X \oplus_1 Y$ .*

PROOF Let  $T \in \mathcal{B}(X, Y)$ . If  $(x_n) \rightarrow x$  in  $X$ , then  $Tx_n \rightarrow Tx$  in  $Y$ . Thus if  $(x, y) \in \overline{\Gamma(T)}$ , then  $(x, y) = \lim(x_n, Tx_n)$  where  $(x_n, Tx_n) \in \Gamma(T)$ . But then

$$\|y - Tx\| \leq \|y - Tx_n\| + \|Tx_n - Tx\| \leq \|x - x_n\| + \|y - Tx_n\| + \|Tx_n - Tx\| = \|(x - y) - (x_n, Tx_n)\|_1$$

so in fact  $y = Tx$  so  $(x, y) = (x, Tx)$ .

Conversely, if  $\Gamma(T)$  is closed in  $X \oplus_1 Y$ , then  $\Gamma(T)$  is a Banach space. Define  $S : \Gamma(T) \rightarrow X$  by  $S(x, Tx) = x$ . Notice that  $S$  is linear, and

$$\|S(x, Tx)\| = \|x\| \leq \|(x, Tx)\|_1$$

so  $\|S\| \leq 1$ , so  $S$  is bounded. It is also clear that  $S$  is bijective, with  $S^{-1} : X \rightarrow \Gamma(T)$  given by  $S^{-1}(x) = (x, Tx)$ . Thus the inverse mapping theorem gives that  $S^{-1}$  is also bounded. Hence for any  $x \in X$ ,

$$\|Tx\| \leq \|(x, Tx)\|_1 = \|S^{-1}x\| \leq \|x\| \|S^{-1}\|$$

so that  $T$  is in fact bounded. ■

**6.8 Theorem. (Closed graph test)** *Given normed spaces and  $T \in \mathcal{L}(X, Y)$ , we have that  $\Gamma(T)$  is closed in  $X \oplus_1 Y$  if and only if whenever  $x_n \rightarrow 0$  for which we may assume that  $Tx_n$  converges in  $Y$ , say  $y = \lim Tx_n$ , then  $y = 0$  too.*

PROOF We have  $(x_n, Tx_n) \rightarrow (x, z) \in \overline{\Gamma(T)}$  if and only if  $(x_n - x, T(x_n - x)) \rightarrow (x, z) - (x, Tx) = (0, z - Tx)$ . Set  $y = z - Tx$ . We have  $(x, z) \in \Gamma(T)$  if and only if  $z = Tx$  if and only if  $y = 0$ . ■

## 6.1 TESTING HYPOTHESIS OF OMT

- (i) Let  $1 \leq p < r < \infty$ . We have that  $\ell_p \subseteq \ell_r$ , with  $\|x\|_r \leq \|x\|_p$  for  $x \in \ell_p$ . First, suppose  $x \in B(\ell_p)$ , so for each  $k$ ,  $|x_k| \leq \|x\|_p \leq 1$  so  $|x_k|^{r/p} \leq |x_k|$ . Hence

$$\|x\|_r = \left( \sum_{k=1}^{\infty} |x_k|^r \right)^{1/r} \leq \left( \sum_{k=1}^{\infty} |x_k|^p \right)^{1/r} = \|x\|_p^{p/r} \leq 1$$

so if  $x \in \ell_p \setminus \{0\}$ , then the result follows.

Let  $S : (\ell_p, \|\cdot\|_p) \rightarrow (\ell_p, \|\cdot\|_r)$  be the identity map. Then  $\|S\| \leq 1$ , and furthermore  $S$  is bijective. If  $S$  were open, then by the proof of inverse mapping theorem, we would see that  $\|S^{-1}\| < \infty$ . Define  $x^{(n)} \in \ell_p$  by

$$x_k^{(n)} = \begin{cases} \frac{1}{ck^{1/p}} & k \leq n \\ 0 & k > n \end{cases}, c = \sum_{k=1}^{\infty} \frac{1}{k^{r/p}}$$



We compute that  $\|x^{(n)}\|_r < 1$  while  $\|x^{(n)}\|_p = \frac{1}{c} \left( \sum_{k=1}^n \frac{1}{k} \right)^{1/p}$ . In other words,  $\|S^{-1}x^{(n)}\|_p$  goes to infinity, while  $\|x^{(n)}\|_r < 1$ , contradicting  $\|S^{-1}\| < \infty$ . The moral of this is that if the range space is not complete, then OMT may not hold.

- (ii) Take  $X = C_b(0, 1)$ ,  $X_0 = \{f \in X : f \text{ is differentiable on } (0, 1), f' \in C_b(0, 1)\}$ . We have  $X_0 \subseteq X$ , and we put the uniform norm  $\|\cdot\|_\infty$  on both spaces. We let  $D : X_0 \rightarrow X$ ,  $Df = f'$ . If  $h_n(t) = t^n$ , then  $\|h_n\|_\infty = 1$  while  $\|Dh_n\|_\infty = n$ , so  $D$  is not bounded. Despite this, we have that  $\Gamma(D) = \{(f, f') : f \in X_0\}$  is closed in  $X_0 \oplus_1 X$ . We apply the closed graph test: let  $(f_n, f'_n) \rightarrow (0, g)$  in  $X_0 \oplus_1 X$ . Notice that  $\|f'_n\|_\infty < \infty$ , so  $f_n$  is Lipschitz on  $(0, 1)$ , so  $f_n$  is uniformly continuous on  $(0, 1)$ , so  $f_n(0^+) = \lim_{t \rightarrow 0^+} f_n(t)$  exists. Thus by the fundamental theorem of calculus,  $f_n(t) = f_n(0^+) + \int_0^t f'_n$  for  $t \in (0, 1)$ . In particular,

- $f_n \rightarrow 0$  uniformly, so  $f_n(0^+) \rightarrow 0$
- $f'_n \rightarrow g$  uniformly, so for each  $t \in (0, 1)$ ,

$$\int_0^t g = \lim_{n \rightarrow \infty} \int_0^t f'_n = \lim_{n \rightarrow \infty} [f_n(t) - f_n(0^+)] = 0$$

and again, by the FT of  $C$ ,  $g(t) = 0$ . Thus  $g = 0$ , so  $\Gamma(D)$  is closed. We say that  $D : X_0 \rightarrow X$  is a **closed** operator. The moral here is that if the domain is not complete, then closedness of the graph does not imply boundedness of the operator.

Now, let  $J : X \rightarrow X_0$  have  $Jg(t) = \int_0^t g$  for  $t \in (0, 1)$ . By the FT of  $C$ ,  $D \circ J(G) = g$ , in other words that  $D \circ J = I$ . We have for  $g \in X$ ,

$$\|Jg\|_\infty = \sup_{t \in (0, 1)} \left| \int_0^t g \right| \leq \sup_{t \in (0, 1)} t \|g\|_\infty \leq \|g\|_\infty$$

so  $\|J\| \leq 1$ . Hence  $J(D(X)) \subseteq D(X_0)$ , and we apply  $D$  to see  $D(X) \subseteq D(D(X_0))$ , in other words, that  $D$  is open. As an exercise, show that  $C_b(0, 1) = X$  is not separable, while  $X_0$  is separable.

Let  $X \subsetneq Y$  be  $\mathbb{F}$ -vector spaces. We can always find a subspace  $Z \subset Y$  so  $X + Z = Y$  and  $X \cap Z = \{0\}$ . Indeed, let  $B$  be a basis for  $X$ , and  $B' = B \cup B'$  is a basis for  $Y$ , and take  $Z = \text{span } B'$ .

**6.9 Theorem.** *Let  $Y$  be a Banach space and  $X \subsetneq Y$  a closed subspace. Then  $X$  admits a closed complement  $Z$  if and only if there is some  $P \in \mathcal{B}(Y)$  such that  $P \circ P = P$  and  $\text{im } P = P(Y) = X$ .*

*Remark.* We say that  $X \subsetneq Y$  is **boundedly complemented** if either of the above conditions hold.

**PROOF** ( $\Leftarrow$ ) Let  $Z = \ker P$ , which is closed. If  $y \in Y$ , then  $y = Py + (I - P)y$  where  $Py \in X$  and  $P(I - P)y = 0$  so  $(I - P)y \in \ker P$ . If  $z \in Z \cap X$ , then  $z = Py$  for some  $y \in Y$  so  $Pz = P^2y = Py = z$ , but  $z \in \ker P$ , so  $z = Pz = 0$ .

( $\Rightarrow$ ) Let  $S : X \oplus_1 Z \rightarrow Y$  be given by  $S(x, z) = x + z$ . Then  $S$  is surjective and if  $(x, z) \in \ker S$ , then  $x + z = 0$  so  $x = -z \in X \cap Z = \{0\}$ , hence  $S$  is injective. Furthermore,

$$\|S(x + z)\| = \|x + z\| \leq \|(x, z)\|_1$$

so  $\|S\| \leq 1$ . Hence  $S$  is a bounded bijection between Banach space and hence  $S^{-1}$  is bounded by the inverse mapping theorem. Let  $P_1 : X \oplus_1 Z \rightarrow X$  be given by  $P_1(x, z) = x$ ; and  $J : X \rightarrow Y$  by  $Jx = x$ . Notice that  $\|P_1\| = 1$  and  $\|J\| = 1$ . Define  $P : Y \rightarrow Y$  by  $Py = JP_1S^{-1}y$ . Then

- $\text{im } J = X$ , and each of  $P_1, S^{-1}$  are surjective, so  $\text{im } P = X$
- If  $y \in Y$ ,  $\|Py\| = \|JP_1S^{-1}y\| \leq \|S^{-1}\| \|y\|$  so  $\|P\| \leq \|S^{-1}\|$
- Clearly  $P^2 = JP_1S^{-1}JP_1S^{-1} = P$

■

**6.10 Theorem.**  $c_0$  is not boundedly complemented in  $\ell_\infty$ .

**PROOF** Let us assume otherwise; hence, there is  $P = P^2 \in \mathcal{B}(\ell_\infty)$  such that  $\text{im } P = c_0$ . Note that  $c_0 = \ker(I - P)$ . As in A2, we let  $\mathcal{F} \subset \mathcal{P}(\mathbb{N})$  be a family of infinite subsets such that for  $E \neq F$  in  $\mathcal{F}$ ,  $|E \cap F| < \infty$  and  $|\mathcal{F}| = \mathfrak{c}$ . For each  $F \in \mathcal{F}$ , we let  $y_F = (I_P)\chi_F \neq 0$ . If  $\alpha_1, \dots, \alpha_n \in F$  are pairwise distinct,  $F_1, \dots, F_m \in \mathcal{F}$ , then

$$\sum_{i=1}^n \alpha_i \chi_{F_i} = \underbrace{\sum_{i=1}^m \alpha_i \chi_{F_i \setminus \bigcup_{j \in [m] \setminus \{i\}} F_j}}_{:=z} + \underbrace{\sum_{k=2}^m \sum_{1 \leq i_1 < \dots < i_k \leq m} (\alpha_{i_1} + \dots + \alpha_{i_k}) \chi_{F_{i_1} \cap \dots \cap F_{i_k}}}_{\in c_0}$$

where  $\|z\|_\infty = \max_{k=1, \dots, m} |\alpha_k|$ . Hence

$$\left\| \sum_{i=1}^m \alpha_i y_{F_i} \right\| = \|(I - P)z\| \leq \|I - P\| \|z\| = \|I - P\| \max_{k=1, \dots, m} |\alpha_k| \quad (6.1)$$

Now, let for  $n, k \in \mathbb{N}$ ,  $\mathcal{F}_{n,k} = \{F \in \mathcal{F} : |\delta_k(y_F)| \geq \frac{1}{n}\}$  where  $\delta_k(x_i)_{i=1}^\infty = x_k$ , so  $\delta_k \in \ell_\infty^*$  with  $\|\delta_k\| \leq 1$ . Let  $F_1, \dots, F_m$  be pairwise disjoint in  $\mathcal{F}_{n,k}$ , and  $\alpha_i = \text{sgn } \delta_k(y_{F_i})$ . Then we have each  $|\alpha_i| = 1$ , so by (6.1), we find

$$\|I - P\| \geq \left\| \sum_{i=1}^\infty \alpha_i y_{F_i} \right\|_\infty \geq |\delta_k| \sum_{i=1}^n \alpha_i y_{F_i} = \sum_{i=1}^m |\delta_k(y_{F_i})| \geq \frac{m}{n}$$

so  $m \leq n \|I - P\|$  and it follows that  $\mathcal{F}_{n,k}$  is finite. Since each  $y_F \neq 0$  for  $F \in \mathcal{F}$ , we see that  $\mathcal{F} = \bigcup_{n=1}^\infty \bigcup_{k=1}^\infty \mathcal{F}_{n,k}$ , which contradicts that  $|\mathcal{F}| = \mathfrak{c}$ . Hence such a  $P$  must not exist. ■

**6.11 Theorem.** If  $X$  is a finite dimensional vector space over  $\mathbb{F}$ , then any two norms are equivalent.

**PROOF** Let  $\|\cdot\|$  be a norm on  $X$ . Fix a basis  $(e_1, \dots, e_n)$  for  $X$ , and let  $x = \sum_{k=1}^n x_k e_k$ ,  $x_i \in \mathbb{F}$ ,  $\|x_k\|_\infty = \max_{k=1, \dots, n} |x_k|$ . This is easily checked to be a norm. Moreover,  $B_\infty = \{x \in X : \|x\|_\infty \leq 1\}$  admits a homeomorphic identification

$$B_\infty = \begin{cases} [-1, 1]^n & \mathbb{F} = \mathbb{R} \\ \overline{D}^n & \mathbb{F} = \mathbb{C} \end{cases}$$

and hence is compact. Thus  $S_\infty = \{x \in X : \|x\|_\infty = 1\}$  is compact as well. Hence, for  $x = \sum_{k=1}^\infty x_k e_k$ , we have

$$\|x\| \leq \sum_{k=1}^n |x_k| \|e_k\| \leq \|x\|_\infty \underbrace{\sum_{k=1}^n \|e_k\|}_{:=M}$$

Now for  $x, y \in X$ , we have  $|||x|| - ||y||| \leq ||x - y|| \leq M ||x - y||_\infty$  so  $||\cdot||$  is Lipschitz with respect to  $||\cdot||_\infty$ , and hence  $\tau_{||\cdot||_\infty}$ -continuous. Thus the extreme value theorem tells us that  $m = \inf_{x \in S_\infty} ||x|| > 0$ . Hence for  $x \in X \setminus \{0\}$ ,  $||x|| = ||x||_\infty \cdot \left\| \frac{1}{||x||_\infty} x \right\| \geq ||x||_\infty m$ . In general,  $m ||x||_\infty \leq ||x|| \leq M ||x||_\infty$ . We thus have that  $||\cdot|| \sim ||\cdot||_\infty$ , so any norms are equivalent. ■

**6.12 Corollary.** *Let  $(X, ||\cdot||)$  be a finite dimensional normed space. Then*

- (i)  $K \subseteq X$  is compact if and only if  $K$  is closed and bounded.
- (ii)  $(X, ||\cdot||)$  is a Banach space
- (iii) For any normed space  $Y$ , we have  $\mathcal{L}(X, Y) = \mathcal{B}(X, Y)$
- (iv) We have  $X' = X^*$ .

**PROOF** (i) The forward direction is immediate. If  $K$  is closed and bounded, is contained in some scaled copy of  $B_\infty$ , which is compact.  
 (ii) Cauchy sequences are bounded, and thus contained in some scaled copy of  $B_\infty$ , which is compact.  
 (iii) Let  $T \in \mathcal{L}(X, Y)$ , and let  $||x||_0 = ||x|| + ||Tx||$ . Then the result follows by equivalence of norms.  
 (iv) Immediate. ■

**6.13 Proposition.** *A finite dimensional subspace of normed space is always closed and boundedly complemented.*

**PROOF** Let  $Y \subseteq X$  be so  $Y$  is finite dimensional and  $X$  a normed space. We can find a basis  $(e_1, \dots, e_n)$  for  $Y$ . We may assume that each  $||e_k|| = 1$ . We define  $f_1, \dots, f_n \in Y' = Y^*$  by

$$f_k \left( \sum_{j=1}^n \alpha_j e_j \right) = \alpha_k$$

By Hahn-Banach, get  $F_1, \dots, F_n \in X^*$  such that  $F_k|_Y = f_k$  and  $||F_k|| = ||f_k||$ . Define  $P : X \rightarrow X$  by  $Px = \sum_{k=1}^n F_k(x) e_k$ . Notice that  $\text{im } P \subseteq Y$  and by choice of  $F_k|_Y = f_k$ , we have  $P|_Y = I_Y$ . Thus  $P^2 = P$ . Finally, for  $x \in X$ ,  $||Px|| \leq \sum_{k=1}^n ||f_k|| ||x||$  so  $||P|| \leq \sum ||f_k|| < \infty$ , i.e.  $P$  is bounded. Closedness of  $Y$  thus follows from the last corollary. Alternatively,  $Y = \ker(I - P)$ . ■

## 7 ON COMPACTNESS OF THE UNIT BALL

**7.1 Lemma.** *Let  $X$  be a normed space and  $Y \subsetneq X$  a closed subspace. Then given  $\epsilon \in (0, 1)$  there is  $x_0 \in D(X) \subseteq B(X)$  such that  $d(x_0, Y) > 1 - \epsilon$ .*

**PROOF** Let  $x \in X \setminus Y$  and let  $f : Y + \mathbb{F}x \rightarrow \mathbb{F}$  be given by  $f(y + \alpha x) = \alpha$ ,  $y \in Y$ ,  $\alpha \in \mathbb{F}$ . Then  $f$  is linear and  $\ker f = Y$  is closed,  $Y \subsetneq Y + \mathbb{F}x$ , so  $f$  is bounded. Let  $F \in X^*$  be any Hahn-Banach extension of  $f$  with  $||F|| = ||f||$ .

Now, we find  $x_0 \in D(X)$  such that  $|F(x_0)| > (1 - \epsilon)||F||$ . Since  $Y \subseteq \ker F$ , we have for  $y \in Y$  that  $||F|| ||x_0 - y|| \geq |f(x_0 - y)| = |F(x_0)| > (1 - \epsilon)||F||$ , so  $||x_0 - y|| > 1 - \epsilon$ . Hence  $d(x_0, Y) = \inf_{y \in Y} ||x_0 - y|| \geq 1 - \epsilon$ . ■

**7.2 Theorem.** *Let  $X$  be a normed space. Then  $B(X)$  is compact if and only if  $X$  is finite dimensional.*

**PROOF** The reverse implication is standard. Thus suppose  $X$  is not finite dimensional. Let  $\epsilon \in (0, 1)$  and let  $x_1 \in B(X) \setminus \{0\}$ . Inductively,

- Find  $x_2 \in B(X)$  such that  $\text{dist}(x_2, \mathbb{F}x_1) \geq 1 - \epsilon$
- Find  $x_3 \in B(X)$  such that  $\text{dist}(x_3, \text{span}\{x_1, x_2\}) \geq 1 - \epsilon$
- Find  $x_{n+1} \in B(X)$  such that  $\text{dist}(x_{n+1}, \text{span}\{x_1, \dots, x_n\}) \geq 1 - \epsilon$

Hence we have  $\{x_n\}_{n=1}^\infty \subset B(X)$  such that for  $m < n$ ,

$$\|x_n - x_m\| \geq d(x_n, \text{span}\{x_1, \dots, x_{n-1}\}) \geq 1 - \epsilon$$

so the sequence admits no converging subsequence and  $B(X)$  is not compact.  $\blacksquare$

## 8 MORE TOPOLOGY

**Definition.** Let  $(X, \tau)$  be a topological space. A **base** for  $\tau$  is any family  $\beta \subseteq \tau$  such that for any  $U \in \tau$  and  $x \in U$ , there is  $B \in \beta$  such that  $x \in B \subseteq U$ . A **subbase** for  $\tau$  is any family  $\alpha \subseteq \tau$  such that  $\{\bigcap_{k=1}^n U_k : n \in \mathbb{N}, U_1, \dots, U_n \in \alpha\}$  is a base for  $\tau$ .

Note that if  $\emptyset \neq X$  and  $\beta \subseteq \mathcal{P}(X)$  for which  $\bigcup_{B \in \beta} B = X$  and  $\beta$  is closed under finite intersections, then

$$\tau_\beta = \left\{ \bigcup_{i \in I} B_i : \{B_i\}_{i \in I} \subset \beta, I \text{ any index set with } |I| \leq |\beta| \right\}$$

is a topology.

**Definition.** Let  $X \neq \emptyset$ . Suppose we are given

- a family  $\{(X_\alpha, \tau_\alpha)\}_{\alpha \in A}$  of topological spaces, and
- for each  $\alpha \in A$ , a function  $f_\alpha : X \rightarrow X_\alpha$

Then the **initial topology** on  $X$  given this data is denoted

$$\sigma = \sigma(X, (f_\alpha)_{\alpha \in A}) = \sigma(X, (f_\alpha, \tau_\alpha)_{\alpha \in A})$$

and is the topology with base

$$\bigcap_{k=1}^n f_{\alpha_k}^{-1}(U_{\alpha_k}), n \in \mathbb{N}, \alpha_1, \dots, \alpha_n \in A, \text{ each } U_{\alpha_k} \in \tau_{\alpha_k}$$

In particular,  $\{f_\alpha^{-1}(U_\alpha) : U_\alpha \in \tau_\alpha, \alpha \in A\}$  is a subbase for  $\sigma$ .

**Remark.** The topology is chosen so that each  $f_\alpha : X \rightarrow X_\alpha$  is  $\sigma - \tau_\alpha$ -continuous. Furthermore, if  $\tau \subseteq \mathcal{P}(X)$  is any topology for which every  $f_\alpha$  is  $\sigma - \tau_\alpha$ -continuous, then  $\sigma \subseteq \tau$ . We say that  $\sigma$  is the **coarsest** topology so that all the  $f_\alpha$  are continuous.

**Example.** (i) *Metric topology:* If  $(X, d)$  is a metric space, for each  $x \in X$ , let  $d_x$  be given by  $d_x(x') = d(x, x')$ . Then  $\sigma(X, (d_x)_{x \in X}) = \tau_d$ .

(ii) *Relative topology:* If  $(Y, \tau)$ -topological space,  $\emptyset \neq X \subseteq Y$ , and  $i : X \rightarrow Y$  is the inclusion map. Then  $\tau|_X = \sigma(X, \{i\})$ .

(iii) *Product topology:* Let  $\{(X_\alpha, \tau_\alpha)\}_{\alpha \in A}$  be a family of topological spaces. Let  $X = \prod_{\alpha \in A} X_\alpha$ . Let for  $\alpha \in A$ ,  $p_\alpha : X \rightarrow X_\alpha$  denote the projection map onto the component  $\alpha$ . Then the product topology  $\pi = \sigma(X, \{p_\alpha\}_{\alpha \in A})$ . Hence,  $V \in \pi$  if and only if for any  $x \in V$ , there is  $\alpha_1, \dots, \alpha_n \in A$  and  $U_{\alpha_k} \in \tau_{\alpha_k}$  such that  $x_{\alpha_k} = p_{\alpha_k}(x) \in U_{\alpha_k}$  and  $x \in \bigcap_{k=1}^n p_{\alpha_k}^{-1}(U_{\alpha_k}) \subseteq V$ .

Note that if  $X = \prod_{n=1}^\infty X_n$ , each  $(X_n, \tau_n)$  is a topological space, then the basic open sets look like  $U_1 \times U_2 \times \dots \times U_m \times X_{m+1} \times X_{m+2} \times \dots$ .

- (iv) *Linear topology*: Let  $X$  be a vector space and  $Z \subseteq X'$  a subspace. Then  $\sigma(X, Z)$  is the coarsest topology allowing each  $f \in Z$  to be continuous,  $f : X \rightarrow \mathbb{F}$ . The basic open sets are given as follows: let  $x_0 \in X$ ,  $\epsilon > 0$ , and  $D = D(\mathbb{F})$ , and we consider for  $f \in Z$

$$f^{-1}(f(x_0) + \epsilon D) = \underbrace{\{x \in X : |f(x) - f(x_0)| < \epsilon\}}_{\text{"affine hypertube"}} = \{x \in X : |\frac{1}{\epsilon}f(x) - \frac{1}{\epsilon}f(x_0)| < 1\}$$

so that

$$\left\{ \bigcap_{k=1}^n \{x \in X : |f_k(x) - f_k(x_0)| < 1\} : f_1, \dots, f_n \in Z, n \in \mathbb{N} \right\}$$

is a base for  $\sigma(X, Z)$ .

- (v) Now let  $X$  be a normed space. Then the **weak topology** on  $X$  is  $\omega = \sigma(X, X^*)$ . Certainly  $\omega \subseteq \tau_{\|\cdot\|}$ . Similarly, the **weak\*-topology** on  $X^*$  is  $\omega^* = \sigma(X^*, \hat{X})$  (recall for  $x \in X$ ,  $\hat{x}(f) = f(x)$ ). Since  $\hat{X} \subseteq X^{**}$ , we have  $\omega^* \subseteq \omega = \sigma(X^*, X^{**}) \subseteq \tau_{\|\cdot\|}$ .

