

# Geometry of TVS's

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## Introduction

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# Chapter 2

## Prerequisite Knowledge

### 2.1 Weak Topologies And Dual Spaces Of Seminormed Spaces

#### 2.1.1 Quotient Maps

**Definition 2.1.1** (Topological Space).  $(Z, \mathcal{T}_Z)$

**Definition 2.1.2** (Homeomorphism).

**Definition 2.1.3** (Neighborhood Filter). Let  $(Z, \mathcal{T}_Z)$  be a **Topological Space**. Let  $x \in Z$ . We denote with  $\mathcal{U}_{\mathcal{T}_Z}(x)$  the collection of all elements of  $\mathcal{T}_Z$  containing  $x$ . We call  $\mathcal{U}_{\mathcal{T}_Z}(x)$  a **Neighborhood Filter** of  $\mathcal{T}_Z$  at  $x$ .

**Definition 2.1.4** (relation of equal neighborhood filters). Let  $(Z, \mathcal{T}_Z)$  be a topological space. Define the relation  $\cong$  on  $Z$  by setting, for  $x, y \in Z$ ,

$$x \cong y \iff \mathcal{U}_{\mathcal{T}_Z}(x) = \mathcal{U}_{\mathcal{T}_Z}(y) \quad (2.1)$$

We call  $\cong$  the **Relation Of Equal Neighborhood Filters** on  $(Z, \mathcal{T}_Z)$

**Proposition 2.1.5** (Equal Neighborhood Filters Equivalence Relation). *The relation of equal neighborhood filters  $\cong$  on a topological space  $(Z, \mathcal{T}_Z)$  forms an equivalence relation on  $Z$ .*

*Proof.* Let  $x \in (Z, \mathcal{T}_Z)$ . Then  $\mathcal{U}_{\mathcal{T}_Z}(x) = \mathcal{U}_{\mathcal{T}_Z}(x)$ , so  $x \cong x$ . Thus  $\cong$  is reflexive.

Let  $x, y \in (Z, \mathcal{T}_Z)$ . Suppose  $x \cong y$ . Then  $\mathcal{U}_{\mathcal{T}_Z}(x) = \mathcal{U}_{\mathcal{T}_Z}(y)$ , so trivially  $\mathcal{U}_{\mathcal{T}_Z}(y) = \mathcal{U}_{\mathcal{T}_Z}(x)$ , and thus  $y \cong x$ . Hence,  $\cong$  is symmetric.

Let  $x, y, z \in (Z, \mathcal{T}_Z)$ . Let  $x \cong y$  and  $y \cong z$ . Then,  $\mathcal{U}_{\mathcal{T}_Z}(x) = \mathcal{U}_{\mathcal{T}_Z}(y) = \mathcal{U}_{\mathcal{T}_Z}(z)$  so that  $x \cong z$ . Thus  $\cong$  is transitive.

Since  $\cong$  is Reflexive, Symmetric, and Transitive, it is an equivalence relation.

□

**Definition 2.1.6** (Equivalence Class). Let  $X \neq \emptyset$ . Let  $\cong$  be an equivalence relation defined on  $X$ . Let  $x \in X$ . We define the set  $[x]_{\cong}$  by

$$[x]_{\cong} = \{y \in X \mid y \cong x\} \quad (2.2)$$

We call  $[x]_{\cong}$  the **Equivalence Class** of  $x$  in  $(X, \cong)$ .

**Proposition 2.1.7** (Equivalence Classes Partition). Let  $X \neq \emptyset$ . Let  $\cong$  be an equivalence relation defined on  $X$ . Let  $x, y \in X$ . The following statements are equivalent.

1.  $[x]_{\cong} \cap [y]_{\cong} \neq \emptyset$
2.  $x \cong y$
3.  $[x]_{\cong} = [y]_{\cong}$
4.  $[x]_{\cong} \subset [y]_{\cong}$
5.  $[y]_{\cong} \subset [x]_{\cong}$

*Proof That 1  $\implies$  2.* Suppose  $M := [x]_{\cong} \cap [y]_{\cong} \neq \emptyset$ . Then there exists  $z \in M$ . Then  $z \cong x$ , so by symmetry,  $x \cong z$ . But by transitivity, pair with  $z \cong y$ , we conclude  $x \cong y$ .  $\square$

*Proof That 2  $\implies$  4.* Let  $x \cong y$  and let  $z \in [x]_{\cong}$ . Then  $z \cong x \cong y$ , so  $z \cong y$  and  $z \in [y]_{\cong}$ . Since  $z$  was arbitrary, we're done.  $\square$

*Proof That 2  $\implies$  5.* Let  $x \cong y$ . By symmetry,  $y \cong x$ , so by (2  $\implies$  4), we are done.  $\square$

*Proof That 2  $\implies$  3.* Since 2  $\implies$  4 and 2  $\implies$  5 and 5 and 4 together imply 3, we have this.  $\square$

*Proof That 5  $\implies$  1.* Let  $[y]_{\cong} \subset [x]_{\cong}$ . Then  $y \in [y]_{\cong} = [y]_{\cong} \cap [x]_{\cong}$ . Hence 1 holds.  $\square$

**Definition 2.1.8** (Quotient Set). Let  $X \neq \emptyset$ . Let  $\cong$  be an equivalence relation defined on  $X$ . We define the set  $X/\cong$  by

$$X/\cong = \{[x]_{\cong} : x \in X\} \quad (2.3)$$

We call  $X/\cong$  the **Quotient Set** of  $X$  under the relation  $\cong$ .

**Remark 2.1.9** (Quotient Set Partition). By 2.1.7,  $X/\cong$  is a partition of  $X$ .

**Definition 2.1.10** (Quotient Map). Let  $X \neq \emptyset$ . Let  $\cong$  be an equivalence relation on  $X$ . Let  $X/\cong$  be the **Quotient Set** of  $X$  with respect to the relation  $\cong$ . Define  $T : X \rightarrow X/\cong$  by setting, for each  $x \in X$ ,

$$T(x) = [x]_{\cong} \quad (2.4)$$

We call  $T$  the **Quotient Map** of  $X$  under the relation  $\cong$ .

**Proposition 2.1.11** (Quotient Map Surjective). *Let  $X \neq \emptyset$ . Let  $\cong$  be an equivalence relation on  $X$ . Let  $T : X \rightarrow X/\cong$  be the **Quotient Map** of  $X$  under the relation  $\cong$ . Then  $T$  is a surjection.*

*Proof.* Let  $K \in Z/\cong$ . Then for some  $x \in Z$ ,  $K = [x]$ . Then  $T(x) = K$ . Since  $K$  was arbitrary, we are done.  $\square$

**Definition 2.1.12** (Quotient Space Topology). *Let  $(Z, \mathcal{T}_Z)$  be a topological space. Let  $\cong$  be the **Relation Of Equal Neighborhood Filters** on  $(Z, \mathcal{T}_Z)$ . Let  $T$  be the **Quotient Map** of  $Z$  under the relation  $\cong$ . Define  $\mathcal{T}_{Z/\cong}$  by*

$$\mathcal{T}_{Z/\cong} = \left\{ \bigcup_{x \in U} \{T(x)\} \in 2^{Z/\cong} \mid U \in \mathcal{T}_Z \right\} \quad (2.5)$$

By 2.1.13,  $\mathcal{T}_{Z/\cong}$  is a topology on  $Z/\cong$ . We call  $\mathcal{T}_{Z/\cong}$  the **Quotient Topology** and we call  $(Z/\cong, \mathcal{T}_{Z/\cong})$  the **Quotient Topological Space** of  $(Z, \mathcal{T}_Z)$ .

**Proposition 2.1.13** (Quotient Space Topology). *Let  $(Z, \mathcal{T}_Z)$  be a topological space with **Quotient Topological Space**  $(Z/\cong, \mathcal{T}_{Z/\cong})$  and **Quotient Map**  $T$ .*

*Then the following are true.*

1.  $\mathcal{T}_{Z/\cong}$  is a topology on  $Z/\cong$ .
2.  $T : (Z, \mathcal{T}_Z) \rightarrow (Z/\cong, \mathcal{T}_{Z/\cong})$  is continuous.
3. If  $U$  is open (closed) in  $(Z, \mathcal{T}_Z)$  then  $T(U)$  and  $T(Z \setminus U)$  partition  $Z/\cong$ .
4. If  $U$  is open in  $(Z, \mathcal{T}_Z)$ , then  $T^{-1}(T(U)) = U$ .
5. If  $K$  is closed in  $(Z, \mathcal{T}_Z)$ , then  $T^{-1}T(K) = K$ .
6.  $T : (Z, \mathcal{T}_Z) \rightarrow (Z/\cong, \mathcal{T}_{Z/\cong})$  is an open mapping.
7.  $T : (Z, \mathcal{T}_Z) \rightarrow (Z/\cong, \mathcal{T}_{Z/\cong})$  is a closed mapping.
8.  $(Z, \mathcal{T}_Z)$  is a compact space if and only if  $(Z/\cong, \mathcal{T}_{Z/\cong})$  is a compact space.
9. If  $\mathcal{B}$  is a basis for  $\mathcal{T}_z$ , then  $\{T(U) \mid U \in \mathcal{B}\}$  is a basis for  $\mathcal{T}_{Z/\cong}$ .
10. If  $T$  is injective, then it is a **Homeomorphism**.