Let  $(X, \tau)$  be a topological space.

**Definition.** A subset  $K \subseteq X$  is called **compact** if for any collection  $\{U_\alpha\}_{\alpha \in A} \subseteq \tau$  with  $\bigcup_{\alpha \in A} U_\alpha \supseteq K$ , there exists some finite  $U_1, \dots, U_n$  covering  $K$ . If  $X$  itself is  $\tau$ -compact, we call  $(X, \tau)$  a compact space.

**Definition.** A set  $F \subseteq X$  is **closed** if  $X \setminus F \in \tau$ . If  $S \subseteq X$ , then the **closure** of  $S$  is  $\bar{S} = \bigcap \{F \subseteq X : S \subseteq F, X \setminus F \in \tau\}$ .

Note that  $\bar{S} = \{x \in X : \text{for any } U \in \tau \text{ with } x \in U, U \cap S \neq \emptyset\}$ .

**Definition.** A family  $\mathcal{F} \subseteq \mathcal{P}(X)$  has the **finite intersection property** if for any  $F_1, \dots, F_n \in \mathcal{F}$ ,  $\bigcap_{i=1}^n F_i \neq \emptyset$ .

**8.1 Proposition.** Let  $(X, \tau)$  be a topological space. Then  $(X, \tau)$  is compact if and only if any  $\mathcal{F} \subseteq \mathcal{P}(X)$  with the finite intersection property has  $\bigcap_{F \in \mathcal{F}} \bar{F} \neq \emptyset$ .

**PROOF** Suppose  $X$  is compact and  $\mathcal{F} \subseteq \mathcal{P}(X)$  has the finite intersection property but with  $\bigcap_{F \in \mathcal{F}} \bar{F} = \emptyset$ , then  $\{X \setminus \bar{F}\}_{F \in \mathcal{F}}$  is an open cover of  $X$  with no finite subcover.

Conversely, if  $\mathcal{O} \subseteq \tau$  is an open cover of  $X$ , then  $\mathcal{F} = \{X \setminus U\}_{U \in \mathcal{O}}$  satisfies  $\bigcap_{F \in \mathcal{F}} F = \emptyset$ , so there is  $F_1, \dots, F_n \in \mathcal{F}$  with  $\bigcap_{k=1}^n F_k = \emptyset$ . Then  $\{X \setminus F_i\}_{i=1}^n$  is a finite subcover. ■

**Definition.** Let  $X$  be a non-empty set. An **ultrafilter** is a family  $\mathcal{U} \subseteq \mathcal{P}(X)$  such that

- $\mathcal{U}$  has the finite intersection property
- If  $A \in \mathcal{P}(X)$ , then either  $A \in \mathcal{U}$  or  $X \setminus A \in \mathcal{U}$ .

**Example.** (i) *Principal / trivial ultrafilter*: If  $x_0 \in X$ , let  $U_{x_0} = \{U \subseteq X : x_0 \in U\}$ .

**8.2 Lemma. (Ultrafilter)** If  $\mathcal{F} \subseteq \mathcal{P}(X)$  is any set with the finite intersection property, then there is an ultrafilter  $\mathcal{U}$  with  $\mathcal{F} \subseteq \mathcal{U}$ .

**PROOF** Let  $\Phi = \{\mathcal{G} \subseteq \mathcal{P}(X) : \mathcal{F} \subseteq \mathcal{G}, \mathcal{G} \text{ has f.i.p.}\}$ . Then  $\Phi$  is partially ordered by inclusion. If  $\Gamma \subseteq \Phi$  is a chain, then  $\mathcal{G}_\Phi = \bigcup_{\mathcal{G} \in \Gamma} \mathcal{G}$  contains  $\mathcal{F}$  and has the finite intersection property. Hence  $\Phi$  admits a maximal element  $\mathcal{U}$ . Let  $A \in \mathcal{P}(X) \setminus \mathcal{U}$ . Then  $U \cup \{A\} \not\supseteq \mathcal{U}$ , so  $\mathcal{U} \cup \{A\}$  fails the finite intersection property. Hence get  $U_1, \dots, U_n$  so  $A \cap \bigcap_{k=1}^n U_k = \emptyset$ . Now if  $V_1, \dots, V_m \in \mathcal{U}$ , then  $\bigcap_{j=1}^m V_j \cap \bigcap_{k=1}^n U_k \subseteq \bigcap_{k=1}^n U_k \subseteq X \setminus A$ , so  $(X \setminus A) \cap \bigcap_{j=1}^m V_j \neq \emptyset$ . Thus  $\mathcal{U} \cup \{X \setminus A\}$  has finite intersection property, so  $X \setminus A \in \mathcal{U}$  by maximality. ■

**8.3 Corollary.** *If  $\mathcal{U} \subseteq \mathcal{P}(X)$  is an ultrafilter, then*

- (i) *If  $A \in \mathcal{P}(X)$ ,  $A \in \mathcal{U}$  if and only if  $A \cap U \neq \emptyset$  for each  $U \in \mathcal{U}$*
- (ii) *If  $A, B \in \mathcal{P}(X)$ , then  $A \cup B \in \mathcal{U}$  implies at least one of  $A$  or  $B$  is in  $\mathcal{U}$*
- (iii) *If  $A \in \mathcal{U}$  and  $A \subseteq V$  implies  $V \in \mathcal{U}$*

PROOF The forward implication of (i) follows since  $\mathcal{U}$  has finite intersection. Conversely,  $X \setminus A \notin \mathcal{U}$ , so  $A \in \mathcal{U}$ . (ii) and (iii) follow consequently. ■

**8.4 Corollary.** *If  $X$  is an infinite set, it admits a non-principle ultrafilter.*

PROOF Let  $\mathcal{F} = \{F \in \mathcal{P}(X) : X \setminus F \text{ is finite}\}$ . Then  $\mathcal{F}$  has the finite intersection property. Apply the lemma. ■

**8.5 Proposition.** *There are at least  $\mathfrak{c}$  many ultrafilters in  $\mathcal{P}(\mathbb{N})$ .*

PROOF We let  $\mathcal{F} \subset \mathcal{P}(\mathbb{N})$  be a collection of infinite sets such that  $E \neq F$  in  $\mathcal{F}$  implies  $|E \cap F| < \infty$ , and  $|\mathcal{F}| = \mathfrak{c}$ . For each  $F \in \mathcal{F}$ , we let  $\mathcal{F}_F = \mathcal{F}_0 \cup \{F\}$ , which has the finite intersection property. Moreover, if  $E \in \mathcal{F} \setminus \{F\}$ , then  $\mathcal{F}_F \cup \{E\}$  would fail f.i.p. Hence, for  $F \in \mathcal{F}$ , let  $\mathcal{U}_F$  be any ultrafilter containing  $\mathcal{F}_F$ , giving  $\mathfrak{c}$  many ultrafilters. ■

*Remark.* It can be shown (with a lot more work) that  $\mathbb{N}$  admits  $2^{\mathfrak{c}}$  ultrafilters.

Let  $\mathcal{U} \subset \mathcal{P}(\mathbb{N})$  be a non-principal ultrafilter. Define  $\delta_{\mathcal{U}} : \mathcal{P}(\mathbb{N}) \rightarrow \{0, 1\} \subset \mathbb{R}$  by  $\delta_{\mathcal{U}}(A) = 1$  if  $A \in \mathcal{U}$ , and 0 if  $X \setminus A \in \mathcal{U}$ . Since  $\mathbb{N} \in \mathcal{U}$ , we see that  $\delta_{\mathcal{U}}(\emptyset) = 0$ . If  $\emptyset \neq A, B \in \mathcal{P}(\mathbb{N})$  with  $A \cap B = \emptyset$ , then if  $A \cup B \in \mathcal{U}$ , then exactly one of  $A$  or  $B$  is in  $\mathcal{U}$ . Thus  $\delta_{\mathcal{U}}(A \cup B) = \delta_{\mathcal{U}}(A) + \delta_{\mathcal{U}}(B)$ . If  $E_1, \dots, E_n \subseteq \mathbb{N}$  with  $E_j \cap E_k = \emptyset$  for  $j \neq k$ , then  $\sum_{k=1}^n |\delta_{\mathcal{U}}(E_k)| \leq 1$  so  $\|\delta_{\mathcal{U}}\|_{\text{var}} \leq 1$ . Since  $\delta_{\mathcal{U}}(\mathbb{N}) = 1$ , we have  $\|\delta_{\mathcal{U}}\|_{\text{var}} = 1$ . Let  $L_{\mathcal{U}} \in \ell_{\infty}^*$  be the linear functional associated to  $\delta_{\mathcal{U}}$ . We then have (with some verification possibly needed)

- (i)  $L_{\mathcal{U}}(1) = 1$ ,  $\|L_{\mathcal{U}}\| = 1$
- (ii)  $L_{\mathcal{U}}|_{\mathfrak{c}_0} = 0$ , so if  $x \in \ell_{\infty}^{\mathbb{R}}$ , then  $\liminf_{n \rightarrow \infty} x_n \leq L_{\mathcal{U}} \leq \limsup_{n \rightarrow \infty} x_n$
- (iii) Exactly one of  $2\mathbb{N}$  and  $2\mathbb{N}-1$  is in  $\mathcal{U}$ , so  $L(\chi_{2\mathbb{N}}) \neq L_{\mathcal{U}}(\chi_{2\mathbb{N}-1})$ , so  $L_{\mathcal{U}}$  is not translation invariant.
- (iv) Let  $S \in \mathcal{B}(\ell_{\infty})$  be given by  $Sx = \left(\frac{x_1 + \dots + x_n}{n}\right)_{n=1}^{\infty}$ . Then  $L_{\mathcal{U}} \circ S$  is a Banach limit.

**Definition.** If  $(X, \tau)$  is a topological space,  $\mathcal{U}$  an ultrafilter on  $X$ , we say that  $x_0 \in X$  is a  $(\tau-)$ limit point for  $\mathcal{U}$  if for each  $U \in \tau$  with  $x_0 \in U$ , we have  $U \in \mathcal{U}$ .

**8.6 Proposition.** *Let  $(X, \tau)$  be a topological space. Then  $(X, \tau)$  is compact if and only if any ultrafilter on  $X$  admits a  $\tau$ -limit point.*

PROOF Let us begin with an observation: if  $x \in X$  and  $\mathcal{U}$  is an ultrafilter on  $X$ , then

$$x \in \bigcap_{V \in \mathcal{U}} \overline{V} \Leftrightarrow \text{for any } U \in \tau \text{ with } x \in U, U \cap V \neq \emptyset \text{ for each } V \in \mathcal{U} \\ \Leftrightarrow x \text{ is a } \tau\text{-limit point of } \mathcal{U}$$

If  $(X, \tau)$  is compact, then  $\bigcap_{V \in \mathcal{U}} \overline{V} \neq \emptyset$ . If  $\mathcal{F} \subseteq \mathcal{P}(X)$  has the finite intersection property, then there exists an ultrafilter  $\mathcal{U} \supseteq \mathcal{F}$ , so  $\bigcap_{F \in \mathcal{F}} \overline{F} \supseteq \bigcap_{V \in \mathcal{U}} \overline{V} \neq \emptyset$ . ■

**8.7 Theorem. (Tychonoff)** Let  $\{(X_\alpha, \tau_\alpha)\}_{\alpha \in A}$  be a family of compact spaces, and  $X = \prod_{\alpha \in A} X_\alpha$  with the product topology  $\pi$ . Then  $(X, \pi)$  is compact.

**PROOF** Let  $\mathcal{U}$  be an ultrafilter on  $X$ ; we will show that it admits a  $\pi$ -limit point. Fix  $\alpha \in A$  and let  $\mathcal{U}_\alpha = \{p_\alpha(V) : V \in \mathcal{U}\}$ , where  $p_\alpha$  is the coordinate projection onto  $\alpha$ . If  $\emptyset \neq S_\alpha \subseteq X_\alpha$ , then  $S_\alpha = p_\alpha^{-1}(p_\alpha^{-1}(S_\alpha))$ , so  $S_\alpha \in \mathcal{U}_\alpha$  if and only if  $p_\alpha^{-1}(S_\alpha) \in \mathcal{U}$ , and since  $p_\alpha^{-1}$  commutes with complementation,  $\mathcal{U}_\alpha$  is an ultrafilter. The last proposition provides a  $\tau_\alpha$ -limit point  $x_\alpha$  for  $\mathcal{U}_\alpha$ . Now let  $x = (x_\alpha)_{\alpha \in A}$ , where  $x_\alpha$  is found as above. If  $W \in \pi$  with  $x \in W$ , then there are  $\alpha_1, \dots, \alpha_n$  in  $A$ ,  $U_{\alpha_i} \in \tau_{\alpha_i}$  with  $x \in \bigcap_{i=1}^n p_{\alpha_i}^{-1}(U_{\alpha_i}) \subseteq W$ . Since each  $x_{\alpha_k}$  is a  $\tau_{\alpha_k}$ -limit point of  $\mathcal{U}_{\alpha_k}$ , we see that each  $U_{\alpha_k} \in \mathcal{U}_{\alpha_k}$ , so  $p_{\alpha_k}^{-1}(U_{\alpha_k}) \in \mathcal{U}$ . Thus we see that  $W \in \mathcal{U}$ , so  $x$  is a  $\pi$ -limit point of  $\mathcal{U}$ . ■

*Remark.* (i) Tychonoff's theorem implies the axiom of choice. Given  $\{X_\alpha\}_{\alpha \in A}$  be a family of non-empty sets. Find  $y$  which is not a member of any  $X_\alpha$ , and let  $Y_\alpha = X_\alpha \cup \{y\}$  and  $\tau_\alpha = \{\emptyset, \{y\}, X_\alpha, Y_\alpha\}$ , and  $(Y_\alpha, \tau_\alpha)$  is compact. The constant element  $y$  is an element of  $Y$ , so by Tychonoff,  $(Y, \pi)$  is compact. Given  $\alpha_1, \dots, \alpha_n \in A$ , then  $\bigcup_{k=1}^n p_{\alpha_k}^{-1}(\{y\})$ . Since  $\prod_{k=1}^n X_{\alpha_k} \neq \emptyset$ , we see that  $Y \subsetneq \bigcup_{k=1}^n p_{\alpha_k}^{-1}(\{y\})$ . Hence by compactness,  $Y \not\subseteq \bigcup_{\alpha \in A} p_\alpha^{-1}(\{y\})$ . Hence  $\prod_{\alpha \in A} X_\alpha = Y \setminus \bigcup_{\alpha \in A} p_\alpha^{-1}(\{y\}) \neq \emptyset$ .

(ii) If we are given  $(X_\alpha, \tau_\alpha)_{\alpha \in A}$  a family of topological spaces,  $X = \prod_{\alpha \in A} X_\alpha$ , we can define the **box topology**, i.e. the topology with base  $\{\prod_{\alpha \in A} U_\alpha : U_\alpha \in \tau_\alpha \setminus \{\emptyset\} \text{ for each } \alpha\}$  Of course,  $\pi \subseteq \tau$ , and the inclusion is proper on infinite products.

**8.8 Proposition.** Let  $(X, \tau)$  be a compact space.

(i) If  $K \subseteq X$  is closed, then  $K$  is compact.

(ii) If  $(Y, \sigma)$  is a topological space and  $f : X \rightarrow Y$  is continuous, then  $f(X)$  is compact.

**PROOF** Immediate. ■

*Remark.* If  $X$  is a normed space,  $w^* = \sigma(X^*, \hat{X})$ , if  $x \in X$ ,  $\hat{x} \in X^{**}$ ,  $\hat{x}(f) = f(x)$ ,  $\hat{X} = \{\hat{x} : x \in X\}$ . If  $A, B$  are non-empty sets,  $A^B \cong \{f : B \rightarrow A\}$ .

**8.9 Theorem. (Alaoglu)** Let  $X$  be a normed space. Then  $B(X^*)$  is  $w^* = \sigma(X^*, \hat{X})$ -compact

**PROOF** Let  $\Gamma : X^* \rightarrow \mathbb{F}^X$  be given by  $\Gamma(f) = (f(x))_{x \in X}$ , so  $\Gamma$  is injective. Let  $\pi = \sigma(\mathbb{F}^X, \{p_x\}_{x \in X})$  be the product topology. If  $U_1, \dots, U_n \subseteq \mathbb{F}$  are open and  $x_1, \dots, x_n \in X$ , then

$$\Gamma\left(\bigcap_{k=1}^n \hat{x}_n^{-1}(U_k)\right) = \bigcap_{k=1}^n \Gamma(\hat{x}_n^{-1}(U_k)) = \bigcap_{k=1}^n \hat{x}_n^{-1}(U_k) \cap \Gamma(X^*)$$

so  $\Gamma$  is an open map onto its image in  $\mathbb{F}^X$ . Similarly, it is easy to show that  $\Gamma^{-1}$  is also an open map, so in fact  $\Gamma$  is a homeomorphism onto its image.

We now consider  $\overline{\Gamma(B(X^*))} \subset \mathbb{F}^X$ . Let  $g \in \overline{\Gamma(B(X^*))}$  and let  $D = D(\mathbb{F})$ . Given  $x, y \in X$  and  $\alpha \in \mathbb{F}$ , and then given  $\epsilon > 0$ , we find  $f \in B(X^*)$  such that

$$\Gamma(f) \in p_x^{-1}\left(g(x) + \frac{\epsilon}{3}D\right) \cap p_y^{-1}\left(g(y) + \frac{\epsilon}{3(|\alpha|+1)}D\right) \cap p_{x+\alpha y}^{-1}\left(g(x+\alpha y) + \frac{\epsilon}{3}D\right)$$

We have that  $f$  is linear with  $\Gamma(f)(x) = f(x)$ , etc. so we have

$$|g(x) + \alpha g(y) - g(x + \alpha y)| \leq |g(x) - f(x)| + |\alpha| |g(y) - f(y)| + |g(x + \alpha y) - f(x + \alpha y)| < \epsilon$$

and since  $\|f\| \leq 1$ , we have  $|g(x)| \leq |g(x) - f(x)| + |f(x)| < \epsilon/3 + \|x\|$ . Then since  $\epsilon > 0$  is arbitrary, get  $g \in X'$  and  $|g(x)| \geq \|x\|$ , i.e.  $g \in B(X^*)$ . Hence we have that  $g = \Gamma(g)$ .

Thus  $\Gamma(B(X^*)) \subseteq \prod_{x \in X} \|x\| \overline{D} \subseteq \mathbb{F}^X$  is a closed subset of a compact subset of  $\mathbb{F}^X$ . Thus  $B(X^*)$  is the continuous image of a compact set and hence compact. ■

*Remark.* If  $r > 0$ , then we may replace  $B(X^*)$  with  $rB(X^*)$  in the proof above, with trivial modifications. Thus any ball is  $w^*$ -compact. Hence bounded  $w^*$ -closed sets in  $X^*$  are automatically  $w^*$ -compact.

**Definition.** A topological space  $(X, \tau)$  is Hausdorff if given  $x \neq y$  in  $X$ , there are  $U_x, V_y \in \tau$  such that  $x \in U_x$  and  $y \in V_y$  and  $U_x \cap V_y = \emptyset$ .

*Example.* (i) A metric space is Hausdorff.

(ii)  $X$  a normed space,  $w = \sigma(X, X^*)$  is Hausdorff (by Hahn-Banach and A2Q1).

(iii) If  $X$  is a normed space, then  $w^* = \sigma(X^*, \hat{X})$  on  $X^*$  is Hausdorff.

(iv)  $\{(X_\alpha, \tau_\alpha)\}_{\alpha \in A}$  family of topological spaces,  $X = \prod_{\alpha \in A} X_\alpha$  with  $\pi$  the product topology. Then  $(X, \pi)$  is Hausdorff if and only if all  $(X_\alpha, \tau_\alpha)$  are Hausdorff. (Straightforward exercise).

**8.10 Proposition.** Let  $(X, \tau)$  be a Hausdorff space,  $K \subseteq X$   $\tau$ -compact. Then  $K$  is  $\tau$ -closed.

PROOF Straightforward exercise. ■

**8.11 Proposition.** Let  $(X, \tau)$  be a compact space.

(i) If  $(Y, \sigma)$  is a Hausdorff space and  $\phi : X \rightarrow Y$  is continuous and bijective, then  $\phi^{-1} : Y \rightarrow X$  is continuous.

(ii) If  $\tau' \subseteq \tau$  is a Hausdorff topology on  $X$ , so  $\tau' = \tau$ .

PROOF (i) If  $F \subseteq X$  is  $\tau$ -closed, then it is  $\tau$ -compact. Hence  $(\phi^{-1})^{-1}(F) = \phi(F)$  is  $\sigma$ -closed, so by A1Q1,  $\phi^{-1}$  is continuous.

(ii)  $\text{id} : X \rightarrow X$  is continuous, so if  $U \in \tau'$ , then  $\text{id}^{-1}(U) = U \in \tau$ , so  $\text{id}$  is continuous. Hence by (1)  $\text{id}^{-1}$  is continuous so  $\tau \subseteq \tau'$ . ■

**8.12 Theorem. (Metrization)** If  $X$  is a separable normed space, then  $B(X^*)$  is  $w^*$ -metrizable, i.e. there exists a metric  $\rho$  on  $B(X^*)$  such that  $w^*|_{B(X^*)} = \tau_\rho$ .

PROOF Let  $\{x_n\}_{n=1}^\infty \subset B(X)$  be any set which is separating for  $X^*$ , i.e. if  $f \in X^* \setminus \{0\}$ , then  $f(x_n) \neq 0$  for some  $n$  (for example, take any dense subset of  $D(X) \setminus \{0\}$ ). Let  $\rho$  be given by

$$\rho(f, g) = \sum_{k=1}^{\infty} \frac{|(f - g)(x_k)|}{2^k} \leq 2$$

It is easy to see that this is a metric.

Given  $f_0 \in B(X^*)$ , take  $\epsilon > 0$  and let

- $n$  be so  $\sum_{k=n+1}^{\infty} \frac{2}{2^k} < \frac{\epsilon}{2}$ , and



•  $V = \bigcap_{k=1}^n \{f \in B(X^*) : |\hat{x}_k(f) - \hat{x}_k(f_0)| < \epsilon/2\} \in w^*|_{B(X^*)}, f_0 \in V$ .  
Then if  $f \in V$ ,

$$g(f, f_0) = \sum_{k=1}^n \frac{|f(x_k) - f_0(x_k)|}{2^k} + \sum_{k=n+1}^{\infty} \frac{|f(x_k) - f_0(x_k)|}{2^k} < \epsilon$$

so  $f_0 \in V \subset B_{\rho, \epsilon}^\circ(f_0)$ . Since  $f_0$  is arbitrary, we have  $\tau_\rho \subseteq w^*|_{B(X^*)}$ , but since  $w^*$  is compact and  $\tau_\rho$  is Hausdorff, these must be equal. ■

- (i) Note that different separating families from  $B(X)$  may produce different metrics, but always the same topology.
- (ii) The definition of  $\rho$  above extends to all of  $X^* \times X^*$ . However,  $X^*$  with the weak\* topology is not metrizable if  $X$  is infinite dimensional.
- (iii)  $X^* = \bigcup_{n=1}^{\infty} nB(X^*)$ , so each  $nB(X^*)$  is metrizable and compact, and thus  $w^*$ -separable. Thus if  $X$  is separable, then  $X^*$  is itself separable.

## 9 NETS

**Definition.** A pair  $(N, \leq)$  is a **preorder** on  $N$  if

- $v \leq v$  for  $v \in N$
- $v_1 \leq v_2$  and  $v_2 \leq v_3$  implies  $v_1 \leq v_3$ .

This pair is **cofinal** if for any  $v_1, v_2 \in N$ , there is  $v_3 \in N$  so  $v_1 \leq v_3$  and  $v_2 \leq v_3$ . Then  $(N, \leq)$  is a **directed set** if  $\leq$  is a cofinal preorder. Given a non-empty set  $X$ , a **net** is a function  $x : N \rightarrow X$ .

**Definition.** If  $(x_\nu)_{\nu \in N}$  is a net in  $X$ ,  $A \subseteq X$ , we say that  $(x_\nu)_{\nu \in N}$  is

- **eventually** in  $A$  if there is  $v_A \in N$  so  $x_\nu \in A$  whenever  $\nu \geq v_A$
- **frequently** in  $A$  if for any  $v \in N$ , there is  $v' \in N$  with  $v' \geq v$  so  $x_{v'} \in A$ .

**Definition.** Now, let  $(M, \leq)$  be another directed set. A map  $\phi : M \rightarrow N$  is **eventually cofinal** if for any  $v \in N$ , there is  $\mu_v \in M$  s  $\phi(\mu) \geq v$  whenever  $\mu \geq \mu_v$ . Given a net  $(x_\nu)_{\nu \in N}$  and an eventually cofinal  $\phi : M \rightarrow N$ , we call  $(x_{\phi(\mu)})_{\mu \in M}$  a **subnet**.