*Proof of 1.* Since  $\emptyset \in \mathcal{T}_Z$ , we have

$$\emptyset = \bigcup_{x \in \emptyset} \{Tx\} \in \mathcal{T}_{Z/\cong} \quad (2.6)$$

Since  $Z \in \mathcal{T}_Z$ , and by 2.1.9,

$$Z/\cong = \bigcup_{x \in Z} \{[x]\} = \bigcup_{x \in Z} \{T(x)\} \in \mathcal{T}_{Z/\cong} \quad (2.7)$$



Let  $\{U_\alpha | \alpha \in A\} \subset \mathcal{T}_{Z/\cong}$ . For each  $\alpha \in A$ , there exists  $B_\alpha \in \mathcal{T}_Z$  such that we have

$$U_\alpha = \bigcup_{x \in B_\alpha} \{Tx\} \quad (2.8)$$

Since  $\bigcup_{\alpha \in A} B_\alpha \in \mathcal{T}_Z$ , we have

$$\bigcup_{\alpha \in A} U_\alpha = \bigcup_{\alpha \in A} \bigcup_{x \in U_\alpha} \{T(x)\} = \bigcup_{x \in \bigcup_{\alpha \in A} B_\alpha} \{T(x)\} \in \mathcal{T}_{Z/\cong} \quad (2.9)$$

Let  $\{U_i\}_{i=1}^n \subset \mathcal{T}_{Z/\cong}$ . For each  $i \in \{1, \dots, n\}$ , there exists  $B_i \in \mathcal{T}_Z$  such that

$$U_i = \bigcup_{x \in B_i} \{T(x)\} \quad (2.10)$$

Suppose

$$[x_0] \in \bigcap_{i=1}^n \bigcup_{x \in B_i} \{T(x)\} \quad (2.11)$$

Then for each  $i \in \{1, \dots, n\}$ , there is a  $y_i \in B_i$  such that  $y_i \cong x_0$ . Since each  $B_i$  is open, the definition of  $\cong$  implies that  $x_0 \in B_i$  for every  $i$ . Hence,

$$x_0 \in \bigcap_{i=1}^n B_i \quad (2.12)$$

Implying

$$[x_0] \in \bigcup_{x \in \bigcap_{i=1}^n B_i} \{[x]\} \quad (2.13)$$

Hence,

$$\bigcap_{i=1}^n \bigcup_{x \in B_i} \{T(x)\} \subset \bigcup_{x \in \bigcap_{i=1}^n B_i} \{[x]\} \quad (2.14)$$

Furthermore, since the reverse inclusion is obvious, and since  $\bigcap_{i=1}^n B_i \in \mathcal{T}_Z$ , we have

$$\bigcap_{i=1}^n U_i = \bigcap_{i=1}^n \bigcup_{x \in B_i} \{T(x)\} = \bigcup_{x \in \bigcap_{i=1}^n B_i} \{T(x)\} \in \mathcal{T}_{Z/\cong} \quad (2.15)$$

□

*Proof of 2.* Let  $V \in \mathcal{T}_{Z/\cong}$ . Let  $x_0 \in T^{-1}(V)$ . Then  $[x_0] \in V$ . By definition, there is a  $U \in \mathcal{T}_Z$  such that

$$T(U) \subset \bigcup_{x \in U} \{T(x)\} = V \quad (2.16)$$

Hence there is a  $y_0 \in U$  such that

$$[x_0] \in T(y_0) = \{[y_0]\} \quad (2.17)$$

Therefore,  $x \cong y$ . Definition of the relation of equal neighborhood filters implies  $\mathcal{U}(x_0) = \mathcal{U}(y_0)$ . Hence,  $x_0 \in U \subset T^{-1}(V)$ .  $\square$

*Proof of 3.* Let  $K$  be closed in  $(Z, \mathcal{T}_Z)$ . Then each point  $x_0$  in  $Z \setminus K$  has some  $U_{x_0} \in \mathcal{U}_{\mathcal{T}_Z}(x_0)$  which is disjoint from  $K$ . Hence  $y_0 \not\cong x_0$  for any  $y_0 \in K$ ,  $x_0 \in Z \setminus K$ . Hence  $T(K)$  is disjoint from  $T(Z \setminus K)$ . This fact, paired with 2.1.1, implies  $T(Z \setminus K)$  and  $T(K)$  partition  $Z/\cong$ .  $\square$

*Proof of 4.* Let  $U \in \mathcal{T}_Z$ . The nontrivial direction to prove is  $T^{-1}(T(U)) \subset U$ . Let  $y \in T^{-1}(T(U))$ . Then  $[y] = Ty \in T(U)$ . Hence,  $[y] = T(x) = [x]$  for some  $x \in U$ . Since  $y \cong x$  and  $x \in U \in \mathcal{U}_{\mathcal{T}_Z}(x)$ , we have  $U \in \mathcal{U}_{\mathcal{T}_Z}(y)$ . Hence  $y \in U$ . Since  $y$  was arbitrary,  $T^{-1}(T(U)) \subset U$ , and equality is obvious because the other direction of inclusion is trivial.  $\square$

*Proof of 5.* Let  $K$  be closed in  $(Z, \mathcal{T}_Z)$ . Part 3 Of this result implies  $Z/\cong$  is partitioned by  $T(K)$  and  $T(Z \setminus K)$ .

By part 4 of this proposition,

$$\begin{aligned} T^{-1}(T(K)) &= T^{-1}(T(Z) \setminus T(Z \setminus K)) \\ &= T^{-1}(Z/\cong \setminus T(Z \setminus K)) \\ &= T^{-1}(Z/\cong) \setminus T^{-1}(T(Z \setminus K)) \\ &= Z \setminus (Z \setminus K) \\ &= K \end{aligned}$$

$\square$

*Proof of 6.* Let  $U \in \mathcal{T}_Z$ . Then by definition of the **Quotient Topology**

$$TU = \bigcup_{x \in U} \{T(x)\} \in \mathcal{T}_{Z/\cong} \quad (2.18)$$

$\square$

*Proof of 7.* Let  $K$  be closed in  $(Z, \mathcal{T}_Z)$ . Then  $Z \setminus K \in \mathcal{T}_Z$ . By Parts 3 and five of this proposition, we know  $T(K) = Z/\cong \setminus T(Z \setminus K)$  and also that  $T(Z \setminus K) \in \mathcal{T}_{Z/\cong}$ . Hence  $T(K)$  is closed in  $(Z/\cong, \mathcal{T}_{Z/\cong})$ .  $\square$

*Proof of 8.* Let  $(Z, \mathcal{T}_Z)$  be compact. Let  $\{U_\alpha\}_{\alpha \in A}$  be an open covering of  $(Z/\cong, \mathcal{T}_{Z/\cong})$ . Then  $\{T^{-1}(U_\alpha) \mid \alpha \in A\}$  is an open covering of  $(Z, \mathcal{T}_Z)$ . Compactness of  $(Z, \mathcal{T}_Z)$  guarantees the existence of a finite subcovering  $\{T^{-1}(U_{\alpha_i}) \mid i \in \{1, \dots, n\}\}$ . Hence  $\{U_{\alpha_i} \mid i \in \{1, \dots, n\}\} = \{TT^{-1}(U_{\alpha_i}) \mid i \in \{1, \dots, n\}\}$  is an open covering of  $(Z/\cong, \mathcal{T}_{Z/\cong})$ . And the compactness of  $(Z/\cong, \mathcal{T}_{Z/\cong})$  is verified.

Now, suppose  $(Z/\cong, \mathcal{T}_{Z/\cong})$  is compact. Let  $\{V_\beta \mid \beta \in B\}$  be an open covering of  $(Z, \mathcal{T}_Z)$ . Since  $T$  is an open mapping,  $\{T(V_\beta) \mid \beta \in B\}$  is an open covering of  $(Z/\cong, \mathcal{T}_{Z/\cong})$  which by compactness has a finite subcover  $\{T(V_{\beta_i}) \mid i \in \{1, \dots, n\}\}$ . By part 4 of 2.1.13,  $\{V_{\beta_i} \mid i \in \{1, \dots, n\}\} = \{T^{-1}(T(V_{\beta_i})) \mid i \in \{1, \dots, n\}\}$  is then an open subcovering of  $(Z, \mathcal{T}_Z)$ .  $\square$