**Definition.** We call  $\phi : M \rightarrow N$  a **directed map** if

- (i)  $\mu \leq \mu'$  in  $M$  implies  $\phi(\mu) \leq \phi(\mu')$  in  $N$
- (ii) For any  $v \in N$ , there is  $\mu \in M$  s  $v \leq \phi(\mu)$ .

Directed maps are always cofinal. Different sources use directed maps over eventually cofinal maps.

**Example.** (i)  $(\mathbb{N}, \leq)$  is directed, and subsequences are special types of subnets.

(ii)  $(\mathbb{R}, \leq)$  is directed

(iii) (*Riemann sums*) Let  $a < b$  in  $\mathbb{R}$ . We let

$$N = \{(P, P^*) : P = \{a = t_0 < t_1 < \dots < t_n = b\}, P^* = \{t_1^*, \dots, t_n^*\}, t_k^* \in [t_{k-1}, t_k]\}$$

and say  $(P, P^*) \leq (Q, Q^*)$  if  $P \subseteq Q$ . One can verify that this is a net (the Riemann sum net).

(iv) (*Nets from filtering families*). We say that  $\mathcal{F} \subset \mathcal{P}(X) \setminus \{\emptyset\}$  is a **filtering family** if for each  $F_1, F_2 \in \mathcal{F}$ , there is  $F_3 \in \mathcal{F}$  such that  $F_3 \subseteq F_1 \cap F_2$ . For example, an ultrafilter is a filtering family. Let

$$N_{\mathcal{F}} = \{(x, F) : x \in F, F \in \mathcal{F}\}$$

equipped with the pre-order  $(x, F) \leq (x', F')$  if and only if  $F \supseteq F'$ . Since  $\mathcal{F}$  is a filtering family,  $(N_{\mathcal{F}}, \leq)$  is directed. Let  $x_{(x, F)} = x$ , so  $(x)_{(x, F) \in N_{\mathcal{F}}}$  is the net built from  $\mathcal{F}$ . Note that if  $F \in \mathcal{F}$ , then  $(x)_{(x, F) \in \mathcal{F}}$  is eventually in  $F$ .

An **ultranet**  $(x_v)_{v \in N} \subset X$  is a net for which any  $A \in \mathcal{P}(X)$ ,  $(x_v)_{v \in N}$  is either eventually in  $A$  or eventually in  $X \setminus A$ . If  $\mathcal{F}$  is an ultrafilter, then  $(x)_{(x, F) \in N_{\mathcal{F}}}$  is an **ultranet**.

### 9.1 NETS AND TOPOLOGY

Now, suppose  $(X, \tau)$  is a topological space.

**Definition.** We say that  $x_0 \in X$  is

- Some  $x_0 \in X$  is a **limit point** if for any  $U \in \tau$  with  $x_0 \in U$ ,  $(x_v)_{v \in N}$  is eventually in  $U$ . That is, there is  $v_U$  such that  $x_v \in U$  whenever  $v \geq v_U$ . We write  $x_0 = \lim_{v \in N} x_v$ , the  $\tau$ -limit of  $(x_v)_{v \in N}$ . Note that this is an abuse of notation, since limit points need not be unique (when  $(X, \tau)$  is not Hausdorff).
- Some  $x_0 \in X$  is a **cluster point** of  $(x_v)_{v \in N}$  if for any  $U \in \tau$  with  $x_0 \in U$ ,  $(x_v)_{v \in N}$  is frequently in  $U$ .

**9.1 Proposition.** If  $(x_v)_{v \in N}$  is a net in  $(X, \tau)$  and  $x_0 \in X$ , then  $x_0$  is a cluster point for  $(x_v)_{v \in N}$  if and only if  $x_0$  is a  $\tau$ -limit point of  $x_{v_\mu}$  for some subnet  $(x_{v_\mu})_{\mu \in M}$  of  $(x_v)_{v \in N}$ .

**PROOF** ( $\implies$ ) Suppose  $x_0$  is a cluster point for  $(x_v)_{v \in N}$ . Then for each  $v \in N$  and  $U \in \tau$  containing  $x_0$ , define

$$F_{v, U} = \{v' \in N : v' \geq v, x_{v'} \in U\}$$

which is non-empty since  $x_0$  is a cluster point. Then set

$$\mathcal{F} = \{F_{v, U} : v \in N, U \in \tau, x_0 \in U\} \subset \mathcal{P}(N)$$

Let's see that  $\mathcal{F}$  is filtering: suppose  $F_{v, U}$  and  $F_{v', U'}$  are in  $\mathcal{F}$ . Get  $\mu \geq v$  and  $\mu \geq v'$  by definition of a net and set  $V = U \cap U'$ , which is open and contains  $x_0$ . Then since  $x_0$  is a cluster point, get some  $\mu' \geq \mu$  such that  $x_{\mu'} \in V$ , so  $F_{\mu', V} \subseteq F_{v, U} \cap F_{v', U'}$ . We then let  $M = N_{\mathcal{F}}$  be the net construction from the filtering family and set  $v_{(v, F)} = V$ .

Now set  $N_{\mathcal{F}} = \{(v, F) : v \in F, F \in \mathcal{F}\}$  with the standard preorder and  $v_{(v, F)} = v$ . Then the map  $(v, F) \mapsto v$  from  $N_{\mathcal{F}} \rightarrow N$  is eventually cofinal: if  $v_0 \in N$  is arbitrary, take any  $F_0 = F_{v_0, U} \in \mathcal{F}$ . Then  $F_0 = \{v \in N : v \geq v_0, x_v \in U\}$ , so if  $F_{\mu, V} \in \mathcal{F}$  with  $F_{\mu, V} \subseteq F_0$ , we let  $M = N_{\mathcal{F}}$  as in (iv) above, and  $v_{v, \mathcal{F}} = v$ . Check that  $(x_v)_{(v, F) \in N_{\mathcal{F}}}$  is eventually in  $U$  for any  $U \in \tau$  with  $x_0 \in U$ . [Check:  $(v, F) \mapsto v : N_{\mathcal{F}} \rightarrow N$  is cofinal, but is not evidently directed]

( $\impliedby$ ) If for some subnet  $(x_{v_\mu})_{\mu \in M}$  is eventually in  $U$  for any  $U \in \tau$  with  $x_0 \in U$ , then  $(x_v)_{v \in N}$  is frequently in  $U$  for such  $U$  by definition of a subnet. ■

**9.2 Proposition.** If  $(Y, \sigma)$  is another topological space, then  $f : X \rightarrow Y$  is continuous if and only if for any  $x_0 \in X$  and net  $(x_v)_{v \in N}$  with having  $x_0$  as a limit,  $f(x_0) = \lim_{v \in N} f(x_v)$ .

**PROOF** If  $V \in \sigma$  with  $f(x_0) \in V$ , then  $f^{-1}(V) \in \tau$  with  $x_0 \in f^{-1}(V)$ . Since  $(x_v)_{v \in N}$  is eventually in  $f^{-1}(V)$ , so  $(f(x_v))_{v \in N}$  is eventually in  $V$ .

Conversely, let  $\tau_{x_0} = \{U \in \tau : x_0 \in U\}$ , which is filtering on  $X$ . Let  $N_{\tau_{x_0}} = \{(x, U) : x \in U, U \in \tau_{x_0}\}$  be directed by  $(x, U) \leq (x', U')$  if and only if  $U \supseteq U'$  as in (iv) above. Then  $x_0 = \lim_{(x, U) \in N_{\tau_{x_0}}} x$ . Now, let  $V \in \sigma$  with  $f(x_0) \in V$ . The assumptions on  $f$  tell us there is  $v - V \in N_{\tau_{x_0}}$  such that for  $v \geq v_V$ , we have  $f(x_0) \in V$ . We have  $v_V = (x, U)$  for some

$U \in \tau_{x_0}$  and  $x \in U$ , so for any  $x' \in U$ ,  $(x', U) \geq (x, U)$  and  $f(x') = f(x_{x', U}) \in V$ , so that  $x_0 \in U = \bigcup_{x' \in U} \{x'\} \subseteq f^{-1}(V)$ , so  $f$  is continuous at  $x_0$ . But  $x_0 \in X$  was arbitrary. ■

*Remark.* We get the following consequences of this result:

- (i) Given topologies  $\tau, \tau'$  on  $X$ ,  $\tau' \subseteq \tau$  if and only if  $\tau' - \lim_{v \in N} x_v = x_0$  whenever  $\tau - \lim_{v \in N} x_v = x_0$  for any  $x_0 \in X$ .
- (ii) (limits in product topology)  $\{(x_\alpha, \tau_\alpha)\}_{\alpha \in A}$  be topological space and  $X = \prod_{\alpha \in A} X_\alpha$  equipped with the product topology  $\pi$ . If  $(x^{(v)})_{v \in N}$  is a net in  $X$  and  $x^{(0)} \in X$ , then  $\pi - \lim_{v \in N} x^{(v)} = x^{(0)}$  if and only if for every  $\alpha \in A$ ,  $\tau_\alpha - \lim_{v \in N} x_\alpha^{(v)} = x_\alpha^{(0)}$ . Recall that  $\pi$  is the coarsest topology making each  $\mu_\alpha$  continuous.
- (iii) If  $X$  is a normed space and  $(f_v)_{v \in N} \subset X^*$ ,  $f_0 \in X^*$ , then  $w^* - \lim_{v \in N} f_v = f_0$  if and only if  $\lim_{v \in N} f_v(x) = f_0(x)$  for each  $x \in X$ .

## 9.2 ROLES OF WEAK AND WEAK\* TOPOLOGIES IN CONVEXITY

We begin with a useful technical lemma:

**9.3 Lemma.** *Let  $X$  be an  $\mathbb{F}$ -vector space and  $f_0, f_1, \dots, f_n \in X'$  with  $\ker f_0 \supseteq \bigcap_{i=1}^n \ker f_i$ . Then  $f_0 \in \text{span}\{f_1, \dots, f_n\}$ .*

**PROOF** Define  $T : X \rightarrow \mathbb{F}^n$  by  $Tx = (f_1(x), \dots, f_n(x))$ . Then  $\ker T = \bigcap_{i=1}^n \ker f_i$ . Let  $\mathcal{R} = \text{im } T \subseteq \mathbb{F}^n$  and  $g_0 \in \mathcal{R}'$  by  $g_0(Tx) = f_0(x)$ . Then  $g_0$  is well-defined: if  $Tx = Ty$ , then  $x - y \in \ker T \subseteq \ker f_0$ , so  $f_0(x - y) = 0$  so  $f_0(x) = f_0(y)$ . Also  $g_0$  is linear. Let  $g \in (\mathbb{F}^n)'$  such that  $g|_{\mathcal{R}} = g_0$ . Hence there are  $\alpha_1, \dots, \alpha_n \in \mathbb{F}$  such that  $g(y_1, \dots, y_n) = \sum_{j=1}^n \alpha_j y_j$ . Hence for  $x \in X$ ,

$$f_0(x) = g_0(Tx) = g(Tx) = g(f_1(x), \dots, f_n(x)) = \sum_{j=1}^n \alpha_j f_j(x)$$

so that  $f_0 = \sum_{j=1}^n \alpha_j f_j$ . ■

We now show that we have an analogue of norm separation with respect to the  $w^*$ -topology:

**9.4 Theorem. ( $w^*$ -Separation)** *Let  $X$  be a normed space,  $A, B \subset X^*$  each be non-empty and convex, with  $A \cap B = \emptyset$  and  $B$   $w^*$ -open. Then there is  $x \in X$  and  $\alpha \in \mathbb{R}$  such that*

$$\text{Re } f(x) \leq \alpha < \text{Re } g(x)$$

for  $f \in A$  and  $g \in B$ .

**PROOF** Since  $w^* \subseteq \tau_{\|\cdot\|}$ , the norm separation theorem gives  $F \in X^{**}$  and  $\alpha \in \mathbb{R}$  such that  $\text{Re } F(f) \leq \alpha < \text{Re } F(g)$  for  $f \in A$ ,  $g \in B$ . It suffices to show that  $F = \hat{x}$  for some  $x \in X$ : assuming this, we have  $\text{Re } f(x) = \text{Re } \hat{x}(f) \leq \alpha < \text{Re } \hat{x}(g) = \text{Re } g(x)$ , which is the desired result.

Fix some  $f_0 \in B$ , and by  $w^*$ -continuity get  $x_1, \dots, x_n$  in  $X$  such that

$$f_0 \in U = \bigcap_{i=1}^n \hat{x}_i^{-1}(V_i) \subseteq B$$

where each  $V_i \subset \mathbb{F}$  is an open neighbourhood of  $f_0(x_i)$ . Let  $Y = \bigcap_{i=1}^n \ker \hat{x}_i \subseteq X^*$ . Then for each  $i = 1, \dots, n$ ,

$$\hat{x}_i(f_0 + Y) = \{f_0(x_i)\} \subset V_i,$$

so that  $f_0 + Y \subseteq U \subseteq B$ . Thus if  $f \in Y$  is arbitrary, then  $f_0 + f \in B$  so that  $\operatorname{Re} F(f_0 + f) > \alpha$ , or equivalently  $\operatorname{Re} F(f) > \alpha - \operatorname{Re} F(f_0) =: c$  where  $c$  is a fixed quantity. But  $Y$  is a vector subspace, and hence closed under scalar multiplication; thus  $\alpha \operatorname{Re} F(f) > c$  for any  $\alpha \in \mathbb{F}$ , forcing  $F(f) = 0$ . Thus  $Y \subseteq \ker F$ , and apply [Lemma 9.3](#) so that  $F \in \operatorname{span}\{\hat{x}_1, \dots, \hat{x}_n\} \subseteq \hat{X}$ . Thus  $F = \hat{x}$  for some  $x \in X$ . ■

**9.5 Theorem. ( $w^*$ -Closed Convex Hull)** If  $S \subset X^*$ , then

$$\overline{\operatorname{co}}^{w^*} S = \cap \{f \in X^* : \operatorname{Re} f(x) \leq \alpha\} \supseteq S : x \in X, \alpha \in \mathbb{R}$$

**PROOF** The set on the right is  $w^*$ -closed and convex being the intersection of such. Conversely, if  $f \in X^* \setminus \overline{\operatorname{co}}^{w^*} S$ , which is open, then there is a basic  $w^*$ -open neighbourhood

$$B = \bigcap_{j=1}^n \hat{x}_j^{-1}(f(x_j) + \mathbb{D}) \subseteq X^* \setminus \overline{\operatorname{co}}^{w^*} S$$

so that  $B \cap \overline{\operatorname{co}}^{w^*} S = \emptyset$ . Also,  $B$  is convex. ■

*Remark.* If  $X$  is a normed space, a closed half space  $H = \{x \in X : \operatorname{Re} f(x) \leq \alpha\}$  for some  $f$  in  $X^*$ ,  $\alpha \in \mathbb{R}$ . Hence,  $H$  is weakly closed  $(\operatorname{Re} f)^{-1}([\alpha, \infty)) = f^{-1}(\{z \in \mathbb{C} : \operatorname{Re} z \geq \alpha\})$  is  $w$ -closed. Thus if  $S \subset X$ , we have  $\overline{\operatorname{co}} S \in w = \sigma(X, X^*) \subseteq \tau_{\|\cdot\|}$ , so  $\overline{\operatorname{co}} S$  is automatically weakly closed. Hence if  $C \subseteq X$  is convex, then  $C$  is norm closed if and only if  $C$  is  $w$ -closed.

**Definition.** Let  $X$  be a normed space. If  $E \subseteq X$  (non-empty), the **polar** of  $E$  is given by

$$\begin{aligned} E^\circ &= \{f \in X^* : \operatorname{Re} f(x) \leq 1 \text{ for all } x \text{ in } E\} \subseteq X^* \\ &= \bigcap_{x \in E} \{f \in X^* : \operatorname{Re} \hat{x}(f) \leq 1\} \end{aligned}$$

so  $E^\circ$  is convex and  $w^*$ -closed in  $X^*$ , and  $0 \in E^\circ$ .

If  $F \subseteq X^*$  (non-empty), let the **pre-polar** of  $F$  be given by

$$F_\circ = \{x \in X : \operatorname{Re} f(x) \leq 1 \text{ for all } f \text{ in } F\}$$

so, like above,  $F_\circ$  is convex,  $(w-)$ closed, and  $0 \in F_\circ$ .

**9.6 Theorem. (Bipolar)** (i) If  $\emptyset \neq E \subseteq X$ , then  $(E^\circ)_\circ = \overline{\operatorname{co}}(E \cup \{0\})$ .

(ii) If  $\emptyset \neq F \subseteq X^*$ , then  $(F_\circ)^\circ = \overline{\operatorname{co}}^{w^*}(F \cup \{0\})$ .

**PROOF** (i) Note that  $E \cup \{0\} \subseteq (E^\circ)_\circ$ , so  $\overline{\operatorname{co}}(E \cup \{0\}) \subseteq (E^\circ)_\circ$ . If  $x_0 \in X \setminus \overline{\operatorname{co}}(E \cup \{0\})$ , then the separation theorem provides  $f \in X^*$ ,  $\alpha \in \mathbb{R}$  so  $\operatorname{Re} f(x_0) > \alpha \geq \operatorname{Re} f(x)$  for  $x \in E \cup \{0\}$ . Notice that  $\alpha \geq \operatorname{Re} f(0) = 0$ , and we let  $\beta = \frac{1}{2}[\operatorname{Re} f(x_0) + \alpha] > 0$ , so  $\operatorname{Re} f(x_0) > \beta \geq \operatorname{Re} f(x)$  for  $x \in E \cup \{0\}$ ,  $\beta > 0$ . Let  $g = \frac{1}{\beta}f$  and we see that  $g \in E^\circ$  and as  $\operatorname{Re} g(x_0) > 1$ ,  $x_0 \notin (E^\circ)_\circ$ .

(ii) Similar, use  $w^*$ -separation. ■

*Remark.* Let  $Y \subseteq X$  be a subspace. If  $f \in Y^\circ$ , then  $\operatorname{Re} f(y) \leq 1$  for  $y \in Y$  implies that  $f(y) = 0$  for all  $y \in Y$ . We write  $Y^a = Y^\circ$ , and  $Y^a = \{f \in X^* : f|_Y = 0\}$  is called the **annihilator** of  $Y$ . Likewise, if  $Z \subseteq X^*$  is a subspace, then  $Z_a = Z_\circ$  where  $Z_a = \{x \in X : f(x) = 0 \text{ for each } f \in Z\}$  is called the **pre-annihilator**. Notice that  $Y^a$  and  $Z_a$  are subspaces.

**9.7 Corollary.** (i) If  $Y \subseteq X$  is a subspace, then  $(Y^a)_a = \overline{Y}$ .

(ii) If  $Z \subseteq X^*$  is a subspace, then  $(Z_a)^a = \overline{Z}^{w^*}$ .

**9.8 Lemma.** If  $X$  is a normed space, then  $B(X)^0 = B(X^*)$  and  $B(X^*)_0 = B(X)$ .

**PROOF** If  $f \in B(X)^0$ , then  $\operatorname{Re} f(x) \leq 1$  for  $x \in B(X)$ . Thus for  $x \in B(X)$ ,  $|f(x)| = \operatorname{sgn} f(x) f(x) = f(\operatorname{sgn} f(x)x) \leq 1$ , so  $\|f\| \leq 1$  and  $f \in B(X^*)$ . Conversely, if  $f \in B(X^*)$ ,  $x \in B(X)$ , then  $\operatorname{Re} f(x) \leq |f(x)| \leq 1$  so  $f \in B(X)^0$ . Then use the Bipolar theorem. ■

**9.9 Theorem. (Goldstine)** If  $X$  is a normed space, then  $\overline{B(\hat{X})}^{w^*} = B(X^{**})$ . Note that  $w^* = \sigma(X^{**}, \hat{X}^*)$ .

**PROOF** The Bipolar theorem provides  $\overline{B(\hat{X})}^{w^*} = \overline{B(\hat{X})}^{w^*} = (B(\hat{X})_0)^\circ$ . But, in  $X^*$ ,

$$\begin{aligned} B(X)^\circ &= \{f \in X^* : \operatorname{Re} f(x) \leq 1 \text{ for } x \in B(X)\} \\ &= \{f \in \hat{X}^* : \operatorname{Re} \hat{x}(f) \leq 1 \text{ for } x \in B(X)\} \\ &= B(\hat{X})_0 \end{aligned}$$

Hence we have, using the lemma,

$$\overline{B(\hat{X})}^{w^*} = (B(\hat{X})_0)^\circ = (B(X)^\circ)^\circ = B(X^*)^\circ = B(X^{**})$$

**Example.** (i) Recall that  $c_0^* \cong \ell_1$  and  $\ell_1^* \cong \ell_\infty$ , where  $c_0 \subseteq \ell_\infty$ . Thus by Goldstine,  $\overline{B(c_0)}^{w^*} = B(\ell_\infty)$ , so  $w^* = \sigma(\ell_\infty, \ell_1)$ . Since  $\ell_1$  is separable, we have that  $(B(\ell_\infty), w^*)$  is metrizable. In fact, if  $x \in \ell_\infty$ , then if  $x^{(n)} = (x_1, \dots, x_n, 0, 0, \dots) \in c_0$ , we have  $x = w^* - \lim_{n \rightarrow \infty} x^{(n)}$ .

(ii)  $\ell_\infty^* \cong \operatorname{FA}(\mathbb{N})$ . But  $B(\operatorname{FA}(\mathbb{N}), w^*)$  is not metrizable. Since  $\ell_1^* \cong \ell_\infty$ , there is a natural isometric embedding  $\ell_1 \hookrightarrow \operatorname{FA}(\mathbb{N})$ . Then  $y^{(n)} = \frac{1}{n}(1, 1, \dots) \in B(\ell_1)$ , and  $w^*$ -cluster point of  $(y^{(n)})_{n=1}^\infty \subset B(\operatorname{FA}(\mathbb{N}))$  is a Banach limit.

**9.10 Corollary.** If  $F \in X^{**}$ , there always exists a net  $(x_\nu)_{\nu \in N} \subset X$  such that

$$F = w^* - \lim_{\nu \in N} \hat{x}_\nu \text{ and } \|x_\nu\| \leq \|F\|$$

**PROOF** If  $F \neq 0$ ,  $\frac{1}{\|F\|}F \in B(X^{**}) = \overline{B(\hat{X})}^{w^*}$ , and we may find  $(y_\nu)_{\nu \in N} \subset B(X)$  such that  $(\hat{y}_\nu)_{\nu \in N} \subset B(\hat{X})$  and  $\frac{1}{\|F\|}F = w^* - \lim_{\nu \in N} \hat{y}_\nu$ . Let  $x_\nu = \|F\|y_\nu$ . ■

Consider  $\mathcal{F} = w^*_{\frac{1}{\|F\|}F} = \{U \in w^*|_{B(X^{**})} : F \in U\}$  is a filtering family. Each  $U \in w^*_{\frac{1}{\|F\|}F}$  has  $U \cap B(\hat{X}) \neq \emptyset$  by Goldstine. Let  $N_{\mathcal{F}} = \{(x, U) : x \in B(X), \hat{x} \in U, U \in \mathcal{F}\}$ . Then  $(x_\nu)_{\nu \in N_{\mathcal{F}}} = (x)_{(x, U) \in N_{\mathcal{F}}}$  works.

**Definition.** A normed space  $X$  is **reflexive** if  $\hat{X} = X^{**}$ .

Notice that  $X^{**} = (X^*)^*$  is complete, and  $x \mapsto \hat{x}$  is an isometry, so a reflexive space is always complete.

**9.11 Theorem.** Let  $X$  be a Banach space. The following are equivalent:

- (i)  $X$  is reflexive
- (ii)  $B(X)$  is  $w$ -compact
- (iii)  $w^* = w$  on  $X^*$
- (iv)  $X^*$  is reflexive.

PROOF The map  $\iota : x \mapsto \hat{x}$  is a  $w - w^*|_{\hat{X}}$ -homeomorphism. Recall  $w^* = \sigma(X^{**}, \hat{X}^*)$ , and  $w^*|_{\hat{X}} = \sigma(\hat{X}, (\hat{X}^*)^*|_{\hat{X}})$  and we have for  $x_0 \in X$ , net  $(x_\nu)_{\nu \in N}$  in  $X$ ,

$$\begin{aligned} w - \lim_{\nu \in N} x_\nu = x_0 &\iff \lim_{\nu \in N} f(x_\nu) = f(x_0) \forall f \in X^* \\ &\iff \lim_{\nu \in N} \hat{x}_\nu(f) = \hat{x}_0(f) \forall f \in X^* \\ &\iff \lim_{\nu \in N} \hat{f}(\hat{x}_\nu) = \hat{f}(\hat{x}_0) \end{aligned}$$

and having the same convergent nets means that the topologies are the same.

(i  $\Rightarrow$  ii) By assumption,  $\widehat{B(X)} = B(\hat{X}) = B(X^{**})$ . Since  $B(X^{**})$  is  $w^*$ -compact, and hence  $\iota^{-1}(B(X^{**})) = B(X)$  is  $w$ -compact

(ii  $\Rightarrow$  i) If  $B(X)$  is  $w$ -compact, then since  $x \mapsto \hat{x} : X \rightarrow X^{**}$  is continuous, we see that  $B(\hat{X}) = \widehat{B(X)}$  is  $w^*$ -compact.

(i  $\Rightarrow$  iii) We have  $\hat{X} = X^{**}$  so on  $X^*$ , we have  $w = \sigma(X^*, X^{**}) = \sigma(X^*, \hat{X}) = w^*$ .

(iii  $\Rightarrow$  iv)  $B(X^*)$  is compact, hence  $w$ -compact, so by (ii) implies (i) applied to  $X^*$ , we have that  $X^*$  is reflexive.

(iv  $\Rightarrow$  i) We assume  $\widehat{X^*} = X^{***}$ . Thus on  $X^{***}$ , we have  $w = \sigma(X^{**}, X^{***}) = \sigma(X^{**}, \widehat{X^*}) = w^*$ . Now  $B(\hat{X}) = B(X^{**}) \cap \hat{X}$  is norm-closed and convex, hence  $w$ -closed, by Closed Convex Hull theorem. Thus from above,  $B(\hat{X})$  is  $w^*$ -closed, so  $B(\hat{X}) = \overline{B(\hat{X})}^{w^*} = B(X^{**})$  by Goldstine, so  $\hat{X} = X^{**}$ . ■

**9.12 Corollary.** (i) Any finite dimensional normed space is reflexive.

(ii) Any closed subspace  $Y$  of a normed space  $X$  is reflexive.

PROOF (i) A finite dimensional normed space is complete, and its closed ball is compact, and thus  $w$ -compact as  $\tau_{\|\cdot\|} \supseteq w$ .

(ii) By Hahn-Banach,  $Y^* = X^*|_Y$ , so  $\sigma(Y, Y^*) = \sigma(Y, X^*|_Y) = \sigma(X, X^*)|_Y$ . Now  $B(Y) = B(X) \cap Y$  is norm-closed and convex, hence  $w$ -closed in  $B(X)$ . But  $B(X)$  is  $w$ -compact, so  $B(Y)$  is a  $w$ -closed subset of a  $w$ -compact space and thus  $w$ -compact. ■

### 9.3 EXTREME POINTS AND THE KREIN-MILMAN THEOREM

**Definition.** Let  $X$  be a vector space and  $C \subset X$  convex. A **face**  $F$  of  $C$  is any non-empty subset such that if  $x \in F$ ,  $x = (1-t)y + tz$ ,  $t \in (0, 1)$ ,  $y, z \in C$  implies that  $y, z \in F$ . A **extreme point** of  $C$  is a singleton face, i.e.  $\text{ext } C = \{x \in C : \{x\} \text{ is a face of } C\}$ . Hence  $x \in \text{ext } C$  if for any  $t \in (0, 1)$  and  $y, z \in C$ , if  $x = (1-t)y + tz$  then  $x = y = z$ .

*Remark.* (i) Faces of  $C$  are not necessarily convex.

(ii) A face  $F'$  of a convex face  $F$  of  $C$  is itself a face of  $C$ .

(iii)  $\text{ext } F \subseteq \text{ext } C$ .

(iv) If  $f \in X'$  and  $\text{Re } f(C) = [a, b]$ , then  $(\text{Re } f)^{-1}(\{b\})$  is itself a face of  $C$ .

**9.13 Theorem. (Krein-Milman)** Let  $X$  be a normed space and  $C \subset X^*$  convex and  $w^*$ -compact. Then  $C = \overline{\text{co}}^{w^*} \text{ext } C$ .

**PROOF** We first verify that any  $w^*$ -closed face of  $C$  admits an extreme point. We let  $\mathcal{F} = \{F : F \text{ is a convex } w^*\text{-closed face of } C\}$ , which is partially ordered by reverse inclusion. If  $\mathcal{C}$  is a chain in  $\mathcal{F}$  with  $F_1, \dots, F_n \in \mathcal{C}$ , we may assume  $F_1 \supseteq \dots \supseteq F_n$  so that  $\mathcal{C}$  has the finite intersection property. Thus  $\emptyset \neq F_0 = \bigcap_{F \in \mathcal{C}} F$ . If  $x \in F_0$ ,  $t \in (0, 1)$ ,  $y, z \in C$  and  $x = (1 - t)y + tz$ , then  $x \in F$  for any  $F \in \mathcal{C}$  so  $y, z \in F$  for any  $F \in \mathcal{C}$ . Thus  $y, z \in \bigcap_{F \in \mathcal{C}} F = F_0$ . Also  $F_0$  is closed, so  $F_0 \in \mathcal{F}$ . Thus  $F_0$  is an upper bound in  $\mathcal{F}$  for  $\mathcal{C}$ , so by Zorn, get some maximal element  $M$ .

Let  $M$  be a minimal  $w^*$ -closed convex face of  $F$ . Then given  $x \in X$ ,  $\text{Re } \hat{x} : X^* \rightarrow \mathbb{R}$  is  $w^*$ -continuous, and hence  $\text{Re } \hat{x}(M) = [a_x, b_x]$  since the only compact convex subsets of  $\mathbb{R}$  are compact intervals. But then  $F_x = (\text{Re } \hat{x})^{-1}(\{b_x\}) \cap M$  is a  $w^*$ -closed convex face in  $M$ , so that  $F_x = M$ . If  $f, g \in M$ , then  $\text{Re } f(x) = \text{Re } \hat{x}(f) = b_x = \text{Re } \hat{x}(g) = \text{Re } g(x)$ , so  $f = g$  and hence  $M = \{f\}$  and  $f \in \text{ext } F$ .

Now let  $f_0 \in X^* \setminus \overline{\text{co}}^{w^*} \text{ext } C$ . Since  $C$  is  $w^*$ -compact and convex,  $\text{Re } \hat{x}(C) = [a_x, b_x]$ , so  $C_x = (\text{Re } \hat{x})^{-1}(\{b_x\}) \cap C$  is a  $w^*$ -closed convex face of  $C$ . Hence by above, there is  $f \in \text{ext } C_x \subseteq \text{ext } C$  with  $\text{Re } \hat{x}(f) = b_x$ . But then  $\text{Re } \hat{x}(f_0) > a_x \geq \text{Re } \hat{x}(f) = b_x$ , so  $\text{Re } \hat{x}(f_0) \notin [a_x, b_x] = \text{Re } \hat{x}(C)$ , so  $f_0 \notin C$ . Thus  $C \subseteq \overline{\text{co}}^{w^*} \text{ext } C$ , where the converse inclusion is obvious. ■

**9.14 Corollary.** (i) If  $C \subset X$  is a  $w$ -compact convex set, then  $C = \overline{\text{co}} \text{ext } C$ .

(ii) If  $C \subset X$  is a norm-compact convex set, then  $C = \overline{\text{co}} \text{ext } C$ .

**PROOF** (i) We have that  $x \mapsto \hat{x} : X \rightarrow \hat{X} \subseteq X^{**}$  is continuous. Hence  $\hat{C}$  is  $w^*$ -compact in  $X^{**}$ , so  $x \mapsto \hat{x} : C \rightarrow \hat{C}$  is a homeomorphism. In  $\hat{C}$ , we have

$$\widehat{\overline{\text{co}}^{w^*} \text{ext } C} = \overline{\text{co}}^{w^*} \text{ext } \hat{C} = \hat{C}$$

so that  $C = \overline{\text{co}}^w \text{ext } C = \overline{\text{co}} \text{ext } C$  by the closed convex hull theorem.

(ii) Since  $w \subseteq \tau_{\|\cdot\|}$ , any norm-compact is  $w$ -compact. ■

**Remark.** Let  $X$  be a normed space. Then  $\text{ext } B(X) \subseteq S(X)$ .

**9.15 Proposition.** Let  $1 < p < \infty$ . Then  $\text{ext } B(\ell_p) = S(\ell_p)$ .

**PROOF** Let  $x \in S(\ell_p)$ , so  $x = (1 - t)y + tz$ . Then

$$1 = \|x\|_p \leq (1 - t)\|y\|_p + t\|z\|_p \leq 1$$

so that  $\|y\|_p = \|z\|_p = 1$  and  $\|x\|_p = (1 - t)\|y\|_p + t\|z\|_p$ . Thus by the equality case for Minkowski, there is  $s \geq 0$  so  $s(1 - t)y = tz$ . Taking norms, we have  $y = z$ . ■

**9.16 Proposition.** We have  $\text{ext } B(c_0) = \emptyset$ .

**PROOF** Let  $x = (x_1, x_2, \dots) \in B(c_0)$ . Since  $\lim x_n = 0$ , get  $n_0$  so  $|x_{n_0}| \leq 1/2$ . If  $x_{n_0} \neq 0$ , let  $y = (x_1, \dots, x_{n_0-1}, 2x_{n_0}, x_{n_0+1}, \dots)$  and  $z = (x_1, \dots, x_{n_0-1}, 0, x_{n_0+1}, \dots)$ , and similarly for  $x_{n_0} = 0$ . Thus we have in each case that  $y, z \in B(c_0)$  and  $x = y/2 + z/2$ . ■

**9.17 Corollary.** There exists no normed space  $X$  for which  $c_0 \cong X^*$ .

PROOF If there were such  $X$ , then  $B(c_0)$  would be  $w^*$ -compact, and hence Krein-Milman would imply  $\text{ext } B(c_0) \neq \emptyset$ . ■

**Definition.** Let  $(X, \tau)$  be a compact Hausdorff space, and let

$$P(X) = \{\mu \in B(C^{\mathbb{R}}(X, \tau)^*) : \mu(1) = 1\}$$

**9.18 Theorem.**  $\text{ext } P(X) = \{\hat{x} : x \in X\}$ , where  $\hat{x}(f) = f(x)$ . Furthermore,  $\overline{\text{co}}^{w^*} \text{ext } P(X) = P(X)$ .

PROOF Write  $C = C^{\mathbb{R}}(X, \tau)$ . Note that  $P(X) = B(C^*) \cap \hat{\mathbf{1}}^{-1}(\{1\})$  is  $w^*$ -compact and convex. Hence by Krein-Milman, we have that  $\overline{\text{co}}^{w^*} \text{ext } P(X) = P(X)$ . It remains to describe  $\text{ext } P(X)$ .

(I) Some inequalities. Fix  $\mu \in P(X)$ . If  $0 \leq f \leq 1$  in  $C$ , then  $0 \leq 1 - f \leq 1$  so  $\|f\|_{\infty}, \|1 - f\|_{\infty} \leq 1$ . Thus  $|\mu(f)| \leq 1$  and  $|1 - \mu(f)| = |\mu(1 - f)| \leq 1$ . Thus  $0 \leq \mu(f) \leq 1$ . Then if  $g \neq 0$  and  $g \geq 0$  in  $C$ , then we have  $\mu(g/\|g\|_{\infty}) \geq 0$ , so  $\mu(g) > 0$ ; if  $g \leq h$  in  $C$ , then  $h - g \geq 0$  and  $\mu(h) \geq \mu(g)$ .

If  $g \in C$ ,  $g^+ = \max\{g, 0\}$ ,  $g^- = \max\{-g, 0\} \in C$ , and  $g = g^+ - g^-$  while  $|g| = g^+ + g^-$ . Hence if  $0 \leq f \leq 1$  in  $C$  and let  $\mu_f(g) = \mu(fg)$  for  $g \in C$ , we have

$$\begin{aligned} |\mu_f(g)| &= |\mu_f(g^+ - g^-)| = |\mu(fg^+) - \mu(fg^-)| \leq \mu(fg^+) + \mu(fg^-) = \mu(fg) \\ &\leq \mu(f\|g\|_{\infty}) = \mu(f)\|g\|_{\infty} \end{aligned} \quad (9.1)$$

and, with  $f = 1$ , we have

$$|\mu(g)| \leq \mu(|g|) \quad (9.2)$$

(II) Let  $\delta \in \text{ext } P(X)$ . We first show for  $h, g$  in  $C$  that  $\delta(hg) = \delta(h)\delta(g)$ . To see this, since  $\delta \neq 0$ , we may find  $0 \leq f \leq 1$  such that  $0 < \delta(f) < 1$ . Now let  $\mu = \frac{1}{\delta(f)}\delta_f$  so, for  $g \in C$ , (9.1) provides

$$|\mu(g)| = \frac{1}{\delta(f)}|\delta_f(g)| \leq \frac{1}{\delta(f)}\delta(f)\|g\|_{\infty} = \|g\|_{\infty}$$

so that  $\mu \in B(C^*)$ . We also know that  $\mu(1) = 1$ . Hence  $\mu \in P(X)$ . Likewise,  $\nu = \frac{1}{1-\delta(f)}\delta_{1-f} \in P(X)$ . We have that

$$\delta(f)\mu + (1 - \delta(f))\nu = \delta$$

so by assumption on  $\delta$ ,  $\mu = \delta$ . Thus  $\frac{1}{\delta(f)}\delta(fg) = \mu(g) = \delta(g)$ , so that  $\delta(fg) = \delta(f)\delta(g)$ . Note that  $C = \text{span}\{f \in C : 0 \leq f \leq 1\}$ , so we get multiplicativity of  $\delta$ .

Suppose now for each  $x \in X$ , there exists some  $f_x \in \ker \delta$  so that  $f_x(x) \neq 0$ . Let  $U_x = f_x^{-1}(\mathbb{R} \setminus \{0\})$ , so  $X = \bigcup_{x \in X} \{x\} = \bigcup_{x \in X} U_x$  so there are  $x_1, \dots, x_n$  in  $X$  so  $X = \bigcup_{j=1}^n U_{x_j}$ . Then  $f = \sum_{j=1}^n f_{x_j}^2 > 0$  on  $X$  (by definition of each  $U_{x_j}$ ), so  $1/f \in C$ . Then

$$1 = \delta(1) = \delta\left(\frac{1}{f}\right)\delta(f) = \delta\left(\frac{1}{f}\right)\sum_{j=1}^n \delta(f_{x_j})^2 = 0$$

since each  $f_{x_j} \in \ker \delta$ , which is absurd. Hence there is  $x \in X$  so  $f(x) = 0$  whenever  $f \in \ker \delta$ , so  $\ker \delta \supseteq \ker \hat{x}$ , so  $\delta \in \mathbb{R}\hat{x}$  and since  $\delta(1) = 1 = \hat{x}(1)$ , so  $\delta = \hat{x}$ .

(III) If  $\hat{x} = (1 - t)\mu + t\nu$  and  $t \in (0, 1)$ ,  $\mu, \nu \in P(X)$ , then by (9.2),

$$t|\nu(f)| \leq t\nu(|f|) \leq \hat{x}(|f|) = |f(x)|$$

so  $\ker \nu \supseteq \ker \hat{x}$  and as above,  $\nu = \hat{x}$ . Then  $\mu = \hat{x}$ . ■



*Remark.* For  $\mathbb{F} = \mathbb{R}$  or  $\mathbb{F} = \mathbb{C}$ , it is similar to show that  $\text{ext } B(C^{\mathbb{F}}(X, \tau)^*) = \{z\hat{x} : z \in \mathbb{F}, |z| = 1, x \in X^*\}$ .

Let  $PA(\mathbb{N}) = \{\mu \in \text{FA}(\mathbb{N}) : \|\mu\|_{\text{var}} \leq 1, \mu(\mathbb{N}) = 1\}$  so, as above,  $PA(\mathbb{N})$  is a  $w^* = \sigma(\text{FA}(\mathbb{N}), \ell_{\infty})$ -compact set.

**9.19 Proposition.**  $\text{ext } PA(\mathbb{N}) = \{\delta_{\mathcal{U}} : \mathcal{U} \text{ is an ultrafilter on } \mathbb{N}\}$

**PROOF** If  $\delta \in \text{ext } PA(\mathbb{N})$ , let  $f_{\delta} \in \ell_{\infty}^*$  be as in A1. As above, we compute that  $f_{\delta}(\chi_E \chi_F) = f_{\delta}(\chi_E) f_{\delta}(\chi_F)$ , and we have  $\chi_E \chi_F = \chi_{E \cap F}$  and hence  $\delta(E \cap F) = \delta(E) \delta(F)$ . Hence

$$\mathcal{U} = \{E \subseteq \mathbb{N} : \delta(E) \neq 0\} = \{E \subseteq \mathbb{N} : \delta(E) = 1\}$$

is an ultrafilter. The converse is easy. ■

## 10 EUCLIDEAN AND HILBERT SPACES

**Definition.** Let  $X$  be a vector space over  $\mathbb{F}$  ( $\mathbb{R}$  or  $\mathbb{C}$ ). A form  $[\cdot, \cdot] : X \rightarrow \mathbb{F}$  is called **Hermitian** if for  $x, x', y$  in  $X$ ,  $\alpha \in \mathbb{F}$ , we have

- (i)  $[x + \alpha x', y] = [x, y] + \alpha [x', y]$
- (ii)  $\overline{[y, x]} = [x, y]$

and furthermore **positive** if

- 3.  $[x, x] \geq 0$  for all  $x \in X$

and **non-degenerate** if

- 4.  $[x, y] = 0$  for all  $y \in X$  implies  $x = 0$ .

**10.1 Proposition.** Let  $[\cdot, \cdot]$  be a positive Hermitian form. Let  $p(x) = [x, x]^{1/2}$ , so  $p : X \rightarrow [0, \infty)$ . Then for  $x, y \in X$  and  $\alpha \in \mathbb{F}$ , we have

- (i)  $p(\alpha x) = |\alpha| p(x)$
- (ii)  $[x, y] \leq p(x) p(y)$
- (iii)  $p(x + y) \leq p(x) + p(y)$
- (iv)  $[\cdot, \cdot]$  is non-degenerate if and only if  $[x, x] > 0$  for  $x \in X \setminus \{0\}$ .

Furthermore, in this case, we have

- Equality in (ii) if and only if  $x, y$  are linearly dependent
- $[x, y] = p(x) p(y)$  if and only if there is  $s \geq 0$  such that  $x = sy$  or  $y = sx$  if and only if equality holds in (iii).

**PROOF** (i)  $p(\alpha x) = (\alpha \bar{\alpha} [x, x])^{1/2} = |\alpha| p(x)$

(ii) If  $\alpha \in \mathbb{F}$ , then

$$\begin{aligned} 0 \leq [x - \alpha y, x - \alpha y] &= [x, x] - \bar{\alpha} [x, y] - \overline{\bar{\alpha} [x, y]} + |\alpha|^2 [y, y] \\ &= p(x)^2 - 2 \text{Re } \bar{\alpha} [x, y] + |\alpha| p(y)^2 \end{aligned}$$

Set  $\alpha = \text{sgn } [x, y]$  so that  $\bar{\alpha} [x, y] = |[x, y]|$  so

$$|[x, y]| \leq \frac{1}{2} (p(x)^2 + p(y)^2)$$

Then if  $t > 0$ , by (i),

$$|[x, y]| = \left| \left[ tx, \frac{1}{t}y \right] \right| \leq \frac{1}{2}(t^2 p(x)^2 + \frac{1}{t^2} p(y)^2)$$

If  $p(x) = 0$ , we let  $t \rightarrow \infty$  so that  $[x, y] = 0$ ; if  $p(y) = 0$ , we let  $t \rightarrow 0^+$  and again that  $[x, y] = 0$ . If  $[x, y] \neq 0$ , set  $t = p(y)/p(x)$  and we are done.

(iii)

$$\begin{aligned} p(x+y)^2 &= [x+y, x+y] = p(x)^2 + 2\operatorname{Re}[x, y] + p(y)^2 \\ &\leq p(x)^2 + 2|[x, y]| + p(y)^2 \\ &\leq p(x)^2 + 2p(x)p(y) + p(y)^2 = (p(x) + p(y))^2 \end{aligned}$$

(iv) We see, by (iii), if  $p(x)^2 = [x, x] = 0$ , then  $[x, y] = 0$  for all  $y$ . Hence  $[\cdot, \cdot]$  is non-degenerate if and only if  $[x, x] > 0$  for  $x \in X \setminus \{0\}$ . If  $x, y$  are linearly dependant, then equality holds in (ii) by direct computation. If  $x, y$  are not linearly dependent, then the choice of  $\alpha = \operatorname{sgn}[x, y]$  in (ii) gives strict inequality. The condition  $[x, y] = p(x)p(y)$  requires non-negativity of  $[x, y]$ , showing one is a  $R_{\geq 0}$  multiple of the other. This is equivalent to having equality in (iii). ■

**Definition.** A non-degenerate positive Hermitian form on a vector space  $\mathcal{E}$  is called an **inner product**. The pair  $(\mathcal{E}, (\cdot, \cdot))$  is called a Euclidean space. If, further,  $\mathcal{E}$  is complete with respect to the induced norm  $\|x\| = (x, x)^{1/2}$ , then we call  $(\mathcal{E}, (\cdot, \cdot))$  a **Hilbert space**.

*Example.* (i) (Euclidean Space)  $(C[0, 1], \langle \cdot, \cdot \rangle)$  given by  $(f, g) = \int_0^1 f \bar{g}$

(ii) (Euclidean Space) Recall  $\ell = \{x \in \mathbb{F}^{\mathbb{N}} : x_n = 0 \text{ for all but finitely many } n\}$ , and  $(\ell, \langle \cdot, \cdot \rangle)$  with  $\langle x, y \rangle = \sum_{j=1}^{\infty} x_j \bar{y}_j$

(iii) (Hilbert Space)  $(L_2[0, 1], (\cdot, \cdot))$ ,  $(f, g) = \int_{[0, 1]} f \bar{g}$ .

(iv) (Hilbert Space)  $(\ell_2, (\cdot, \cdot))$ ,  $(x, y) = \sum_{j=1}^{\infty} x_j \bar{y}_j$  (convergence by Hölder's inequality)

(v) (Non-separable Hilbert Space) Let  $\Gamma$  be an uncountable set. If  $a = (a_\gamma)_{\gamma \in \Gamma} \in [0, \infty)^\Gamma$ , we let  $\mathcal{F} = \{F \subset \Gamma : |F| < \infty\}$ . We define  $\sum_{\gamma \in \Gamma} a_\gamma = \sup_{F \in \mathcal{F}} \sum_{\gamma \in F} a_\gamma = \lim_{F \in \mathcal{F}} \sum_{\gamma \in F} a_\gamma$  where  $\mathcal{F}$  is pre-ordered by inclusion. Suppose that  $\sum_{\gamma \in \Gamma} a_\gamma < \infty$ . Let  $\Gamma_n = \{\gamma \in \Gamma : a_\gamma \geq 1/n\}$  and we have

$$\infty > \sum_{\gamma \in \Gamma} a_\gamma \geq \sup_{F \in \mathcal{F}} \sum_{\gamma \in F \cap \Gamma_n} a_\gamma \geq \sum_{F \in \mathcal{F}} \frac{|F \cap \Gamma_n|}{n}$$

so that  $|\Gamma_n| < \infty$ . Thus  $\Gamma_a = \{\gamma \in \Gamma : a_\gamma > 0\} = \bigcup_{n=1}^{\infty} \Gamma_n$  is countable.

Now, define  $\ell_2(\Gamma) = \{x = (x_\gamma) \in \mathbb{F}^\Gamma : \sum_{\gamma \in \Gamma} |x_\gamma|^2 < \infty\}$ . If  $x, y \in \ell_2(\Gamma)$ , then we may let  $\Gamma_{|x|^2} \cup \Gamma_{|y|^2} \subseteq \{\gamma_k\}_{k=1}^{\infty}$  so Hölder's inequality for  $\ell_2$  says that

$$\sum_{k=1}^{\infty} |x_{\gamma_k} \bar{y}_{\gamma_k}| \leq \left( \sum_{k=1}^{\infty} |x_{\gamma_k}|^2 \right)^{1/2} \left( \sum_{k=1}^{\infty} |y_{\gamma_k}|^2 \right)^{1/2} < \infty.$$

Thus,  $\sum_{k=1}^{\infty} x_{\gamma_k} \overline{y_{\gamma_k}}$  is absolutely converging. Write  $(x, y) = \sum_{\gamma \in \Gamma} x_{\gamma} \overline{y_{\gamma}} = \sum_{k=1}^{\infty} x_{\gamma_k} \overline{y_{\gamma_k}}$ . Now if  $(x^{(n)})_{n=1}^{\infty} \subset \ell_2(\Gamma)$  is  $\|\cdot\|_2$ -Cauchy, then  $\Gamma' = \bigcup_{n=1}^{\infty} \Gamma_{|x^{(n)}|^2}$  is countable. Then since  $\ell_2(\Gamma') \cong \ell_2$  (up to counting  $\Gamma'$ ), so the Cauchy sequence has a limit. Thus  $\ell_2(\Gamma)$  is a Hilbert space. It is immediate that  $(\ell_2(\Gamma), \|\cdot\|_2)$  is non-separable.