*Proof of 9.* Let  $\mathcal{B}$  be a basis for  $\mathcal{T}_z$  and let  $V \in \mathcal{T}_{Z/\cong}$ . Then  $T^{-1}(Z) \in \mathcal{T}_Z$ , and so there is a subcollection  $\{U_\alpha\}_{\alpha \in A} \subset \mathcal{B}$  such that  $T^{-1}(V) = \bigcup_{\alpha \in A} U_\alpha$ . Hence,

$$\begin{aligned} V &= T(T^{-1}(V)) \\ &= T\left(\bigcup_{\alpha \in A} U_\alpha\right) \\ &= \bigcup_{\alpha \in A} T(U_\alpha) \end{aligned}$$

□

*Proof of 10.* If  $T$  is Injective, then since it is Continuous Part 2 of this result, open by part 6 of this result, and surjective by 2.1.1, it is a bicontinuous bijection, that is, a **Homeomorphism**. □

## 2.1.2 Pseudometrics

**Definition 2.1.14** (Triangle Inequality). *Let  $X$  and  $Y$  be sets. We say that a map  $f : X \times X \rightarrow Y$  is a **Symmetric Map** for each  $x_0, x_1 \in X$ ,  $f(x_0, x_1) = f(x_1, x_0)$ .*

**Definition 2.1.15** (Symmetric Map). *Let  $X$  be a set and  $(Y, +, \leq)$  be a totally ordered magma. We say that a map  $f : X \times X \rightarrow Y$  satisfies the **Triangle Inequality** if for each  $x_0, x_1, x_2 \in X$ , we have*

$$f(x_0, x_2) \leq f(x_0, x_1) + f(x_1, x_2)$$

**Definition 2.1.16** (Pseudometric). *Let  $X \neq \emptyset$ . Let  $d : X \times X \rightarrow [0, \infty)$  be a **Symmetric Map** that satisfies the **Triangle Inequality** and further satisfies, for each  $x \in X$ ,*

$$d(x, x) = 0 \tag{2.19}$$

Under these conditions we call  $d$  a **Pseudometric** on  $X$  and we call  $(X, d)$  a **Pseudometric Space**.

**Definition 2.1.17** (Metric). *Let  $(X, d)$  be a **Pseudometric Space**. If  $d$  has the property that for  $x, y \in X$ , if  $x \neq y$ , then*

$$d(x, y) \neq 0$$

Then we call  $d$  a **Metric** on  $X$  and we call  $(X, d)$  a **Metric Space**

**Definition 2.1.18** (Pseudometric Cauchy Sequence). *Let  $(X, d)$  be a **Pseudometric Space**. We say that a sequence  $\{x_i\}_{i \in \mathbb{N}}$  is a **Pseudometric Cauchy Sequence** if, for each  $\epsilon > 0$ , there exists an  $N \in \mathbb{N}$ , such that for each pair  $m, n \in \mathbb{N}$  such that  $m > N$  and  $n > N$ , we have*

$$d(x_m, x_n) < \epsilon \tag{2.20}$$

**Definition 2.1.19** (Pseudometric Convergence). *Let  $(X, d)$  be a pseudometric space and let  $\{x_i\}_{i \in \mathbb{N}}$  be a sequence in  $(X, d)$ . Let  $x_0 \in X$ . We say that  $\{x_i\}_{i \in \mathbb{N}}$  exhibits **Pseudometric-Convergence** to  $x_0$  in  $d$ , or we say that  $\{x_i\}_{i \in \mathbb{N}}$  **Pseudometric-Converges** to  $x_0$  in  $d$  or we say that  $\{x_i\}_{i \in \mathbb{N}}$  is **Pseudometrically-Convergent** to  $x_0 \in d$  if, for every  $\epsilon > 0$ , there is an  $N \in \mathbb{N}$  such that for every  $n > N$ , we have*

$$d(x_0, x_n) < \epsilon \quad (2.21)$$

**Proposition 2.1.20** (Convergent Implies Cauchy). *Let  $(X, d)$  be a **Pseudometric Space**. Let  $\{x_i\}_{i \in \mathbb{N}}$  be a **Pseudometrically-Convergent** sequence. Then  $\{x_i\}_{i \in \mathbb{N}}$  is a **Pseudometric Cauchy Sequence**.*

*Proof.* Since  $\{x_i\}$  converges, let  $x_i \rightarrow x$ . Let  $\epsilon > 0$ . Then there exists  $N \in \mathbb{N}$  such that for  $n > N$ , we have  $d(x_i, x) < \frac{\epsilon}{2}$ . For this  $N$ , if  $m, n > N$ , then we have

$$d(x_m, x_n) \leq d(x_m, x) + d(x, x_n) < \epsilon \quad (2.22)$$

and so the sequence is a **Pseudometric Cauchy Sequence**, as advertised.  $\square$

**Definition 2.1.21** (Uniformly Cauchy). *Let  $(X_\alpha, d_\alpha)$  be a **Pseudometric Space** for  $\alpha \in A$  where  $A$  is some indexing set. For each  $\alpha \in A$ , let  $\phi_\alpha := \{x_i^\alpha\}_{i \in \mathbb{N}} \subset X_\alpha$  be a sequence. We say that the collection  $\{\phi_\alpha\}_{\alpha \in A}$  is **Uniformly Cauchy** if for each  $\epsilon > 0$ , there exists an  $N \in \mathbb{N}$  such that for each pair  $m, n \in \mathbb{N}$  such that  $m > N$  and  $n > N$ , and for each  $\alpha \in A$ , we have*

$$d_\alpha(x_n^\alpha, x_m^\alpha) < \epsilon \quad (2.23)$$

**Definition 2.1.22** (Uniform Convergence). *Let  $(X_\alpha, d_\alpha)$  be a **Pseudometric Space** for  $\alpha \in A$  where  $A$  is some indexing set. For each  $\alpha \in A$ , let  $\phi_\alpha := \{x_i^\alpha\}_{i \in \mathbb{N}} \subset X_\alpha$  be a sequence. We say that the collection  $\{\phi_\alpha\}_{\alpha \in A}$  is **Uniformly Convergent** to  $\{x_\alpha\}_{\alpha \in A} \in \prod_{\alpha \in A} X_\alpha$  if for each  $\epsilon > 0$ , there is an  $N \in \mathbb{N}$  such that for each  $n > N$ , and for every  $\alpha \in A$ , we have*

$$d_\alpha(x_i^\alpha, x_\alpha) < \epsilon \quad (2.24)$$

In this scenario, we may equivalently say that  $\{\phi_\alpha\}$  demonstrates **Uniform Convergence** to  $\{x_\alpha\}_{\alpha \in A}$  or that it **Converges Uniformly**.

When we mention **Uniform Convergence** without reference to what the convergence is to, we are merely claiming the existence of such a limit.

**Proposition 2.1.23** (Uniform Cauchy and Pointwise Convergence implies Uniform Convergence). *Let  $(X_\alpha, d_\alpha)$  be a **Pseudometric Space** for  $\alpha \in A$  where  $A$  is some indexing set. For each  $\alpha \in A$ , let  $\phi_\alpha := \{x_i^\alpha\}_{i \in \mathbb{N}} \subset X_\alpha$  be a sequence. Suppose the collection  $\{\phi_\alpha\}_{\alpha \in A}$  is **Uniformly Cauchy** and that each  $\phi_\alpha$  is **Pseudometrically-Convergent**, say  $x_i^\alpha \rightarrow x_\alpha$ . Then  $\{\phi_\alpha\}_{\alpha \in A}$  is **Uniformly Convergent** to  $\{x_\alpha\}_{\alpha \in A}$ .*

*Proof.* Let  $\epsilon > 0$ . Then, since  $\{\phi_\alpha\}_{\alpha \in A}$  is **Uniformly Cauchy**, there is an  $N \in \mathbb{N}$  such that for  $m, n > N$ , we have  $d_\alpha(x_n^\alpha, x_m^\alpha) < \frac{\epsilon}{2}$ . Also, since each  $\phi_\alpha$  converges to  $x_\alpha$ , there are  $N_\alpha \in \mathbb{N}$  such that for any  $n_\alpha > N_\alpha$ , we have  $d_\alpha(x_{n_\alpha}^\alpha, x_\alpha) < \frac{\epsilon}{2}$ . Define  $M_\alpha = \max(N + 1, N_\alpha + 1)$  for  $\alpha \in A$ . Let  $n > N$ . Then, for any  $\alpha \in A$ , we have.

$$\begin{aligned} d_\alpha(x_n^\alpha, x_\alpha) &\leq d_\alpha(x_n^\alpha, x_{M_\alpha}^\alpha) + d_\alpha(x_{M_\alpha}^\alpha, x_\alpha) \\ &< \frac{\epsilon}{2} + \frac{\epsilon}{2} \\ &= \epsilon \end{aligned}$$

completing the proof. □

**Definition 2.1.24** (Pseudometric Complete). *We say that a **Pseudometric Space**  $(X, d)$  is **Pseudometric-Complete** if each **Pseudometric Cauchy Sequence** sequence in  $(X, d)$  **Pseudometric-Converges** to a limit in  $X$ .*

In the case that  $d$  is a **Metric**, then being **Pseudometric-Complete** is equivalent to being **Complete** in the classical sense, so we will commonly refer to a **Pseudometric Space** which is **Pseudometric-Complete** as simply being **Complete**.