- (vi) Let  $w : \mathbb{N} \rightarrow (0, \infty)$ . Let  $\ell_2^w = \{x \in \mathbb{F}^{\mathbb{N}} : \sum_{k=1}^{\infty} |x_k|^2 w(k) < \infty\}$ . Notice that if  $x, y \in \ell_2^w$ , then  $(x_k w(k)^{1/2})_{k=1}^{\infty}, (y_k w(k)^{1/2})_{k=1}^{\infty} \in \ell_2$ , so it follows that

$$(x, y)_w = \sum_{k=1}^{\infty} x_k \overline{y_k} w(k)$$

defines an inner product, and  $W : \ell_2^w \rightarrow \ell_2$  by  $W(x_k)_{k=1}^{\infty} = (x_k w(k)^{1/2})_{k=1}^{\infty}$  is a surjective linear isometry, so  $\ell_2^w$  is a hilbert space.

### 10.1 VARIOUS IDENTITIES

Let  $[\cdot, \cdot]$  be a Hermitian form on  $X$ . Then we have the *polarization identity*: then over  $\mathbb{R}$ ,  $4[x, y] = [x + y, x + y] - [x - y, x - y]$ , and over  $\mathbb{C}$ ,  $4[x, y] = \sum_{k=0}^3 i^k [x + i^k y, x + i^k y]$ .

Now suppose  $(\mathcal{E}, (\cdot, \cdot))$  is a Euclidean space. We say that  $x, y \in \mathcal{E}$  are **orthogonal** if  $(x, y) = 0$  and write  $x \perp y$ . We call a subset  $E \subset \mathcal{E}$  **orthogonal** if  $x \neq y \in E$  implies  $x \perp y$ . We write  $x \perp E$  if  $x \perp y$  for each  $y \in E$ . We have

- *Pythagoreans' identity*: if  $\{x_1, \dots, x_n\} \subset \mathcal{E}$  orthogonal, then  $\left\| \sum_{j=1}^n x_j \right\|^2 = \sum_{j=1}^n \|x_j\|^2$ .
- *Parallelogram law*:  $\|x + y\|^2 + \|x - y\|^2 = 2\|x\|^2 + 2\|y\|^2$ .

Note that if  $\mathbb{F} = \mathbb{C}$ ,  $(x, y) = \frac{1}{4} \sum_{k=0}^3 i^k \|x + i^k y\|^2$  defines an inner product, for any norm satisfying the parallelogram law.

**10.2 Proposition.** If  $y \in \mathcal{E}$  with  $(\mathcal{E}, (\cdot, \cdot))$  a Euclidean space, then  $f_y : \mathcal{E} \rightarrow \mathbb{F}$  by  $f_y(x) = (x, y)$  is linear with  $\|f_y\| = \|y\|$ . Furthermore,  $|f_y(x)| = \|y\|$  for  $y \neq 0$ ,  $x \in B(\mathcal{E})$  if and only if  $x = \frac{\zeta}{\|y\|} y$  where  $|\zeta| = 1$ .

**PROOF** Linearity is from an assumption on  $(\cdot, \cdot)$ . Furthermore, Cauchy-Schwarz tells us that

$$|f_y(x)| = |(x, y)| \leq \|x\| \|y\| \Rightarrow \|f_y\| \leq \|y\|$$

so the equality case for Cauchy-Schwarz provides the last statement of the proposition, and supplies  $\|f_y\| \geq \|y\|$ . ■

**Definition.** In a Euclidean space  $(\mathcal{E}, (\cdot, \cdot))$ , a set  $E \subset \mathcal{E}$  is called **orthonormal** provided that for  $e, e' \in E$ ,

$$(e, e') = \begin{cases} 1 & : e = e' \\ 0 & : e \neq e' \end{cases}$$

**10.3 Lemma. (Closest Approximation to Finite)** Let  $\{e_1, \dots, e_n\}$  be orthonormal in a Euclidean space  $(\mathcal{E}, (\cdot, \cdot))$  and  $\mathcal{M} = \text{span}\{e_1, \dots, e_n\}$ . Then for  $x \in \mathcal{E}$  we have that

- $P_{\mathcal{M}} x = \sum_{j=1}^n (x, e_j) e_j$  satisfies that  $x - P_{\mathcal{M}} x \perp \mathcal{M}$  and hence  $\|x\|^2 = \|P_{\mathcal{M}} x\|^2 + \|x - P_{\mathcal{M}} x\|^2$
- $d(x, \mathcal{M}) = \left\| x - \sum_{j=1}^n (x, e_j) e_j \right\|^{1/2}$

PROOF (i) If  $1 \leq k \leq n$ , we have

$$(x - P_{\mathcal{M}}x, e_k) = (x, e_k) - \sum_{j=1}^n (x, e_j)(e_j, e_k) = (x, e_k) - (x, e_k) = 0$$

and it follows that  $x - P_{\mathcal{M}}x \perp \mathcal{M}$ . Pythagoras' law provides the second formula.

(ii) Endow  $\mathbb{F}^n$  with the usual inner product  $\|\cdot\|_2$ . By Cauchy-Schwarz, for  $x \in \mathcal{E}$  and  $\alpha \in \mathbb{F}^n$ ,

$$\left| \left( \left( (x, e_j) \right)_{j=1}^n, \alpha \right) \right| = \left| \sum_{j=1}^n (x, e_j) \bar{\alpha}_j \right| \leq \left( \sum_{j=1}^n |(x, e_j)|^2 \right)^{1/2} = \|P_{\mathcal{M}}x\| \|\alpha\|_2$$

so that

$$\begin{aligned} \left\| x - \sum_{j=1}^n \alpha_j e_j \right\|^2 &= \|x\|^2 - 2 \operatorname{Re} \sum_{j=1}^n (x, e_j) \bar{\alpha}_j + \sum_{j=1}^n |\alpha_j|^2 \\ &\geq \|x\|^2 - 2 \left| \left( \left( (x, e_j) \right)_{j=1}^n, \alpha \right) \right| + \|\alpha\|_2^2 \\ &\geq \|x\|^2 - 2 \|P_{\mathcal{M}}x\| \|\alpha\|_2 + \|\alpha\|_2^2 \\ &= \|x - P_{\mathcal{M}}x\|^2 + (\|P_{\mathcal{M}}x\| - \|\alpha\|_2)^2 \end{aligned}$$

We get equality above if  $x \perp \mathcal{M}$  or otherwise there is some  $s \geq 0$  so  $\alpha_j = s(x, e_j)$  for  $j = 1, \dots, n$ . Hence, in this case,

$$\left\| x - \sum_{j=1}^n s(x, e_j) e_j \right\|^2 = \|x - P_{\mathcal{M}}x\|^2 + \|P_{\mathcal{M}}x\|^2 (1 - s)^2$$

which is minimized when  $s = 1$ . ■

*Remark.* (i) The proof above shows that  $P_{\mathcal{M}}x$  is the unique element of  $\mathcal{M}$  satisfying  $\operatorname{dist}(x, \mathcal{M}) = \|x - P_{\mathcal{M}}x\|$ .

(ii) It may be shown that  $P_{\mathcal{M}} : \mathcal{E} \rightarrow \mathcal{E}$  is linear with  $\operatorname{im} P_{\mathcal{M}} = \mathcal{M}$ ,  $P_{\mathcal{M}}^2 = P_{\mathcal{M}}$ , and  $\|P_{\mathcal{M}}\| = 1$  (in other words, this map is actually a projection operator)

#### 10.4 Theorem. (Orthonormal Basis)

let  $(\mathcal{E}, (\cdot, \cdot))$  be a Euclidean space,  $E \subset \mathcal{E}$  an orthonormal set. Then the following are equivalent:

- (i)  $\overline{\operatorname{span} E} = \mathcal{E}$
- (ii) for  $x \in \mathcal{E} = x = \sum_{e \in E} (x, e)e = \lim_{F \in \mathcal{F}} \sum_{e \in F} (x, e)e$ , where  $\mathcal{F} = \{F \subseteq E : |F| < \infty\}$ , directed by inclusion (Bessel's identity)
- (iii) For  $x, y \in \mathcal{E}$ ,  $(x, y) = \sum_{e \in E} (x, e)(e, y)$  (Parseval's identity).

PROOF ( $i \Rightarrow ii$ ) For  $F \in \mathcal{F}$ , let  $\mathcal{E}_F = \operatorname{span} F$ , so that  $\mathcal{E}_F \subseteq \mathcal{E}_{F'}$  if  $F \subseteq F'$  in  $\mathcal{F}$  and  $\operatorname{span} E = \bigcup_{F \in \mathcal{F}} \mathcal{E}_F$ . Hence for  $x \in \mathcal{E}$ , we have

$$0 = \operatorname{dist}(x, \operatorname{span} E) = \operatorname{dist}\left(x, \bigcup_{F \in \mathcal{F}} \mathcal{E}_F\right) = \inf_{F \in \mathcal{F}} \operatorname{dist}(x, \mathcal{E}_F) = \lim_{F \in \mathcal{F}} \operatorname{dist}(x, \mathcal{E}_F)$$

Thus by the f.d. approximation lemma, we have

$$0 = \lim_{F \in \mathcal{F}} \text{dist}(x, \mathcal{E}_F) = \lim_{F \in \mathcal{F}} \left\| x - \sum_{e \in F} (x, e) e \right\|$$

(ii  $\Leftrightarrow$  iii) We have

$$\begin{aligned} 0 &= \lim_{F \in \mathcal{F}} \left\| x - \sum_{e \in F} (x, e) e \right\|^2 \\ &= \lim_{F \in \mathcal{F}} \left( \|x\|^2 - 2 \operatorname{Re} \sum_{e \in F} \overline{(x, e)} (x, e) + \sum_{e \in F} \|(x, e) e\|^2 \right) \\ &= \lim_{F \in \mathcal{F}} \left( \|x\|^2 - \sum_{e \in F} |(x, e)|^2 \right) \\ &= \|x\|^2 - \sum_{e \in E} |(x, e)|^2 \end{aligned}$$

(ii  $\Rightarrow$  iv) Recall that  $f_y = (\cdot, y) \in \mathcal{E}^*$  so that

$$(x, y) = f_y \left( \lim_{F \in \mathcal{F}} \sum_{e \in F} (x, e) e \right) = \lim_{F \in \mathcal{F}} \sum_{e \in F} (x, e) f_y(e) = \sum_{e \in E} (x, e) (e, y)$$

(iv  $\Rightarrow$  ii) Take  $x = y$ .

(iii  $\Rightarrow$  i) Obvious;  $x = \lim_{F \in \mathcal{F}} \sum_{e \in F} (x, e) e \in \overline{\operatorname{span} E}$ , i.e.  $\mathcal{E} \subseteq \overline{\operatorname{span} E} \subseteq \mathcal{E}$ . ■

**Definition.** Any set  $E \subset \mathcal{E}$  satisfying the above conditions is called a **orthonormal basis** for  $\mathcal{E}$ .

**10.5 Theorem. (Gram-Schmidt)** Let  $(x_1, x_2, \dots)$  be a linearly independent sequence in a euclidean space  $(\mathcal{E}, (\cdot, \cdot))$ . There exists an orthogonal sequence  $(z_1, z_2, \dots)$  which satisfies  $\operatorname{span}\{z_1, \dots, z_n\} = \operatorname{span}\{x_1, \dots, x_n\}$  for  $n = 1, 2, \dots$  so that  $\operatorname{span}\{z_1, z_2, \dots\} = \operatorname{span}\{x_1, x_2, \dots\}$ .

PROOF Let  $\mathcal{E}_n = \operatorname{span}\{x_1, \dots, x_n\}$ . We set

$$\begin{aligned} z_1 &= x_1 & e_1 &= \frac{z_1}{\|z_1\|} \\ z_2 &= x_2 - P_{\mathcal{E}_1} x_2 & e_2 &= \frac{z_2}{\|z_2\|} \\ &\vdots & & \\ z_{n+1} &= x_{n+1} - P_{\mathcal{E}_n} x_{n+1} & e_{n+1} &= \frac{z_{n+1}}{\|z_{n+1}\|} \end{aligned}$$

where  $P_{\mathcal{E}_n} x = \sum_{j=1}^n (x, e_j) e_j$ . Inductively,  $z_n \in \mathcal{E}_n$  and  $z_n \perp \mathcal{E}_k$  for  $k = 1, \dots, n-1$ . Hence each set  $\{z_1, \dots, z_n\}$  is orthonormal and  $\operatorname{span}\{z_1, \dots, z_n\} \subseteq \operatorname{span}\{x_1, \dots, x_n\}$  is of full dimension and hence equal. ■

**10.6 Corollary.** Any separable Euclidean space admits an orthonormal basis.

**PROOF** Let  $\{x_n\}_{n=1}^\infty$  be dense in  $\mathcal{E}$ . Let  $n_1 = \min\{n : x_n \neq 0\}$ , and  $n_{k+1} = \min\{n : x_n \notin \text{span}\{x_{n_1}, \dots, x_{n_k}\}\}$ . Then  $\{x_{n_1}, x_{n_2}, \dots\}$  and normalize to get an orthonormal set  $E = \{e_1, e_2, \dots\}$  which satisfies  $\overline{\text{span} E} = \overline{\text{span}\{x_n\}_{n=1}^\infty} = \mathcal{E}$ . ■

**10.7 Theorem. (Riesz-Fischer)** Let  $(\mathcal{E}, (\cdot, \cdot))$  be a Euclidean space. Then  $\mathcal{E}$  is a Hilbert space if and only if for any orthonormal set  $E$  and  $\alpha = (\alpha_e)_{e \in E} \in \ell_2(E)$ , we have that  $\sum_{e \in E} \alpha_e e \in \mathcal{E}$ .

**PROOF** ( $\implies$ ) If  $\alpha \in \ell_2(E)$  then  $E_\alpha = \{e \in E : \alpha_e \neq 0\}$  is countable, and write  $E_\alpha = \{e_1, e_2, \dots\}$ . If  $m < n$ , we have

$$\left\| \sum_{k=1}^n \alpha_{e_k} e_k - \sum_{k=1}^m \alpha_{e_k} e_k \right\|^2 = \sum_{k=m+1}^n |\alpha_{e_k}|^2 \leq \sum_{k=n+1}^\infty |\alpha_{e_k}|^2 \rightarrow 0$$

so  $x_\alpha = \sum_{k=1}^\infty \alpha_{e_k} e_k = \lim_{n \rightarrow \infty} \sum_{k=1}^n \alpha_{e_k} e_k$  converges. If  $F \in \mathcal{F}$ ,  $F \supseteq \{e_1, \dots, e_n\}$ , then

$$\left\| x_\alpha - \sum_{e \in F} \alpha_e e \right\|^2 = \sum_{e = \{e_1, e_2, \dots\} \setminus F} |\alpha_e|^2 \leq \sum_{k=n+1}^\infty |\alpha_{e_k}|^2 \rightarrow 0$$

so  $x_\alpha = \sum_{e \in E} \alpha_e e = \lim_{F \in \mathcal{F}} \sum_{e \in F} (x, e) e$ .

( $\impliedby$ ) Let  $(x^{(n)})_{n=1}^\infty$  be Cauchy in  $\mathcal{E}$ . Let  $\mathcal{M} = \overline{\text{span}\{x^{(n)}\}_{n=1}^\infty} \subset \mathcal{E}$  so  $\mathcal{M}$  is separable and admits a countable orthonormal basis  $E = (e_1, e_2, \dots)$ . Then we appeal to orthonormal basis to see that for any  $x \in \mathcal{M}$ ,  $\sum_{k=1}^\infty |(x, e_k)|^2 = \|x\|^2 < \infty$  and  $x = \sum_{k=1}^\infty (x, e_k) e_k$ .

Our present assumption show that  $U : \ell_2(E) \rightarrow \mathcal{M}$  given by  $U_\alpha = \sum_{k=1}^\infty \alpha_k e_k$  always converges in  $\mathcal{M} \subseteq \mathcal{E}$ . Then orthonormal basis theorem gives  $\|U_\alpha\| = \|\alpha\|_2$  so  $U$  is a surjective isometry. We let  $\alpha^{(n)} = ((x^{(n)}, e_k))_{k=1}^\infty \in \ell_2(E)$ , then  $\|\alpha^{(n)} - \alpha^{(m)}\|_2 = \|U_\alpha^{(n)} - U_\alpha^{(m)}\| = \|x^{(n)} - x^{(m)}\|$  so  $(\alpha^{(n)})_{n=1}^\infty$  is Cauchy and in  $\ell_2(E)$  and hence admits a limit  $\alpha$ . Furthermore,

$$\left\| \sum_{k=1}^\infty \alpha_k e_k - x^{(n)} \right\| = \|U_\alpha - U_\alpha^{(n)}\| = \|\alpha - \alpha^{(n)}\| \rightarrow 0$$

as required. ■

**Definition.** If  $\emptyset \neq S \subset \mathcal{E}$ ,  $(\mathcal{E}, (\cdot, \cdot))$  a Euclidean space, we define its **perpendicular** by  $S^\perp = \{y \in \mathcal{E} : (x, y) = 0 \text{ for any } x \in S\}$ .

**Remark.** (i)  $S \subseteq T$  implies  $T^\perp \subseteq S^\perp$

(ii)  $S^\perp = \bigcap_{x \in S} \ker f_x$  and is thus closed.

(iii)  $\overline{S}^\perp = S^\perp$ , since  $\overline{S}^\perp \subseteq \overline{S}^\perp$ , and if  $y \in S^\perp$  and  $x \in \overline{S}$ , then  $x = \lim x_n$  with  $x_n \in S$  so  $(x, y) = f_y(x) = f_y \lim x_n = \lim f_y(x_n) = \lim (x_n, y) = 0$ .

(iv)  $(\overline{\text{span} S})^\perp = S^\perp$ . Notice that  $(\text{span} S)^\perp = S^\perp$  (easy test) and use (iii)

(v)  $\overline{\text{span} S} \cap S^\perp = \{0\}$ .

**10.8 Theorem. (Existence of Orthonormal Basis)** Let  $(H, (\cdot, \cdot))$  be a Hilbert space.

(i) Given an orthonormal set  $E \subset H$ ,  $P_E : H \rightarrow H$ ,  $P_E x = \sum_{e \in E} (x, e) e$  satisfies

$$\text{im } P_E \subseteq \overline{\text{span} E} \text{ for } x \in H, x - P_E x \in E^\perp$$

(ii)  $H$  admits an orthonormal basis, i.e. an orthonormal set  $M$  such that  $\overline{\text{span} M} = H$ .

**PROOF** (i) Let  $\mathcal{F} = \{F \subseteq E : |F| < \infty\}$  be directed by inclusion, and for  $F \in \mathcal{F}$ ,  $\mathcal{E}_F = \text{span} F$ . Then as in the proof of OMBT, we have for  $x \in H$

$$0 \leq \text{dist}(x, \text{span} E)^2 = \lim_{F \in \mathcal{F}} \text{dist}(x, \mathcal{E}_F)^2 = \|x\|^2 - \sum_{e \in E} |(x, e)|^2$$

so  $\sum_{e \in E} |(x, e)|^2 \leq \|x\|^2 < \infty$ . Thus appealing to Riesz-Fischer,  $P_E x = \sum_{e \in E} (x, e)e$  converges in  $H$ . Since  $P_E x = \lim_{F \in \mathcal{F}} \sum_{e \in F} (x, e)e$ , we see that  $P_E x \in \overline{\text{span} E}$ , so  $\text{im } P_E \subseteq \overline{\text{span} E}$ . Moreover, if  $e' \in E$ ,  $f_{e'} = (\cdot, e') \in H^*$  so

$$(x - P_E x, e') = (x, e') - f_{e'} \left( \sum_{e \in E} (x, e)e \right) = (x, e') - \sum_{e \in E} (x, e) f_{e'}(e) = -$$

so  $x - P_E x \in E^\perp$ .

(ii) Let  $\mathcal{O} = \{E \subseteq H : E \text{ is orthonormal}\}$ , which is partially ordered by inclusion. Note that  $\emptyset \in \mathcal{O}$  vacuously. If  $\mathcal{C} \subseteq \mathcal{O}$  is a chain, then  $\bigcup_{E \in \mathcal{C}} E$  is an upper bound for  $\mathcal{C}$ . By Zorn' get a maximal element  $M$ .

Suppose  $\overline{\text{span} M} \subsetneq H$ , and get  $x \in H \setminus \overline{\text{span} M}$  and  $y = x - P_M x \in (\overline{\text{span} M})^\perp \setminus \{0\}$ . But then  $M \subsetneq M \cup \{\frac{1}{\|y\|}y\}$ , violating maximality. ■

**10.9 Corollary.** If  $H$  is a Hilbert space with orthonormal basis  $E$ , then the map

$$U : H \rightarrow \ell_2(E), Ux = ((x, e))_{e \in E}$$

is a surjective isometry which respects inner products.

**PROOF** We know  $\|x\|^2 = \sum_{e \in E} |(x, e)|^2 = \|Ux\|_2^2$  from ONBT. It is evident that  $U$  is linear and  $\text{im } U$  is dense in  $\ell_2(E)$  so that  $U$  is surjective. Finally, if  $x, y \in H$ , then

$$(x, y)_H = \sum_{e \in E} (x, e)(e, y) = \sum_{e \in E} (x, e)\overline{(y, e)} = (Ux, Uy)_{\ell_2(E)}$$

as required. ■

*Remark.* If each of  $E, E'$  is an orthonormal basis for a Euclidean space  $(\mathcal{E}, (\cdot, \cdot))$ , then  $|E| = |E'|$ . We let  $\mathbb{k}$  be any countable dense subfield of  $\mathbb{F}$ . Then  $D = \text{span}_{\mathbb{k}} E$ , so  $|D| = \aleph_0 |E| = |E|$  when  $|E|$  is infinite. Since for  $e', e''$  in  $E'$ ,  $\|e' - e''\| = \sqrt{2}$ , we have that any ball  $e' + \frac{1}{\sqrt{2}}D(\mathcal{E})$  contains at least one element of  $D$ , and  $d_{e'} \neq d_{e''}$  if  $e' \neq e''$  in  $E'$ . This shows that  $|E| \geq |E'|$ . Likewise  $|E'| \leq |E|$ .

**10.10 Corollary. (Orthogonal complementation)** Let  $(\mathcal{E}, \|\cdot\|)$  be a Euclidean space and  $\mathcal{M} \subseteq \mathcal{E}$  a subspace which is complete with respect to the norm induced from  $(\cdot, \cdot)$ , i.e.  $(\mathcal{M}, (\cdot, \cdot))$  is a Hilbert space. Then there is a unique operator  $P_{\mathcal{M}} = P : \mathcal{E} \rightarrow \mathcal{E}$  such that  $\text{im } P = \mathcal{M}$  and  $\text{im}(I - P) = \mathcal{M}^\perp$ . Moreover,

- $P$  is linear
- $\|P\| \leq 1$ ,  $\|P\| = 1$  if  $\mathcal{M} \neq \{0\}$
- $P^2 = P$

- for  $x, y \in \mathcal{E}$ ,  $(Px, y) = (Px, Py) = (x, Py)$ .

Such an operator is called the **orthogonal projection**.

**PROOF** The theorem above provides an orthonormal basis  $E$  for  $\mathcal{M}$ . Then  $P_E$ , as defined above, satisfies  $\text{im } P = \mathcal{M}$  and  $\text{im}(I - P) = \mathcal{M}^\perp$ . Moreover, if  $P$  satisfies those conditions, then for  $x \in \mathcal{E}$ ,

$$Px + x - Px = x = P_E x + x - P_e X$$

so that

$$Px - P_e X = [x - P_E x] - [x - Px] \in \mathcal{M} \cap \mathcal{M}^\perp = \{0\}$$

so  $Px = P_e x$ . Then if  $x, y \in \mathcal{E}$  and  $\alpha \in \mathbb{F}$ ,

$$P(x + \alpha y) + x + \alpha y - P(x + \alpha y) = x + \alpha y = Px + x - Px + \alpha[Py + y - Py]$$

so

$$P(x + \alpha y) - [Px + \alpha Py] = x - Px + \alpha[y - Py] - [x + \alpha y - P(x + \alpha y)] \in \mathcal{M} \cap \mathcal{M}^\perp = \{0\}$$

and we have linearity.

If  $x \in \mathcal{E}$ , Pythagoras tells us that  $\|x\|^2 = \|Px\|^2 + \|x - Px\|^2$  so  $\|Px\| \leq \|x\|$ , i.e.  $\|P\| \leq 1$ . If  $e' \in E$ ,  $Pe' = P_E e' = \sum_{e \in E} (e', e)e = e'$ , so  $P|_{\text{span } E} = \text{id}$  and by uniqueness of extension of bounded linear functionals (uniformly continuous), we see that  $P|_{\mathcal{M}} = \text{id}_{\mathcal{M}}$ . This shows that if  $\mathcal{M} \neq \{0\}$ ,  $\|P\| = 1$  and  $P = P^2$ . Furthermore, this also shows that  $\text{im } P = \mathcal{M}$ . Finally,

$$(Px, y) = (Px, Py + y - Py) = (Px, Py)$$

and likewise  $(x, Py) = (Px, Py)$ . ■

**10.11 Corollary.** *Let  $H$  be a Hilbert space.*

- If  $\mathcal{M}$  is a closed subspace, then  $(\mathcal{M}^\perp)^\perp = \mathcal{M}$ .
- If  $\emptyset \neq S \subset H$ , then  $(S^\perp)^\perp = \overline{\text{span}} S$ .

**PROOF** (i) We have  $\mathcal{M} \subseteq \mathcal{M}^{\perp\perp}$  and  $\mathcal{M}$  is complete and thus admits an orthogonal projection  $P_{\mathcal{M}} H \rightarrow H$  with  $\text{im } P_{\mathcal{M}} = \mathcal{M}$  and  $\text{im}(I - P_{\mathcal{M}}) = \mathcal{M}^\perp$ . Now if  $x \in \mathcal{M}^{\perp\perp}$ ,  $P_{\mathcal{M}} x \in \mathcal{M}$  so that  $x - P_{\mathcal{M}} x \in \mathcal{M}^\perp + \mathcal{M} = \mathcal{M}^{\perp\perp}$  so that  $x - P_{\mathcal{M}} x \in \mathcal{M}^\perp$ . Thus

$$x - P_{\mathcal{M}} x \in \mathcal{M}^{\perp\perp} \cap \mathcal{M}^\perp = \{0\}$$

so that  $x \in P_{\mathcal{M}} x \in \mathcal{M}$ . Hence  $\mathcal{M}^{\perp\perp} \subseteq \mathcal{M}$ .

- We have  $(\overline{\text{span}} S)^\perp = S^\perp$  and apply (i). ■

**10.12 Theorem. (Riesz-Fréchet)** *If  $H$  is a Hilbert space and  $f \in H^*$ , then there is a unique  $x_0 \in H$  such that  $f = f_{x_0}$ ; i.e.  $f(x) = (x, x_0)$  for all  $x \in H$ .*

**PROOF** If  $f = 0$ , let  $x_0 = 0$ . If  $f \neq 0$ ,  $\ker f \subsetneq H$  so  $(\ker f)^{\perp\perp} = f$ , so  $(\ker f)^\perp \neq \{0\}$ . If  $x_1, x_2 \in (\ker f)^\perp$ , then  $f(x_2)x_1 - f(x_1)x_2 \in (\ker f)^\perp \cap \ker f = \{0\}$ , so that  $\dim(\ker f)^\perp = 1$  and  $(\ker f)^\perp = \mathbb{F} x_1$ . But then  $f_{x_1} = (\cdot, x_1)$  has  $\ker f_{x_1} = (\mathbb{F} x_1)^\perp = (\ker f)^{\perp\perp} = \ker f$ , so there is  $\alpha \in \mathbb{F}$  so  $f = \alpha f_{x_1} = f_{\alpha x_1}$ . Set  $x_0 = \alpha x_1$ .

Uniqueness holds since  $x \mapsto f_x : H \rightarrow H^*$  is an isometry and thus injective. ■



- Remark.* (i) Many results above may fail in a non-complete Euclidean space. Consider  $(\ell, (\cdot, \cdot))$  where  $\ell$  is the space of finitely supported sequences. Define  $f : \ell \rightarrow \mathbb{F}$  by  $f(x) = \sum_{k=1}^{\infty} \frac{1}{k} x_k$ . By Hölder,  $|f(x)| \leq \left( \sum_{k=1}^{\infty} \frac{1}{k^2} \right) \|x\|_2$  so that  $f \in \ell^*$ . If there were  $x^{(0)} \in \ell$  so that  $f = f_{x^{(0)}}$  for some  $x^{(0)} \in (\ker f)^{\perp} \setminus \{0\}$ , we would then have  $x_k^{(0)} = (e_k, x^{(0)}) = \frac{1}{k}$ , which is non-zero for infinitely many  $k$ , giving a contradiction. In fact,  $(\ker f)^{\perp} = \{0\}$  so that  $(\ker f)^{\perp\perp} = \ell$ .
- (ii) Let  $(\mathcal{E}, (\cdot, \cdot))$  be a Euclidean space. Let  $H = \overline{\mathcal{E}}$  be the metrical completion with respect to  $\|x\|_2$ . If  $x, y \in H$ , then  $x = \lim x_n = \lim x'_n$  with  $x_n, x'_n \in \mathcal{E}$ , and  $y = \lim y_n = \lim y'_n$  similarly. Then

$$\begin{aligned} |(x_n, y_n) - (x_n, y_m)| &\leq |(x_n, y_n) - (x_n, y_m)| + |(x_n, y_m) - (x_n, y_n)| \\ &\leq \|x_n\| \|y_n - y_m\| + \|x_n - x_m\| \|y_m\| \end{aligned}$$

so that  $((x_n, y_n))_{n=1}^{\infty} \subset \mathbb{F}$  is Cauchy, and thus admits a limit. Moreover,  $|(x_n, y_n) - (x'_n, y'_n)| \leq \|x_n\| \|y_n - y'_n\| + \|x_n - x'_n\| \|y'_n\|$ . Thus,  $(x, y) = \lim_{n \rightarrow \infty} (x_n, y_n) = \lim_{n \rightarrow \infty} (x'_n, y'_n)$  is well-defined on  $H \times H$ . It is straightforward to verify that this is an inner product, and  $\|x\| = \lim_{n \rightarrow \infty} \|x_n\| = (x, x)^{1/2}$ . Thus the completion of a Euclidean space is a Hilbert space.

- (iii) As a consequence of (ii), we have  $\mathcal{E}^* = \{f_x : x \in H\}$  where  $H = \overline{\mathcal{E}}$ , as above. Furthermore,  $\overline{\mathcal{E}} \cong H^{**}$ .
- (iv) If  $H$  is a Hilbert space, the map  $f \mapsto f_x$  from  $H \rightarrow H^*$  is
- a conjugate linear map:  $f_{x+\alpha y} = f_x + \overline{\alpha} f_y$
  - an isometry:  $\|f_x\| = \|x\|$

## 11 ADJOINT OPERATORS

**Definition.** Let  $X, Y$  be vector spaces over  $\mathbb{F}$  and  $T \in \mathcal{L}(X, Y)$ . We define the **adjoint** of  $T$  to be the map  $T^* \in \mathcal{L}(Y^*, X^*)$  given by  $T^* f = f \circ T$ .

We can interpret the adjoint in terms of the natural bilinear pairing  $\langle \cdot, \cdot \rangle : V \times V^* \rightarrow \mathbb{F}$  given by  $\langle v, f \rangle = f(v)$ . In particular, if  $T : V \rightarrow W$  is linear map, then  $T^* : W^* \rightarrow V^*$  satisfies

$$\langle Tv, g \rangle_W = g(Tv) = T^* g(v) = \langle v, T^* g \rangle_V.$$

We may also naturally identify  $T^{**}|_{\hat{X}} : \hat{X} \rightarrow Y^{**}$  with  $T$ . Suppose  $\hat{x} \in \hat{X}$  is arbitrary: then  $T^{**}(\hat{x}) = \hat{x} \circ T^*$ , so if  $f \in Y^*$ , then

$$T^{**}(\hat{x})(f) = \hat{x} \circ T^*(f) = \hat{x}(f \circ T) = f(T(x)).$$

so that  $T^{**}(\hat{x}) = \widehat{T(x)}$ . In particular, since  $x \mapsto \hat{x}$  is an isometry,

$$\begin{aligned} \|T^{**}|_{\hat{X}}\| &= \sup_{\hat{x} \in B(\hat{X})} \|T^{**}\hat{x}\| = \sup_{x \in B(X)} \|\widehat{T(x)}\| \\ &= \sup_{x \in B(X)} \|T(x)\| = \|T\| \end{aligned}$$

so that this identification is norm-preserving.

**11.1 Proposition.** Let  $X, Y, Z$  be normed spaces,  $T \in \mathcal{B}(X, Y)$  and  $S \in \mathcal{B}(Y, Z)$ . Then

- (i)  $T^* \in \mathcal{B}(Y^*, X^*)$  with  $\|T^*\| = \|T\|$
- (ii)  $T \mapsto T^* : \mathcal{B}(X, Y) \rightarrow \mathcal{B}(Y^*, X^*)$  is a continuous linear map
- (iii)  $(S \circ T)^* = T^* \circ S^* \in \mathcal{B}(Z^*, X^*)$ .

PROOF We prove (i) and (ii); (iii) is easy and left as an exercise.

(i) If  $f \in Y^*$ , then

$$\|T^*f\| = \sup_{x \in B(X)} |T^*f(x)| \leq \|f\| \cdot \sup_{x \in B(X)} \|Tx\| = \|f\| \cdot \|T\|$$

so  $\|T^*\| \leq \|T\|$ . Conversely, by the preceding remarks and applying the above result to  $T^*$ , we have  $\|T\| = \|T^{**}|_{\hat{X}}\| \leq \|T^{**}\| \leq \|T^*\|$  so equality holds.

(ii) Suppose  $T = \lim_{\nu \in N} T_\nu$ ; then

$$\lim_{\nu \in N} \|T_\nu^* - T^*\| = \lim_{\nu \in N} \|(T_\nu - T)^*\| = \lim_{\nu \in N} \|T_\nu - T\| = 0$$

is sequentially continuous, and hence continuous. ■

If  $H, K$  are Hilber spaces and  $T \in \mathcal{B}(H, K)$ , then for each  $x \in K$ , we define by Riesz-Frechet the element  $T^*x$  by the rule  $f_{T^*x} = T^*f_x$ . Then properties (i) and (iii) still hold, but (ii) is replaced by the observation that  $T \mapsto T^*$  is conjugate linear. Note that, by definition,  $(Tx, y) = (x, T^*y)$  for  $x, y \in H$  and  $T^*$  is unique with this property.

**11.2 Theorem. (Kernel-Annihilator)** *If  $X$  and  $Y$  are Banach spaces,  $T \in \mathcal{B}(X, Y)$ , then  $\ker T = [\text{im}(T^*)]_a$  and  $\ker(T^*) = (\text{im } T)^a$ .*

PROOF We have

$$\ker T = \{x \in X : Tx = 0\} = \{x \in X : T^*g(x) = g(Tx) = 0 \text{ for all } x \in X\} = [\text{im}(T^*)]_a$$

and

$$\ker(T^*) = \{g \in Y^* : T^*g = 0\} = \{g \in Y^* : g(Tx) = T^*g(x) = 0 \text{ for all } x \in X\} = [\text{im}(T)]^a \quad \blacksquare$$

*Remark.* If  $T \in \mathcal{B}(H, K)$  where  $H, K$  are Hilbert spaces, then  $\ker T = (\text{im } T^*)^\perp$ , identifying  $T^{**} = T$  since Hilbert spaces are reflexive.

**11.3 Theorem. (Characterization of Invertibility)** *Let  $X, Y$  be Banach spaces,  $T \in \mathcal{B}(X, Y)$ . Then TFAE:*

- (i)  $T$  is invertible
- (ii)  $T^*$  is invertible
- (iii)  $\overline{\text{im } T} = Y$  and  $\inf\{\|Tx\| : x \in S(X)\} > 0$ , we say that  $T$  is **bounded below**, and
- (iv) both  $T$  and  $T^*$  are bounded below.

PROOF ( $i \Rightarrow ii$ ) Let  $T^{-1} \in \mathcal{B}(Y, X)$ , so  $I_Y = TT^{-1}$ ,  $I_X = T^{-1}T$ . Then  $(T^{-1})^*T^* = (TT^{-1})^* = I_Y^* = I_{Y^*}$  and likewise for the reverse.

( $ii \Rightarrow iii$ ) By the kernel-annihilator theorem, we have  $(\text{im } T)^a = \ker(T^*) = \{0\}$  in  $Y^*$ , so by annihilator-preannihilator,  $\overline{\text{im } T} = (\text{im } T)_a^a = \{0\}_a^a = Y$ . Now if  $x \in S(X)$ , find  $f \in X^*$  so  $f(x) = \|x\| = 1 = \|f\|$  (by Hahn-Banach). Then

$$1 = f(x) = [T^*(T^{-1}-1)f](x) = [(T^*)^{-1}f](Tx) \leq \|(T^*)^{-1}f\| \|Tx\| \leq \|(T^*)^{-1}\| \|Tx\|$$

so that  $\|Tx\| \geq \frac{1}{\|(T^*)^{-1}\|} > 0$  and  $T$  is bounded below.

(iii  $\Rightarrow$  i) Let  $T$  be bounded below, and set  $c = \inf\{\|Tx\| : x \in S(X)\} > 0$ , then for  $x \in X \setminus \{0\}$ ,  $\|Tx\| = \|x\| \left\| T \left( \frac{1}{\|x\|} x \right) \right\| \geq c\|x\|$ . If  $y \in \overline{\text{im } T}$ , then  $y = \lim y_n$ , each  $y_n = Tx_n \in \text{im } T$ . Then

$$\|x_n - x_m\| \leq \frac{1}{c} \|Tx_n - Tx_m\|$$

so  $(x_n)_{n=1}^\infty$  is Cauchy as  $(Tx_n)_{n=1}^\infty$  converges. Then  $x = \lim x_n \in X$  and by continuity of  $T$ ,  $y = Tx \in \text{im } T$ . Notice as well that bounded below implies  $\ker T = \{0\}$ .

We assume that  $T$  is bounded below and  $\text{im } T = \overline{\text{im } T} = Y$ , so  $T$  is bijective, hence invertible.

(i, ii  $\Rightarrow$  iv) Use (iii)

(iv  $\Rightarrow$  iii) We suppose that  $T$  is bounded below, and so is  $T^*$ . Then  $\{0\} = \ker(T^*)$  in  $Y^*$ , so  $Y = \{0\}_a = \ker(T^*)_a = \overline{\text{im } T}$  and  $T$  is bounded below provides  $\text{im } T = \overline{\text{im } T} = Y$ , so  $\ker T = \{0\}$ . ■

*Remark.* Reasons why  $T \in \mathcal{B}(X, Y)$  is not invertible:  $\ker T \supsetneq \{0\}$ ,  $\text{im } T \subsetneq Y$ ,  $T$  is not bounded below.

*Example.* Let  $T : \ell_p \rightarrow \ell_p$  be given by  $T(x_n)_{n=1}^\infty = \left(\frac{1}{n}x_n\right)_{n=1}^\infty$ , so  $\|T\| = 1$ . Notice that  $\ker T = \{0\}$  and  $\overline{\text{im } T} = \ell_p$ . However,  $T$  is not bounded below.

## 12 SPECTRAL THEORY FOR BOUNDED OPERATORS

Let  $X$  be a  $\mathbb{C}$ -Banach space, and  $\mathcal{B}(X) = \mathcal{B}(X, X)$ .

**Definition.** If  $T \in \mathcal{V}(X)$ , we define the **resolvent** of  $T$  by  $\rho(T) = \{\lambda \in \mathbb{C} : \lambda I - T \text{ is invertible}\}$ . Then the **spectrum** of  $T$ ,  $\sigma(T)$ , is given by  $\sigma(T) = \mathbb{C} \setminus \rho(T)$ . We define the **point spectrum**  $\sigma_p(T) = \{\lambda \in \mathbb{C} : \ker(\lambda I - T) \supsetneq \{0\}\}$ , so  $\sigma_p(T) \subseteq \sigma(T)$ .

*Example.* (i) If  $X$  is finite dimensional, then  $\sigma(T) = \sigma_p(T)$ .

(ii) Let  $1 \leq p < \infty$  and define  $S : \ell_p \rightarrow \ell_p$  by  $S(x_1, x_2, \dots) = (0, x_1, x_2, \dots)$ . Notice that  $S$  is linear and  $\|Sx\|_p = \|x\|_p$ , so  $\|S\| = 1$ . Also,  $\ker S = \{0\}$ . Suppose  $\lambda \in \sigma_p$ , so there is  $x \in \ker(\lambda I - S) \setminus \{0\}$ . We let  $k = \min\{n \in \mathbb{N} : x_n \neq 0\}$ , we see  $0 = (Sx)_k = \lambda_{x_k}$ , but  $|S\rangle = \{0\}$ , so  $0 \notin \sigma_p(T)$ , but hence no  $\lambda$  as above exists, so  $\sigma_p(X) = \emptyset$ .

For any  $T \in \mathcal{B}(X)$ , is  $\sigma(T) \neq \emptyset$ ?

Let

$$\mathcal{G}(X) = \{T \in \mathcal{B}(X) : T \text{ is invertible}\}$$

Notice that if  $S, T \in \mathcal{G}(X)$ , then  $(ST)^{-1} = T^{-1}S^{-1}$ , so  $\mathcal{G}(X)$  is a group in  $\mathcal{B}(X)$  with identity  $I$ . Note that  $\mathcal{B}(X)$  is complete, and if  $S, T \in \mathcal{B}(X)$ , then  $\|ST\| \leq \|S\|\|T\|$ , so that  $S \mapsto ST$  and  $S \mapsto TS$  for some  $T \in \mathcal{B}(X)$  are continuous.

**12.1 Theorem. (Inversion)** (i) If  $T \in \mathcal{D}(X)$ , then  $\sum_{k=0}^\infty T^k$  converges in  $\mathcal{B}(X)$ , and  $\sum_{k=0}^\infty T^k = (I - T)^{-1}$ .

(ii) If  $S, T \in \mathcal{B}(X)$  such that  $S \in \mathcal{G}(X)$  and  $\|T - S\| < \frac{1}{\|S^{-1}\|}$ , then  $T \in \mathcal{G}(X)$  with  $T^{-1} = S^{-1} + \sum_{k=1}^\infty [S^{-1}(S - T)]^k S$ .

Thus, we find that  $\mathcal{G}(X)$  is open in  $\mathcal{B}(X)$  and  $T \mapsto T^{-1}$  on  $\mathcal{G}(X)$  is continuous.

PROOF (i) Let  $S_n = \sum_{k=0}^{\infty} T^k$ , so for  $m < n$ , we have

$$\|S_n - S_m\| \leq \sum_{k=m+1}^{\infty} \|T^k\| \leq \sum_{k=m+1}^n \|T\|^k = \frac{\|T\|^{m+1}}{1 - \|T\|} \rightarrow 0$$

since  $\|T\| < 1$ , so  $(S_n)_{n=1}^{\infty}$  is Cauchy, and thus convergent in  $\mathcal{B}(X)$ . Also,

$$(I - T)S_n = I - T^{n+1} \rightarrow U \text{ as } T^{n+1} \rightarrow 0$$

since  $\|T\| < 1$ . Similarly,  $S_n(I - T) \rightarrow I$ , so that  $S = \sum_{k=0}^{\infty} T^k$  has  $S(I - T) = I = (I - T)S$ .

(ii) We have  $\|S^{-1}S - T\| \leq \|S^{-1}\| \|S - T\| < 1$  so by (i)

$$T = S - (S - T) = S[I - S^{-1}(S - T)] \in \mathcal{G}(X)$$

Furthermore,

$$T^{-1} = [I - S^{-1}(S - T)]^{-1} S^{-1} = \sum_{k=0}^{\infty} [S^{-1}(S - T)]^k S^{-1}$$

In particular, we see that for  $S \in \mathcal{G}(X)$ ,  $S + \frac{1}{\|S^{-1}\|} D(X) \subseteq \mathcal{G}(X)$ , so (a) holds. From (ii), we see that

$$\|T^{-1} - S^{-1}\| \leq \sum_{k=1}^{\infty} \|[S^{-1}(T - S)]^k S\| \leq \sum_{k=1}^{\infty} \|S^{-1}\|^k \|T - S\| \|S^{-1}\| = \frac{\|S^{-1}\|^2 \|T - S\|}{1 - \|S^{-1}\| \|T - S\|}$$

so that  $\lim_{TS} \|T^{-1} - S^{-1}\| = 0$ . ■

**Definition.** Suppose  $\mathcal{B}$  is a  $\mathbb{C}$ -Banach space,  $U \subseteq \mathbb{C}$  and  $F : U \rightarrow \mathcal{B}$ . We say that  $F$  is **holomorphic** if for any  $z_0 \in U$  the limit

$$F'(z_0) = \lim_{z \rightarrow z_0} \frac{1}{z - z_0} [F(z) - F(z_0)]$$

exists.

*Remark.* Just as in calculus, a holomorphic function is continuous on its domain.

**12.2 Proposition.** Let  $T \in \mathcal{B}(X)$ . Then

- (i)  $\rho(T)$  is open in  $\mathbb{C}$
- (ii)  $R(z) = R_T(z) = (zI - T)^{-1}$  defines a holomorphic function on  $\rho(T)$ , called the **resolvent function**, and
- (iii)  $\sigma(T) \subseteq \|T\| \overline{\mathbb{D}}$ , and for  $|z| > \|T\|$ ,  $R(z) \leq \frac{1}{|z| - \|T\|}$ .

PROOF (i) Define  $F : \mathbb{C} \rightarrow \mathcal{B}(X)$  by  $F(z) = zI - T$ . Then  $F$  is continuous and  $\rho(T) = F^{-1}(\mathcal{G}(X))$ .

(ii) If  $z, z_0 \in \rho(T)$ , then

$$\begin{aligned} R(z) - R(z_0) &= (zI - T)^{-1} - (z_0I - T)^{-1} = (zI - T)^{-1} [(z_0I - T) - (zI - T)] (z_0I - T)^{-1} \\ &= (z_0 - z)(zI - T)^{-1} (z_0I - T)^{-1} \end{aligned}$$

Hence

$$\frac{1}{z - z_0} [R(z) - R(z_0)] = -(zI - T)^{-1} (z_0I - T)^{-1} \rightarrow -(z_0I - T)^{-2}$$

by continuity of inversion.

- (iii) If  $|z| > \|T\|$ , then  $\left\|\frac{1}{z}T\right\| < 1$  so  $zI - T = z(I - \frac{1}{z}T) \in \mathcal{G}(X)$ , so  $\sigma(T) \subseteq \|T\|\overline{\mathbb{D}}$ . Furthermore, for  $|z| > \|T\|$ , we have

$$R(z) = (zI - T)^{-1} = \frac{1}{z} \left(I - \frac{1}{z}T\right)^{-1} = \frac{1}{z} \sum_{k=0}^{\infty} \frac{1}{z^k} T^k \quad \blacksquare$$

**12.3 Theorem. (Liouville)** If  $f : \mathbb{C} \rightarrow \mathbb{C}$  is holomorphic and bounded, then  $f$  is constant.

PROOF Apply the Cauchy integral formula. ■

**12.4 Theorem. (Liouville for Banach Spaces)** If  $F : \mathbb{C} \rightarrow \mathcal{B}$  is holomorphic and bounded, then  $F$  is constant.

PROOF Let  $f \in \mathcal{B}^*$  and let  $F_f = f \circ F : \mathbb{C} \rightarrow \mathbb{C}$ . Notice that for  $z, z_0 \in \mathbb{C}$ ,

$$\frac{F_f(z) - F_f(z_0)}{z - z_0} = f \left( \frac{1}{z - z_0} [F(z) - F(z_0)] \right) \rightarrow f(F'(z_0))$$

by linearity and continuity of  $f$ , and hence  $F'_f = f \circ F'$ . Also, if  $F$  is bounded, then for  $z \in \mathbb{C}$ ,  $|F_f(z)| = |f(F(z))| \leq \|f\| \|F(z)\|$  shows that  $F_f$  is bounded, so by Liouville's theorem, is constant. In particular, if  $z, z' \in \mathbb{C}$ ,  $f(F(z) - F(z')) = F_f(z) - F_f(z') = 0$ . Thus by Hahn-Banach, we have  $F(z) = F(z')$  for any  $z, z' \in \mathbb{C}$ , so  $F$  is constant. ■

**12.5 Theorem.** If  $T \in \mathcal{B}(X)$ , then  $\sigma(T) \neq \emptyset$  and compact.

PROOF If  $\sigma(T) = \emptyset$ , then  $R : \mathbb{C} \rightarrow \mathcal{B}(X)$  is holomorphic. Hence, as  $\|T\|\overline{\mathbb{D}}$  is compact in  $\mathbb{C}$ ,  $R$  is bounded on  $\|T\|\overline{\mathbb{D}}$ ; and if  $|z| > \|T\|$ , we have

$$\|R(z)\| \leq \frac{1}{|z| - \|T\|} \rightarrow 0$$

It follows that  $R$  is bounded on  $\mathcal{B}(X)$ , and hence constant, and thus  $R = 0$ . But  $R(z)(zI - T) = I$ , a contradiction.

Moreover,  $\rho(T) = \mathbb{C} \setminus \sigma(T)$  is open, and  $\sigma(T) \subseteq \|T\|\overline{\mathbb{D}} \subset \mathbb{C}$ . Thus  $\sigma(T)$  is a non-empty compact set. ■

**12.6 Corollary. (Joke)**  $\mathbb{C}$  is algebraically closed.

PROOF Let  $p(x) \in \mathbb{C}[x]$  be an arbitrary irreducible polynomial with  $p(x) = (x - r_1) \cdots (x - r_n)$  for some  $r_i \in \overline{\mathbb{C}}$ . Consider the operator  $T : \mathbb{C}^n \rightarrow \mathbb{C}^n$  with diagonal  $r_1, \dots, r_n$  and hence characteristic polynomial  $p(x)$ . Then  $\emptyset \neq \sigma(T) = \sigma_p(T) = \{x \in \mathbb{C} : p(x) = 0\}$ , so  $p$  has some root in  $\mathbb{C}$ , so that  $\deg p = 1$ . ■

**12.7 Proposition.** (i) If  $X$  is a (non-Hilbert) Banach space, then  $\sigma(T^*) = \sigma(T)$ .

(ii) If  $H$  is a Hilbert space,  $T \in \mathcal{B}(H)$ , then  $\sigma(T^*) = \{\bar{\lambda} : \lambda \in \sigma(T)\}$ .