**Definition 2.1.25** (Pseudometric Ball). *Let  $(X, d)$  be a **Pseudometric Space**. For each  $x_0 \in X$  and each  $\epsilon > 0$ , we define the following.*

1.  $B_d(x_0, \epsilon) := \{y \in X \mid d(x_0, y) < \epsilon\}$  denotes the **Open Ball** about  $x_0$  with radius  $\epsilon$ .
2.  $\overline{B}_d(x_0, \epsilon) := \{y \in X \mid d(x_0, y) \leq \epsilon\}$  denotes the **Closed Ball** about  $x_0$  with radius  $\epsilon$ .

**Definition 2.1.26** (Pseudometric Topology). *Let  $(X, d)$  be a **Pseudometric Space**, and let  $\mathcal{B}$  be the set of **Open Ball**'s in  $(X, d)$ . By 2.1.2,  $\mathcal{B}$  is the basis for a unique topology  $\mathcal{T}_d$  on  $X$ . We call  $\mathcal{T}_d$  the **Pseudometric Topology** induced by  $d$  on  $X$ .*

**Proposition 2.1.27** (Pseudometric Topology). *Let  $(X, d)$  be a **Pseudometric Space** and let  $\mathcal{B}$  be the set of **Open Ball**'s in  $(X, d)$ . The following are true.*

1. There exists a unique topology  $\mathcal{T}_d$  on  $X$  which  $\mathcal{B}$  is a basis of. That is, the **Pseudometric Topology**  $\mathcal{T}_d$  is well defined.
2. The **Pseudometric Topology** is first countable. That is, each of its points permits a countable neighborhood basis.

*Proof of 1.* Uniqueness is guaranteed by closure under arbitrary unions of a topology. For existence, it is sufficient to show that the collection of arbitrary unions of elements of  $\mathcal{B}$  is closed under finite intersections. Suppose that for  $1 \leq i \leq n$ , we have  $\{U_{\alpha_i} \mid \alpha_i \in A_i\} \subset \mathcal{B}$  and consider the set

$$U = \bigcap_{i=1}^n \bigcup_{\alpha_i \in A_i} U_{\alpha_i} \tag{2.25}$$

Let  $x_0 \in U$ . For each  $i \in \{1, \dots, n\}$ , there exists  $\alpha_i \in A_i$  such that

$$x_0 \in U_{\alpha_i} = B_d(x_i; \epsilon_i) \quad (2.26)$$

For each  $i \in \{1, \dots, n\}$ , define  $\delta_i = d(x_0, x_i)$ . Then  $0 < \delta_i < \epsilon_i$ . Then, for each  $i \in \{1, \dots, n\}$ ,

$$B_d(x_0; \epsilon_i - \delta_i) \subset U_{\alpha_i} \subset \bigcup_{\alpha_i \in A_i} U_{\alpha_i} \quad (2.27)$$

Define

$$\delta_{x_0} = \min_{i=1}^n (\epsilon_i - \delta_i) \quad (2.28)$$

Then  $x_0 \in B(x_0; \delta_{x_0}) \subset U$ . If  $U = \{x_\alpha | \alpha \in A\}$ , then the arbitrary nature of  $x_0$  above means we can repeat this construction, writing

$$U \subset \bigcup_{\alpha \in A} B(x_\alpha; \delta_{x_\alpha}) \subset \bigcup_{\alpha \in A} U = U \quad (2.29)$$

Hence,  $U \in B$  and the proof is complete.  $\square$

*Proof of 2.* Let  $x_0 \in X$ . I claim that

$$\mathcal{B}_{x_0} := \left\{ B_d \left( x_0; \frac{1}{n} \right) \mid n \in \mathbb{N} \right\} \quad (2.30)$$

is a neighborhood basis for  $(X, \mathcal{T}_d)$  at  $x_0$ . Let  $U \in \mathcal{U}_{\mathcal{T}_d}(x)$ . Since  $\mathcal{B}$  is a basis for  $\mathcal{T}_d$ , for some  $y_0 \in X$  and  $\epsilon > 0$ ,  $x_0 \in B_d(y_0; \epsilon) \subset U$ . Let  $\delta = d(x_0, y_0)$ . Then  $\epsilon - \delta > 0$ . Define

$$n = \left\lceil \frac{1}{\epsilon - \delta} \right\rceil \quad (2.31)$$

Then we have

$$B_d \left( x_0; \frac{1}{n} \right) \subset B_d(x_0; \epsilon - \delta) \subset B(y_0; \epsilon) \subset U \quad (2.32)$$