PROOF (i)  $(\lambda I_X - T)^* = \lambda I_{X^*} - T^*$  and is invertible if and only if  $\lambda I_X - T$  is invertible  
(ii) Same. ■

**Definition.** We define the **point spectrum**  $\sigma_p(T) = \{\lambda \in \mathbb{C} : \ker(\lambda I - T) \neq \{0\}\}$ , the **approximate point spectrum**  $\sigma_{ap}(T) = \{\lambda \in \mathbb{C} : \lambda I - T \text{ is not bounded below}\}$ , and the **compression spectrum**  $\sigma_{com}(T) = \{\lambda \in \mathbb{C} : \overline{\text{im}(\lambda I - T)} \subsetneq X\}$ .

*Remark.* (i)  $\sigma_p(T) \subseteq \sigma_{ap}(T)$ .

(ii) We have  $[(\lambda I - T)]^a = \ker(\lambda I - T^*)$  by kernel-annihilator so  $\overline{\text{im}(\lambda I - T)} = \ker(\lambda I - T^*)$  by annihilator-preannihilator, so that  $\sigma_{com}(T) = \sigma_p(T^*)$ .

**12.8 Lemma.** If  $(T_n)_{n=1}^\infty \subset \mathcal{G}(X)$  satisfies that

- $T = \lim_{n \rightarrow \infty} T_n$
- $M = \sup_{n \in \mathbb{N}} \|T_n^{-1}\| < \infty$

then  $T \in \mathcal{G}(X)$ .

**PROOF** Since  $M > 0$ , for sufficiently large  $n$ , we have  $\|T - T_n\| \leq \frac{1}{M} \leq \frac{1}{\|T_n^{-1}\|}$ , so  $T \in \mathcal{G}(X)$  by inversion theorem. ■

**12.9 Proposition.** (i)  $\partial\sigma(T) \subseteq \sigma_{ap}(T)$

(ii)  $\sigma_{ap}(T)$  is closed

Hence  $\sigma_{ap}(T)$  is always a non-empty closed subset of  $\mathbb{C}$ .

**PROOF** (i) Let  $\lambda \in \partial\sigma(T)$ , so there is  $(\lambda_n)_{n=1}^\infty \subset \rho(T) = \mathbb{C} \setminus \sigma(T)$  such that  $\lambda = \lim_{n \rightarrow \infty} \lambda_n$ . Then  $\|(\lambda_n I - T) - (\lambda I - T)\| = |\lambda_n - \lambda| \rightarrow 0$ , but  $\lambda I - T \notin \mathcal{G}(X)$ , so by the lemma,  $\sup_{n \in \mathbb{N}} \|(\lambda_n I - T)^{-1}\| = \infty$ . Passing to a subsequence if necessary, we may suppose  $\lim_{n \rightarrow \infty} \|(\lambda_n I - T)^{-1}\| = \infty$ .

For each index  $n$ , let  $x_n \in S(X)$  so  $\alpha_n = \|(\lambda_n I - T)^{-1} x_n\| > \|(\lambda_n I - T)^{-1}\| - \frac{1}{n}$  so  $\lim_{n \rightarrow \infty} \alpha_n = \infty$ . Then  $y_n = \frac{1}{\alpha_n} (\lambda_n I - T)^{-1} x_n$ , so  $y_n \in S(X)$  and

$$\begin{aligned} (\lambda I - T)y_n &= (\lambda_n I - T)y_n + (\lambda - \lambda_n)y_n \\ &= \frac{1}{\alpha_n} x_n + (\lambda - \lambda_n)y_n \rightarrow 0 \end{aligned}$$

so  $\lambda I - T$  is not bounded below.

(ii) If  $\lambda = \lim_{n \rightarrow \infty} \lambda_n$ , each  $\lambda_n \in \sigma_{ap}(T)$ , for each  $n$  find  $x_n \in S(X)$  so  $\|(\lambda_n I - T)x_n\| < \frac{1}{n}$ . Then

$$\|(\lambda I - T)x_n\| \leq \|(\lambda_n I - T)x_n\| + \|(\lambda - \lambda_n)x_n\| < \frac{1}{n} + |\lambda - \lambda_n| \rightarrow 0$$

so  $\lambda I - T$  is not bounded below. ■

*Example.* Let  $S \in B(\ell_p)$ ,  $1 < p < \infty$ , where  $S(x_1, x_2, \dots) = (0, x_1, x_2, \dots)$ , the *unilateral shift* map. It is immediate that  $\|Sx\|_p = \|x\|_p$  for  $x \in \ell_p$ , so  $\|S\| = 1$ . Recall that  $\ell_p^* \cong \ell_q$  where  $p, q$  are conjugate. Define a bilinear form on  $\ell_p \times \ell_q$  by  $\langle x, y \rangle = \sum_{k=1}^\infty x_k y_k$ . We compute  $\langle x, S^* y \rangle = \langle Sx, y \rangle = \sum_{k=1}^\infty x_k y_{k+1} = \langle x, (y_2, y_3, \dots) \rangle$  so  $S^*(y_1, y_2, \dots) = (y_2, y_3, \dots)$ . Recall that  $\sigma_p(S) = \emptyset$ . However, if  $\lambda \in \mathbb{D}$ , let  $y_\lambda = (1, \lambda, \lambda^2, \dots) \in \ell_q$ . Then  $S^*(y_\lambda) = \lambda \cdot y_\lambda$ . Hence  $\sigma_p(S^*) \supseteq \mathbb{D}$ . Furthermore, if  $\lambda \in \sigma_p(S^*)$  and  $y \in \ker(\lambda I - S^*)$ , then  $\lambda^n y = (S^*)^n y \rightarrow 0$  so  $\lambda^n \rightarrow 0$ , forcing  $|\lambda| < 1$ . Thus

$$\mathbb{D} = \sigma_p(S^*) \subseteq \sigma(S^*) = \sigma(S) \subseteq \overline{\mathbb{D}}$$

since  $\|S\| = 1$ , and since  $\sigma(S)$  is compact,  $\sigma(S) = \overline{D}$ .

We know that  $\sigma_{ap}(S) \supseteq \partial\sigma(S) = \mathbb{S}$ . If  $\lambda \in \mathbb{D}$ , then for  $x \in \ell_p$ ,  $\|(S - \lambda I)x\|_p \geq \|Sx\|_p - \|\lambda x\|_p = (1 - |\lambda|)\|x\|_p$ , so  $S - \lambda I$  is bounded below. Thus  $\sigma_{ap}(S) \cap \mathbb{S} = \emptyset$ , so  $\sigma_{ap}(S) = \mathbb{S}$ . In conclusion,

$$\begin{array}{ll} \sigma(S) = \mathbb{D} & \sigma_p(S) = \emptyset \\ \sigma_{ap}(S) = \mathbb{S} = \partial\sigma(S) & \sigma_{com}(S) = \sigma_p(S^*) = \mathbb{D} \\ \sigma(S^*) = \overline{\mathbb{D}} & \sigma_p(S^*) = \mathbb{D} \\ \sigma_{ap}(S^*) = \partial\sigma(S^*) \cup \sigma_p(S^*) = \overline{\mathbb{D}} & \sigma_{com}(S^*) = \emptyset \end{array}$$

*Remark.* Let  $\sigma_p(T)$ ,  $\sigma_{com}(T)$  may be empty, and if non-empty need not be closed.

*Remark.* If  $p = 1$  and  $S \in B(\ell_1)$  is the unilateral shift, as above, and  $L \in \ell_\infty^*$  be a Banach limit. Then

$$S^{**}L = L \circ S^L$$

so  $\sigma_p(S^{**}) \ni 1$ . Thus  $\sigma_{com}(S^*) = \sigma_p(S^{**}) \neq \emptyset$ .

**12.10 Theorem. (Spectral Mapping)** Let  $T \in \mathcal{B}(X)$ ,  $p \in \mathbb{C}[x]$ , then  $\sigma(p(T)) = p(\sigma(T))$ .

**PROOF** We may assume that  $p \neq 0$ . Let  $\lambda_0 \in \mathbb{C}$  and write  $p(t) - \lambda_0 = \alpha \prod_{k=1}^n (t - \lambda_k)$ . Then

$$p(T) - \lambda_0 I = \alpha \prod_{k=1}^n (T - \lambda_k I)$$

Thus  $p(T) - \lambda_0 I \notin \mathcal{G}(X)$  if and only if some  $T - \lambda_k I \notin \mathcal{G}(X)$ , so  $\lambda_0 \in \sigma(p(T))$  if and only if at least one  $\lambda_k \in \sigma(T)$  if and only if  $p(\lambda) - \lambda_0 = 0$  for some  $\lambda \in \sigma(T)$ , i.e.  $\lambda_0 = p(\lambda) \in p(\sigma(T))$ . ■

**12.11 Theorem. (Spectral Radius Formula)** If  $T \in \mathcal{B}(X)$ , let  $r(T) = \sup\{|\lambda| : \lambda \in \sigma(T)\}$ . Then  $r(T) = \lim_{n \rightarrow \infty} \|T^n\|^{1/n}$ .

**PROOF** By the spectral mapping theorem,  $r(T^n) = r(T)^n$ . Moreover,  $r(T^n) \leq \|T^n\|$  since  $\sigma(T^n) \subseteq \|T^n\| \overline{\mathbb{D}}$ . Thus  $r(T) = r(T^n)^{1/n} \leq \|T^n\|^{1/n}$  so that  $r(T) \leq \liminf_{n \rightarrow \infty} \|T^n\|^{1/n}$ .

Now, let  $f \in \mathcal{B}(X)^*$ . We recall that for  $|z| > \|T\|$ ,

$$\begin{aligned} R(z) &= (zI - T)^{-1} = \frac{1}{z} \left( I - \frac{1}{z} T \right)^{-1} = \frac{1}{z} \sum_{k=0}^{\infty} \frac{1}{z^k} T^k \\ &= \sum_{k=1}^{\infty} \frac{1}{z^k} T^{k-1}. \end{aligned}$$

Thus the Holomorphic function  $F_f = f \circ R : \rho(T) = \mathbb{C} \setminus \sigma(T) \rightarrow \mathbb{C}$  satisfies  $F_f(z) = \sum_{k=1}^{\infty} f(T^{k-1}) \frac{1}{z^k}$ .

From  $\mathbb{C}$ -analysis, the holomorphic function admits a Laurent series for all  $z$  with  $|z| > r(T)$ , and by uniqueness of Laurent series,  $F_f(z) = \sum_{k=1}^{\infty} f(T^{k-1}) \frac{1}{z^k}$  for  $|z| > r(T)$ . Hence if

$|z_0| > r(T)$ , we have that  $\left\{ f \left( \frac{1}{z_0^k} T^k \right) \right\}_{k=1}^{\infty}$  is bounded in  $\mathbb{C}$ . Doing this for any  $f \in \mathcal{B}(X)^*$ , we may apply Banach-Steinhaus to see that  $\left\{ \frac{1}{z_0^k} T^k \right\}_{k=1}^{\infty}$  is bounded in  $\mathcal{B}(X)$ , so

$$\sup_{n \in \mathbb{N}} \left\| \frac{1}{z_0^n} T^n \right\| \leq M < \infty$$

Then  $\|T^n\| \leq M|z_0|^n$  so  $\|T^n\|^{1/n} \leq M^{1/n}|z_0|$ , so that

$$\limsup_{n \rightarrow \infty} \|T^n\|^{1/n} \leq |z_0|.$$

This applies for any  $|z_0| > r(T)$ , so the result follows.  $\blacksquare$

### 13 COMPACT OPERATORS

**Definition.** Let  $X, Y$  be Banach spaces over  $\mathbb{F}$ . A linear operator  $K : X \rightarrow Y$  is called **compact** if  $\overline{K(B(X))}$  is compact in  $Y$ . We let

$$\mathcal{K}(X, Y) = \{K \in \mathcal{L}(X, Y) : K \text{ is compact}\}.$$

Since compact sets in  $Y$  are bounded, we immediately see that  $\mathcal{K}(X, Y) \subseteq \mathcal{B}(X, Y)$ .

**13.1 Proposition.** Let  $X, Y$  be Banach spaces. Then

- (i)  $\mathcal{K}(X, Y)$  is a closed subspace of  $\mathcal{B}(X, Y)$ , and
- (ii) If  $W, Z$  are also Banach spaces,  $S \in \mathcal{B}(Y, Z)$ ,  $T \in \mathcal{B}(W, X)$ ,  $K \in \mathcal{K}(X, Y)$ , then  $SKT \in \mathcal{K}(W, Z)$ .

**PROOF** (i) Let  $K, L \in \mathcal{K}(X, Y)$ ,  $\alpha \in \mathbb{F}$ , and  $(x_n)_{n=1}^\infty \subset B(X)$ . Then  $\overline{K(B(X))} \times \overline{L(B(X))}$  is compact in  $Y \times Y \cong Y \oplus Y$ , so we have converging

$$\left( (Kx_{n_j}, Lx_{n_j}) \right)_{j=1}^\infty \subset \overline{K(B(X))} \times \overline{L(B(X))}$$

Now,  $(K + \alpha L)(x_{n_j}) = Kx_{n_j} + \alpha Lx_{n_j} \rightarrow y + \alpha y'$ , so  $((K + \alpha L)x_n)_{n=1}^\infty$  admits a converging subsequence in  $Y$ .

Now let  $K \in \overline{\mathcal{K}(X, Y)} \subseteq \mathcal{B}(X, Y)$ , so  $K = \lim_{n \rightarrow \infty} K_n$  with each  $K_n \in \mathcal{K}(X, Y)$ . Let  $\epsilon > 0$ . Let  $n_0 \in \mathbb{N}$  be so  $n \geq n_0$  implies  $\|K - K_n\| < \epsilon/3$ . Since  $K_{n_0}$  is compact, there are  $\{x_1, \dots, x_m\} \subset B(X)$  such that

$$K_{n_0}(B(X)) \subseteq \bigcup_{j=1}^m (K_{n_0}x_j + \frac{\epsilon}{3}B(Y))$$

Then for  $x \in B(X)$ , find  $x_j$  so  $K_{n_0}x \in K_{n_0}x_j + \frac{\epsilon}{3}B(X)$  and hence

$$\begin{aligned} \|Kx - Kx_j\| &\leq \|Kx - K_{n_0}x\| + \|K_{n_0}x - K_{n_0}x_j\| + \|K_{n_0}x_j - Kx_j\| \\ &\leq \|K - K_{n_0}\|\|x\| + \frac{\epsilon}{3} + \|K - K_{n_0}\|\|x_j\| < \end{aligned}$$

and we see that  $K(B(X)) \subseteq \bigcup_{j=1}^m (Kx_j + \epsilon B(Y))$ , and hence is totally bounded.

(ii) We have

$$\begin{aligned} \overline{SKT(B(W))} &\subseteq \overline{SK(\|T\|B(X))} = \|T\| \overline{SK(B(X))} \\ &= \|T\| \overline{S(\overline{K(B(X))})} \subseteq \|T\| \overline{S(\overline{K(B(X))})} = \|T\| S(\overline{K(B(X))}) \end{aligned}$$

is a continuous image of a compact set and hence compact.  $\blacksquare$



- Example.* (i) Given Banach spaces  $X, Y$ , let  $\mathcal{F}(X, Y) = \{F \in \mathcal{B}(X, Y) : \text{rank } F < \infty\}$ . Note that  $\text{rank } F = \dim(\text{im } F)$ . If  $F \in \mathcal{F}(X, Y)$ , then  $F(B(X)) \subseteq \|F\| B(\text{im } F)$  is subset of a compact set, so  $F$  is compact. Thus  $\overline{\mathcal{F}}(X, Y) \subseteq \mathcal{K}(X, Y)$ .
- (ii) Also  $W, Z$  Banach spaces,  $S \in \mathcal{B}(Y, Z)$ ,  $T \in \mathcal{B}(W, Z)$ , then  $SFT \in \mathcal{F}(W, Z)$  for  $F \in \mathcal{F}(X, Y)$ .
- (iii) Let  $I = [0, 1]$  and  $k \in C(I^2)$ . Then for  $f \in C(I)$ ,  $x \in I$ , define

$$Kf(x) = \int_0^1 k(x, y)f(y)dy$$

This defines a compact operator in  $\mathcal{K}(C(I), C(I))$ .  
To see this, let

$$\mathcal{A} = \text{span}\{(x, y) \mapsto \phi(x)\psi(y), \phi, \psi \in C(I)\} \subseteq C(I^2).$$

Then  $\mathcal{A}$  is an algebra of functions,  $1 \in \mathcal{A}$ ,  $\mathcal{A}$  is point separating, and if  $H \in \mathcal{A}$ , then  $\bar{H} \in \mathcal{A}$ . Thus by Stone-Weierstrass, the uniform closure  $\overline{\mathcal{A}} = C(I^2)$ . Hence,  $k = \lim k_n$  where each  $k_n(x, y) = \sum_{j=1}^{m_n} \phi_{n_j}(x)\psi_{n_j}(y)$ . Let

$$\begin{aligned} K_n f(x) &= \int_0^1 k_n(x, y)f(y)dy = \int_0^1 \sum_{j=1}^{m_n} \phi_{n_j}(x)\psi_{n_j}(y)f(y)dy \\ &= \sum_{j=1}^{m_n} \left[ \int_0^1 \psi_{n_j}(y)f(y)dy \right] \phi_{n_j}(x) \end{aligned}$$

so that

$$K_n f = \sum_{j=1}^{m_n} \left[ \int_0^1 \psi_{n_j} f \right] \phi_{n_j} \in \text{span}\{\phi_{n_1}, \dots, \phi_{n_{m_n}}\} \subset C(I)$$

so  $K$  has finite rank, and furthermore,

$$|K_n f(x)| \leq \int_0^1 |k_n(x, y)| \|f(y)\| dy \leq \int_0^1 \|k_n\|_\infty \|f\|_\infty dy = \|k_n\|_\infty \|f\|_\infty$$

so that  $\|K_n f\|_\infty \leq \|k_n\|_\infty \|f\|_\infty$ , so  $K_n$  is bounded. Thus each  $K_n \in \mathcal{F}(C(I))$ . Furthermore, for  $f \in C(I)$ ,

$$\|(K - K_n)f\|_\infty \leq \|k - k_n\|_\infty \|f\|_\infty$$

so  $\|K - K_n\| \leq \|k - k_n\|_\infty \xrightarrow{n \rightarrow \infty} 0$  so  $K \in \overline{\mathcal{F}(C(I))} \subseteq \mathcal{K}(C(I))$ .

*Exercise:* if  $1 \leq p < \infty$ , then  $K$ , as above, defines an operator in  $\mathcal{K}(L_p(I))$ . Notice that  $\|Kf\|_p \leq \|k\|_\infty \|f\|_p$ ,  $J : C(I) \rightarrow L_p(I)$  “identity” is bounded.

**13.2 Theorem.** Let  $X, Y$  be Banach spaces,  $K \in \mathcal{B}(X, Y)$ . Then the following are equivalent:

- (i)  $K \in \mathcal{K}(X, Y)$
- (ii)  $K^*|_{B(Y^*)} : B(Y^*) \rightarrow X^*$  is  $w^*$ -norm continuous
- (iii)  $K^* \in \mathcal{K}(Y^*, X^*)$

**PROOF** ( $i \Rightarrow ii$ ) Let  $f_0 = w^* - \lim_{v \in N} f_v$  in  $B(Y^*)$ . Given  $\epsilon > 0$ , let  $\{x_1, \dots, x_n\} \subset B(X)$  such that  $K(B(X)) \subseteq \bigcup_{j=1}^n (Kx_j + \frac{\epsilon}{3}B(X))$ . Hence if  $x \in B(X)$ , there is  $x_j$  such that  $\|Kx - Kx_j\| < \frac{\epsilon}{3}$ . Then for each  $v \in N$ , we have

$$\begin{aligned} |f_v(Kx) - f_0(Kx)| &\leq |f_v(Kx) - f_v(Kx_j)| + |f_v(Kx_j) - f_0(Kx_j)| + |f_0(Kx_j) - f_0(Kx)| \\ &\leq \|f_v\| \|Kx - Kx_j\| + |f_v(Kx_j) - f_0(Kx_j)| + \|f_0\| \|Kx_j - Kx\| \\ &< \frac{2\epsilon}{3} + |f_v(Kx_j) - f_0(Kx_j)| \end{aligned}$$

so

$$\|K^* f_v - K^* f_0\| = \sup_{x \in B(X)} |f_v(Kx) - f_0(Kx)| \leq \frac{2\epsilon}{3} + \max_{j=1, \dots, n} |f_v(Kx_j) - f_0(Kx_j)|$$

and hence there is  $v_0 \in N$  so  $v \geq v_0$  implies that  $|f_v(Kx_j) - f_0(Kx_j)| < \epsilon/3$  for  $j = 1, \dots, n$ , so  $v \geq v_0$  implies that  $\|K^* f_v - K^* f_0\| \leq \epsilon$ .

( $ii \Rightarrow iii$ ) We have that  $B(Y^*)$  is  $w^*$ -compact, so  $K^*(B(Y^*))$  is norm compact.

( $iii \Rightarrow i$ ) By the proof above,  $K^{**}$  is compact. Hence  $K(\widehat{B(X)}) = K^{**}(B(\hat{X})) \subseteq K^{**}(B(X^{**}))$  is compact, and  $\overline{K(B(X))} \cong K(\widehat{B(X)})$  is compact. ■

**13.3 Corollary.** If  $X$  and  $Y$  are reflexive,  $K \in \mathcal{B}(X, Y)$ , then the following are equivalent:

- (i)  $K \in \mathcal{K}(X, Y)$
- (ii)  $K(B(X))$  is compact
- (iii)  $K|_{B(X)} : B(X) \rightarrow Y$  is  $w$ -norm continuous.

**PROOF** In a reflexive space,  $w = w^*$  and  $K = K^{**}$ . ■

*Remark.* Let  $X, Y$  be reflexive,  $K \in \mathcal{B}(X, Y)$ . Then  $K$  is  $w$ -norm continuous if and only if  $K \in \mathcal{F}(X, Y)$ .

## 14 SPECTRAL THEORY FOR COMPACT OPERATORS

**14.1 Lemma.** Let  $K \in \mathcal{K}(X)$ . Suppose there are sequences

- of closed subspaces  $Y_1 \subsetneq Y_2 \subsetneq \dots$  of  $X$
- scalars  $(\alpha_j)_{j=1}^\infty$  such that  $(K - \alpha_j I)Y_j \subseteq Y_{j-1}$  for  $j = 1, 2, 3, \dots$

Then  $\lim_{j \rightarrow \infty} \alpha_j = 0$ .

**PROOF** Suppose not, i.e.  $\limsup_{j \rightarrow \infty} |\alpha_j| > 0$ . Passing to a subsequence if necessary, we may assume  $|\alpha_j| \geq \epsilon > 0$  for all  $j$ . By the Riesz lemma, find  $x_j \in B(Y_j)$  so  $\text{dist}(x_j, Y_{j-1}) > 1/2$ . Then  $y_j = (K - \alpha_j I)x_j \in Y_{j-1}$ , implying that  $Kx_j = y_j + \alpha_j x_j \in Y_j$ . If  $i < j$ , we have

$$\|Kx_j - Kx_i\| = \|y_j + \alpha_j x_j - Kx_i\| = |\alpha_j| \left\| x_j + \frac{1}{\alpha_j} (y_j - Kx_i) \right\| > \frac{|\alpha_j|}{2} \geq \frac{\epsilon}{2}$$

so that  $(Kx_j)_{j=1}^\infty$  admits no Cauchy sequence, a contradiction. ■

*Remark.* If  $T \in \mathcal{B}(X)$ ,  $\{\lambda_1, \dots, \lambda_n\} \subseteq \sigma_p(T)$  distinct. Then  $\{\ker(\lambda_i I - T)\}_{i=1}^n$  is a linearly independent sequence of subspace. This is true for  $n = 1$ , so suppose it holds for  $n - 1$ . Let

$x_j \in \ker(\lambda_j I - T) \setminus \{0\}$  for each  $1 \leq j \leq n$ , and suppose  $\alpha_1, \dots, \alpha_n \in \mathbb{C}$  satisfy  $0 = \alpha_1 x_1 + \dots + \alpha_n x_n$ . Suppose  $\alpha_{j_0} \neq 0$ . Write  $x_{j_0} = \sum_{\substack{j=1 \\ j \neq j_0}}^n \alpha'_j x_j$  where  $\alpha'_j = \alpha_j / \alpha_{j_0}$ . Then

$$\sum_{\substack{j=1 \\ j \neq j_0}}^n \alpha'_j \lambda_{j_0} x_{j_0} = \lambda_{j_0} x_{j_0} = T x_{j_0} = \sum_{\substack{j=1 \\ j \neq j_0}}^n \alpha'_j \lambda_j x_j$$

so that  $0 = \sum_{\substack{j=1 \\ j \neq j_0}}^n \alpha'_j (\lambda_j - \lambda_{j_0}) x_j$ , a contradiction.

**14.2 Theorem. (Spectral Theorem for Compact Operators)** Let  $X$  be an infinite dimensional  $\mathbb{C}$ -Banach space and  $K \in \mathcal{K}(X)$ . Then

- (i)  $\lambda \in \mathbb{C} \setminus \{0\}$ , then each “generalized eigenspace”  $\ker[(\lambda I - K)^n]$  is finite dimensional. Furthermore, there is  $n_\lambda \in \mathbb{N}$  such that  $\ker[(\lambda I - K)^n] = \ker[(\lambda I - K)^{n_\lambda}]$  for  $n \geq n_\lambda$ .
- (ii)  $\sigma(K) = \sigma_p(K) \cup \{0\}$ , where  $\sigma_p(K) = \{\lambda_1, \lambda_2, \dots\}$  with  $\lim_{n \rightarrow \infty} \lambda_n = 0$  if infinite.

**PROOF** (i) We have  $\ker(\lambda I - K) \subseteq \ker[(\lambda I - K)^2] \subseteq \dots$ . If  $n_\lambda$  as above does not exist, let  $n_1 = 1$  and  $n_{k+1} = \min\{n : \ker[(\lambda I - K)^{n_k}] \subsetneq \ker[(\lambda I - K)^n]\}$ , and set  $Y_0 = \{0\}$  and  $Y_k = \ker[(\lambda I - K)^{n_k}]$ . Then  $Y_0 \subsetneq Y_1 \subsetneq \dots$  and  $(\lambda I - K)Y_k \subseteq Y_{k-1}$ . But the preceding lemma implies that  $\lim_{n \rightarrow \infty} \lambda = 0$ , a contradiction.

Now suppose  $\dim \ker[(\lambda I - K)^n] = \infty$  for some  $n = n_\lambda$ . Then let  $k \in \mathbb{N}$  be so  $Y_k$  is infinite dimensional, while  $Y_{k-1}$  is finite dimensional. Thus we can find a linearly independent  $\{x_j\}_{j=1}^\infty \subset Y_k \setminus Y_{k-1}$ . We let  $V_0 = Y_{k-1}$  and  $V_n = \overline{\text{span}}\{V_0, x_1, \dots, x_n\}$  for each  $N \in \mathbb{N}$ . Then  $V_0 \subsetneq V_1 \subsetneq \dots$  and  $(\lambda I - K)V_n \subseteq (\lambda I - K)Y_k \subseteq Y_{k-1} = V_0 \subseteq V_{n-1}$  for  $N \in \mathbb{N}$ . Again by the preceding lemma, we have our contradiction.

- (ii) We first show that  $\sigma_{ap}(K) \subseteq \sigma_p(K) \cup \{0\}$ . If  $\lambda \in \sigma_{ap}(K) \setminus \{0\}$ , then there is  $(x_n)_{n=1}^\infty \subset S(X)$  such that  $(\lambda I - K)x_n \xrightarrow{n \rightarrow \infty} 0$ . Since  $K$  is compact, passing to a subsequence if necessary, we may assume  $y = \lim Kx_n$  exists. Then

$$\|\lambda x_n - y\| \leq \|(\lambda I - K)x_n\| + \|Kx_n - y\| \xrightarrow{n \rightarrow \infty} 0$$

where each  $\|\lambda x_n\| = |\lambda| \neq 0$  so  $y \neq 0$ . Furthermore,  $Ky = \lim_{n \rightarrow \infty} K(\lambda x_n) = \lambda \lim_{n \rightarrow \infty} Kx_n = \lambda y$ , so  $\lambda \in \sigma_p(K)$ .

Now suppose that  $\{\lambda_n\}_{n=1}^\infty \subseteq \partial\sigma(K) \setminus \{0\} \subseteq \sigma_{ap}(K) \setminus \{0\} \subseteq \sigma_p(K)$ . Let  $Y_0 = \{0\}$ ,  $Y_n = \sum_{j=1}^n \ker(\lambda_j I - K)$ . By linear independence of eigenspaces,  $Y_0 \subsetneq Y_1 \subsetneq \dots$  and  $(\lambda_n I - K)Y_n \subseteq Y_{n-1}$  for  $n \in \mathbb{N}$ . Then the previous lemma shows that  $\lim_{n \rightarrow \infty} \lambda_n = 0$ . Hence for each  $n \in \mathbb{N}$  we have that  $\partial\sigma(K) \setminus \frac{1}{n}\mathbb{D}$  is finite, and hence  $\partial\sigma(K) \subseteq \{0\} \cup \bigcup_{n=1}^\infty (\partial\sigma(K) \setminus \frac{1}{n}\mathbb{D})$  is countable. Thus  $\partial\sigma(K)$  is countable, so  $\sigma(K) \setminus \{0\}$  is countable. Moreover, note that  $0 \in \sigma(K)$ , for if not, then  $K \in \mathcal{G}(X)$  and  $I = KK^{-1} \in \mathcal{K}(X)$ , contradicting infinite dimensionality of  $X$ . ■

*Example.* We may have  $\sigma(K) = \{0\}$ ,  $\sigma_p(K) = \emptyset$ . Let  $K : \ell_p \rightarrow \ell_p$  be given by  $K(x_1, x_2, \dots) = (0, x_1, \frac{1}{2}x_2, \frac{1}{3}x_3, \dots)$ . It is easy to see that  $K \in \mathcal{K}(\ell_p)$  with  $\|K\| = 1$ . A straightforward induction shows  $K^n x = (0, \dots, 0, \frac{1}{n!}x_1, \frac{1}{(n+1)!}x_2, \dots)$  so  $\|K^n\| = \frac{1}{n!}$ . The spectral radius formula shows that  $r(K) = \lim_{n \rightarrow \infty} \frac{1}{(n!)^{1/n}} = 0$ , so  $\sigma(K) = \{0\}$ . However, as for the unilateral shift,  $\ker K = \{0\}$  but  $0 \notin \sigma_p(K)$ , so  $\sigma_p(K) = \emptyset$ .

Let  $\mathcal{H}$  be a complex Hilbert space. Recall that  $\mathcal{H}^* = \{f_y : y \in \mathcal{H}\}$  where  $f_y(x) = (x, y)$ . If  $T \in \mathcal{B}(\mathcal{H})$ , implicitly define  $T^*y$  as  $f_{T^*y} = T^*f_y$ . Note that  $(\alpha T)^* = \bar{\alpha}T^*$  and  $(Tx, y) = f_y(Tx) = T^*f_y(x) = f_{T^*y}(x) = (x, T^*y)$ .

**Definition.** Let  $H \in \mathcal{B}(\mathcal{H})$ . Then  $H$  is called **Hermitian** or **self-adjoint** if  $H = H^*$ . Let  $N \in \mathcal{B}(\mathcal{H})$  then  $N$  is **normal** if  $N^*N = NN^*$ .

Certainly Hermitian operators are normal.

**14.3 Proposition.** (i) If  $T \in \mathcal{B}(\mathcal{H})$ , there are unique Hermitian operators  $\operatorname{Re} T$ ,  $\operatorname{Im} T$ , such that  $T = \operatorname{Re} T + i\operatorname{Im} T$ .

(ii)  $T$  is normal if and only if  $(\operatorname{Re} T)(\operatorname{Im} T) = (\operatorname{Im} T)(\operatorname{Re} T)$ .

**PROOF** (i) Let  $\operatorname{Re} T = \frac{1}{2}(T + T^*)$  and  $\operatorname{Im} T = \frac{1}{2i}(T - T^*)$ . If we had  $T = H_1 + iH_2$ ,  $H_1, H_2$  each Hermitian, then

$$H_1 + iH_2 = T = \operatorname{Re} T + i\operatorname{Im} T \implies H_2 - \operatorname{Re} T = i(\operatorname{Im} T - H_2) := S$$

where  $S^* = S = -S^*$  so that  $S^* = 0$  and  $S = 0$ .

(ii) We have

$$TT^* = (\operatorname{Re} T + i\operatorname{Im} T)(\operatorname{Re} T - i\operatorname{Im} T) = (\operatorname{Re} T)^2 + i(\operatorname{Im} T \operatorname{Re} T + \operatorname{Re} T \operatorname{Im} T) + (\operatorname{Im} T)^2$$

and

$$T^*T = (\operatorname{Re} T - i\operatorname{Im} T)(\operatorname{Re} T + i\operatorname{Im} T) = (\operatorname{Re} T)^2 - i(\operatorname{Im} T \operatorname{Re} T - \operatorname{Re} T \operatorname{Im} T) + (\operatorname{Im} T)^2$$

so that  $TT^* = T^*T$  if and only if  $2\operatorname{Im} T \operatorname{Re} T = 2\operatorname{Re} T \operatorname{Im} T$ . ■

**14.4 Proposition. (C\*-identity)** If  $T \in \mathcal{B}(\mathcal{H})$ , then  $\|T^*T\| = \|T\|^2$ .

**PROOF** We have

$$\begin{aligned} \|T\|^2 &= \sup_{x \in \mathcal{B}(\mathcal{H})} \|Tx\|^2 = \sup_{x \in \mathcal{B}(\mathcal{H})} (Tx, Tx) \\ &= \sup_{x \in \mathcal{B}(\mathcal{H})} \|T^*Tx, x\| \leq \sup_{x \in \mathcal{B}(\mathcal{H})} \|T^*Tx\| \|x\| = \|T^*T\| \end{aligned}$$

while  $\|T^*T\| \leq \|T^*\| \|T\| = \|T\|^2$ . ■

**14.5 Proposition.** If  $N \in \mathcal{B}(\mathcal{H})$  is normal, then  $r(N) = \|N\|$ .

**PROOF** Suppose first that  $H = H^*$  in  $\mathcal{B}(\mathcal{H})$ . The  $C^*$ -identity gives  $\|H^2\| = \|H^*H\| = \|H\|^2$  and hence inductively for  $k \in \mathbb{N}$   $\|H^{2k}\| = \|H\|^{2k}$  since  $H^k$  is Hermitian for any  $k$ . Now since  $N^*N = NN^*$ , we see that  $(N^*N)^n = (N^*)^n N^n$  for  $n \in \mathbb{N}$ . Hence if  $k \in \mathbb{N}$ , we use the  $C^*$ -identity to see

$$\|N\|^{2^{k+1}} = \|N^*N\|^{2^k} = \|(N^*N)^{2^k}\| = \|(N^{2^k})^* N^{2^k}\| = \|N^{2^k}\|^2$$

and hence  $\|N\|^{2^k} = \|N^{2^k}\|$ . Now, by the spectral radius formula,  $r(N) = \lim_{n \rightarrow \infty} \|N^n\|^{1/n} = \lim_{k \rightarrow \infty} \|N^{2^k}\|^{1/2^k} = \|N\|$ . ■

*Remark.* If  $T \in \mathcal{B}(X)$ , then  $\sigma(T) = \sigma_{ap}(T) \cup \sigma_{com}(T)$ . Indeed, if  $\lambda \in \sigma(T)$ , then  $\lambda I - T \notin \mathcal{G}(X)$ , and hence at least one of the following holds:

- $\lambda I - T$  is not bounded below, i.e.  $\lambda \in \sigma_{ap}(T)$
- $\text{im}(\lambda I - T)$  is not dense, i.e.  $\lambda \in \sigma_{com}(T)$ .

**14.6 Proposition.** *If  $H = H^*$  in  $\mathcal{B}(\mathcal{H})$ , then  $\sigma(H) = \sigma_{ap}(H) \subseteq \mathbb{R}$ .*

**PROOF** If  $\lambda \in \sigma_{ap}(H)$ , then there is  $(x_n)_{n=1}^\infty \subset S(\mathcal{H})$  such that  $(\lambda I - H)x_n \rightarrow 0$ . Then

$$\lambda - (Hx_n, x_n) = \lambda(x_n, x_n) - (Hx_n, x_n) = ((\lambda I - H)x_n, x_n) \rightarrow 0$$

and  $(Hx_n, x_n) = \overline{(x_n, Hx_n)} = \overline{(Hx_n, x_n)} \in \mathbb{R}$  for each  $n$ , so  $\lambda \in \mathbb{R}$ . Now,  $\sigma_{com}(H) = \{\bar{\lambda} : \lambda \in \sigma_p(H^*) = \sigma_p(H)\}$ , so as  $\sigma_p(H) \subseteq \sigma_{ap}(H) \subseteq \mathbb{R}$ , we see that  $\sigma_{com}(H) \subseteq \sigma_p(H) \subseteq \sigma_{ap}(H)$  and use the remark above. ■

*Remark.* (i)  $(Hx, x) \in \mathbb{R}$  if  $H = H^*$ ,  $x \in \mathcal{H}$ . If we define  $[\cdot, \cdot] : \mathcal{H} \times \mathcal{H} \rightarrow \mathbb{C}$  by  $[x, y] = (Hx, y)$ , then  $[\cdot, \cdot]$  is Hermitian by the Polarization identity.

(ii) If, further,  $(Hx, x) \geq 0$  for any  $x \in \mathcal{H}$ , then  $\sigma(H) \subseteq [0, \infty)$ . We call such  $H$  **positive**

(iii) If  $T \in \mathcal{B}(\mathcal{H})$ , then  $\sigma(T^*T) \subseteq [0, \infty)$  as  $T^*T$  is Hermitian,  $(T^*Tx, x) = \|Tx\|^2 \geq 0$ .

**14.7 Theorem. (Functional Calculus for Bounded Hermitian Operators)** *Let  $H \in \mathcal{B}(\mathcal{H})$  be Hermitian. Then there is a unique bounded operator  $\Phi : C(\sigma(H)) \rightarrow \mathcal{B}(\mathcal{H})$  satisfying*

- $\Phi(1) = I$ ,  $\Phi(\iota) = H$ , where  $\iota$  is the identity function on  $\sigma(H)$
- $\Phi(fg) = \Phi(f)\Phi(g)$  for  $f, g$  in  $C(\sigma(H))$ .

Furthermore,  $\Phi$

- $\Phi$  is an isometry
- $\Phi(f)T = T\Phi(f)$  for any  $f \in C(\sigma(H))$ , provided that  $HT = TH$ .
- $\Phi(f) = \Phi(f)^*$  for  $f \in C(\sigma(H))$

**PROOF** Let  $\text{Pol}(\sigma(H))$  denote the polynomial functions restricted to  $\sigma(H)$ . Then we have

- (i)  $\sigma(p(H)) = p(\sigma(H))$
- (ii)  $\|p(H)\| = r(p(H))$  as  $p(H)$  is normal.
- (iii)  $\|fg\|_\infty \leq \|f\|_\infty \|g\|_\infty$

We let  $\Phi_0 : \text{Pol}(\sigma(H)) \rightarrow \mathcal{B}(\mathcal{H})$  by  $\Phi_0(p) = p(H)$ . Then  $\Phi_0$  is the unique linear operator such that  $\Phi_0(1) = I$ ,  $\Phi_0(\iota) = H$ , and  $\Phi_0(pq) = \Phi_0(p)\Phi_0(q)$  for  $p, q \in \text{Pol}(\sigma(H))$ . Moreover, (ii) shows that  $\|p\|_\infty = r(p(H))$  so that  $r(p(H)) = \|p(H)\|$  so that  $\Phi_0 : \text{Pol}(\sigma(H)) \rightarrow \mathcal{B}(\mathcal{H})$  is an isometry. Thus since  $\sigma(H)$  is compact, by Stone-Weierstrass,  $\overline{\text{Pol}(\sigma(H))}^{\|\cdot\|_\infty} = C(\sigma(H))$ , where we are conjugacy closed since  $\sigma(H) \subseteq \mathbb{R}$ . Hence  $\Phi_0$  admits a unique extension  $\Phi : C(\sigma(H)) \rightarrow \mathcal{B}(\mathcal{H})$ . This is clearly isometric and satisfies the properties of  $\Phi_0$ . If  $f, g \in C(\sigma(H))$ , say  $f = \lim p_n$ ,  $g = \lim q_n$ , then  $\|fg - p_nq_n\|_\infty \rightarrow 0$ , and hence

$$\|\Phi(fg) - \Phi(f)\Phi(g)\| \leq \|\Phi(fg) - \Phi_0(p_nq_n)\| + \|\Phi_0(p_n)\Phi_0(q_n) - \Phi(f)\Phi(g)\| \rightarrow 0$$

so  $\Phi(fg) = \Phi(f)\Phi(g)$ . The other properties follow similarly. ■

**14.8 Theorem. (Spectral Theorem for Compact Hermitian Operators)** *Let  $H = H^*$  in  $\mathcal{K}(\mathcal{H})$  and enumerate  $\sigma(H) \setminus \{0\} = \{\lambda_1, \lambda_2, \dots\} \subseteq \mathbb{R}$ . Then there exists a sequence  $\{P_1, P_2, \dots\}$  of finite rank orthogonal projections such that*

- $H = \sum_{n=1}^{\infty} \lambda_n P_n$  converging in norm
- If  $m \neq n$ ,  $P_n P_m = 0$  so  $\text{im } P_n \perp \text{im } P_m$
- For  $T \in \mathcal{B}(\mathcal{H})$ ,  $TH = HT$  if and only if  $TP_n = P_n T$  for each  $n$ .
- Each  $\text{im } P_n$  is finite dimensional.

PROOF Since  $\sigma(H) = \{\lambda_1, \lambda_2, \dots\} \cup \{0\}$  with  $\lim \lambda_n = 0$ . Then for each  $n$ , let  $\phi_n = \chi_{\{\lambda_n\}}$ , and note that  $\phi_n \in C(\sigma(H))$  and  $\iota = \sum_{n=1}^{\infty} \lambda_n \phi_n$  where the infinite sum converges uniformly. Let  $P_n = \phi_n(H)$ , so that

$$H = \iota(H) = \sum_{n=1}^{\infty} \lambda_n \phi_n(H) = \sum_{n=1}^{\infty} \lambda_n P_n \quad (14.1)$$

Also, if  $n, m \geq 1$ ,  $\phi_n \phi_m = \phi_n$  if and only if  $n = m$ , so  $P_n^2 = \phi_n^2(H) = P_n$ , and  $\|P_n\| = \|\phi_n\|_{\infty} = 1$  so by A4  $P_n$  is an orthogonal projection. If  $n \neq m$ ,  $P_n P_m = \phi_n(H) \phi_m(H) = 0(H) = 0$  so that  $\text{im } P_n \perp \text{im } P_m$ .

Suppose now that  $HT = TH$ . Then  $P_n T = \phi_n(H) T = T \phi_n(H) = T P_n$  for each  $n$ . If  $P_n T = T P_n$  for each  $n$ , then  $T$  commutes with the infinite sum in (14.1) and hence with  $H$ .

Finally, multiplicativity of the functional calculus to see that  $P_n = \frac{1}{\lambda_n} P_n H$  so  $P_n \in \mathcal{K}(\mathcal{H})$ . Moreover,  $B(\text{im } P_n) = P_n(B(\text{im } P_n)) \subseteq P_n(\mathcal{B}(\mathcal{H}))$  is compact, and hence  $\text{im } P_n$  is finite dimensional. ■

**14.9 Corollary. (Spectral Theorem for Compact Normal Operators)** If  $K \in \mathcal{K}(\mathcal{H})$  with  $K^* K = K K^*$ , then given an enumeration  $\{\mu_1, \mu_2, \dots\}$  of  $\sigma(K) \setminus \{0\}$  there is a sequence of finite rank orthogonal projections  $\{P_1, P_2, \dots\}$  such that  $K = \sum_{n=1}^{\infty} \mu_n P_n$  and  $P_n P_m = 0$  if  $n \neq m$ .

PROOF Let  $H_1 = \text{Re } K$ ,  $H_2 = \text{im } K$ , so  $H_1 H_2 = H_2 H_1$ , each is compact Hermitian, and write

$$H_j = \sum_{n=1}^{\infty} \lambda_{jn} P_{jn}$$

as above. Notice that  $P_{1n} P_{2n} = P_{2n} P_{1n}$  for  $n, m$ , so each is a norm 1 idempotent and hence an orthogonal projection. Moreover,  $\text{im } P_{1n} P_{2m} \subseteq \text{im } P_{1n}$  is finite dimensional. Let  $\{P_1, P_2, \dots\}$  be an enumeration of  $\{P_{1n} P_{2m} : m, n \in \mathbb{N} \cup \{0\} \times \mathbb{N} \cup \{0\}\}$  and set  $P_j = P_{\ker H_j}$ . Then  $\{\mu_1, \mu_2, \dots\}$  is an associated enumeration of  $\lambda_{1n} + i \lambda_{2m}$ . ■

**Definition.** Let  $\mathcal{H}$  be a Hilbert space. A **partial isometry** is a linear operator  $U : \mathcal{H} \rightarrow \mathcal{H}$  such that  $U|_{(\ker U)^{\perp}}$  is an isometry. Hence  $\|U\| = 1$ , or  $\|U\| = 0$  if  $\ker U = \mathcal{H}$ .

**14.10 Theorem. (Polar Decomposition)** Let  $T \in \mathcal{B}(\mathcal{H})$ . Then there is an operator  $|T|$  such that  $|T|^* = |T|$  and a partial isometry  $U$  such that  $T = U|T|$ .

PROOF We have  $T^* T$  is Hermitian with  $\sigma(T^* T) \subseteq [0, \infty)$ . Thus we may define by the functional calculus  $|T| = (T^* T)^{1/2}$  is a bounded operator. Notice that  $\sqrt{\cdot} : [0, \infty) \rightarrow [0, \infty)$  is  $\mathbb{R}$ -valued, so  $|T|^* = |T|$ . Given  $x \in \mathcal{H}$ ,

$$\|Tx\|^2 = (|T|x, |T|x) = (|T|^2 x, x) = (T^* T x, x) = (Tx, Tx) = \|Tx\|^2.$$

Define  $U_0 : \text{im } |T| \rightarrow \mathcal{H}$  by  $U_0 |T|x = Tx$ . If  $|T|x = |T|x'$ , then  $x - x' \in \ker |T| = \ker T$ , so  $Tx = Tx'$  so  $U_0$  is well-defined. Similarly,  $U_0$  is linear, and we computed above that  $U_0$

is an isometry. Let  $U_1 : \overline{\text{im } T} \rightarrow \mathcal{H}$  be the unique continuous extension. We note that  $\overline{\text{im } T} = (\ker T)^\perp$ , and define  $U = U_1 P_{\overline{\text{im } T}}$ . Then  $T = U|T|$  by construction of  $U_0$  and  $\ker U = \ker T$ . ■

**14.11 Corollary.** Let  $K \in \mathcal{K}(\mathcal{H})$ . Then there exists a sequence

- $s_1(K) > s_2(K) > \dots$  with  $\lim_{n \rightarrow \infty} s_n(K) = 0$  if infinite
- A sequence  $\{P_1, P_2, \dots\}$  of finite rank orthogonal projections with  $P_n P_m = 0$  if  $n \neq m$
- A partial isometry  $U$  on  $\mathcal{H}$  with  $\ker U = \ker K$  such that  $K = \sum_{n=1}^{\infty} s_n(K) U P_n$

**PROOF** We let  $\{\lambda_1, \lambda_2, \dots\} \subset (0, \infty)$  and  $\{P_1, P_2, \dots\}$  arise from the spectral theorem applied to  $K^*K$ , so  $K^*K = \sum_{n=1}^{\infty} \lambda_n P_n$ . Then  $|K| = (K^*K)^{1/2} = \sum_{n=1}^{\infty} \sqrt{\lambda_n} P_n$ . Let  $s_n(K) = \sqrt{\lambda_n}$  and apply the polar decomposition. ■

- Note that  $\ker U = \ker(K^*K) \perp \text{im } P_n$  so  $U P_n$  is a partial isometry of finite rank.
- $\text{im } U P_n \perp \text{im } U P_m$  for  $n \neq m$ . To see this, for  $x, y \in \mathcal{H}$ , then by polarization,

$$\begin{aligned} (U P_n x, U P_m y) &= \frac{1}{4} \sum_{k=0}^3 i^k (U(P_n x + i^k P_m y), U(P_n x + i^k P_m y)) \\ &= \frac{1}{4} \sum_{k=0}^3 i^k \|U(P_n + i^k P_m y)\|^2 = \frac{1}{4} \sum_{k=0}^3 \|P_n + i^k P_m y\|^2 \\ &= (P_n x, P_m y) = 0 \end{aligned}$$

For example, compute  $U, |K|$  for  $x \in \ell_2$  and  $Kx = (0, x_1, \frac{1}{2}x_2, \frac{1}{3}x_3, \dots)$ .