$\square$

**Definition 2.1.28** (Relation Of Zero Distance). Let  $(X, d)$  be a **Pseudometric Space**. Define the relation  $\cong_d$  on  $X \times X$  by setting, for  $x, y \in X$ ,

$$x \cong_d y \iff d(x, y) = 0 \quad (2.33)$$

We call  $\cong_d$  the **Relation Of Zero Distance** on  $(X, d)$ .

**Proposition 2.1.29** (Relation Of Zero Distance is the Relation Of Equal Neighborhood Filters). Let  $(X, d)$  be a **Pseudometric Space**. Let  $\cong_{\mathcal{T}_d}$  be the **Relation Of Equal Neighborhood Filters** on  $(X, \mathcal{T}_d)$ . Let  $\cong_d$  be the **Relation Of Zero Distance** on  $(X, d)$ . Then  $\cong_{\mathcal{T}_d} = \cong_d$ .

*Proof.* Let  $x, y \in X$  and suppose  $x_0 \cong_d y_0$ . Let  $U \in \mathcal{U}_{\mathcal{T}_d}(x_0)$ . Then for some  $\epsilon > 0$ ,  $x_0 \in B(x_0; \epsilon) \subset U$ . Since  $x_0 \cong_d y_0$ ,  $d(x_0, y_0) = 0$ , so  $y_0 \in B(x_0; \epsilon) \subset U$ . Hence  $U \in \mathcal{U}_{\mathcal{T}_d}(y_0)$ . The arbitrary nature of  $U \in \mathcal{U}_{\mathcal{T}_d}(x_0)$  implies

$$\mathcal{U}_{\mathcal{T}_d}(x_0) \subset \mathcal{U}_{\mathcal{T}_d}(y_0) \quad (2.34)$$

A reverse construction would just as easily show the reverse inclusion, so we conclude that  $x_0 \cong_{\mathcal{T}_d} y_0$ . Now suppose  $x_0 \cong_{\mathcal{T}_d} y$ . Then for each  $n \in \mathbb{N}$ ,

$$y_0 \in B_d \left( x_0; \frac{1}{n} \right) \quad (2.35)$$

Hence  $d(x_0, y_0) < \frac{1}{n}$  for each natural  $n$ , therefore  $d(x_0, y_0) = 0$  and  $x_0 \cong_d y_0$ .  $\square$

**Definition 2.1.30** (Metric Space Induced By Pseudometric). *Let  $(X, d)$  be a **Pseudometric Space**, and let  $\cong$  be the **Relation Of Zero Distance**, which by 2.1.29 is also the **Relation Of Equal Neighborhood Filters** on  $(X, \mathcal{T}_d)$ . Define  $\tilde{d} : X/\cong \rightarrow [0, \infty)$  by*

$$\tilde{d}([x], [y]) = d(x, y) \quad (2.36)$$

By 2.1.31,  $\tilde{d}$  is well defined and is in fact a metric on  $X/\cong$ , so we call  $\tilde{d}$  the **Metric Induced By The Pseudometric  $d$  on  $X$** , or we call it the **Pseudometric Induced Metric** of  $(X, d)$ .

**Proposition 2.1.31** (Metric Space Induced By Pseudometric Space). *Let  $(X, d)$  be a **Pseudometric Space**,  $\cong$  the **Relation Of Zero Distance** on  $(X, d)$  and  $\tilde{d}$  be defined as in 2.1.30. Let  $(X/\cong, \mathcal{T}_{X/\cong})$  be the **Quotient Topological Space** with **Quotient Map**  $T$ , and let  $(X/\cong, \mathcal{T}_{\tilde{d}})$  be the topological space induced by the metric space  $(X/\cong, \tilde{d})$ . The following are true.*

1.  $\tilde{d}$  is in fact well defined, and is a metric on  $X/\cong$ , justifying calling it the **Metric Induced By The Pseudometric  $d$** .
2.  $\mathcal{T}_{X/\cong} = \mathcal{T}_{\tilde{d}}$
3.  $T$  is an isometric surjection  $(X, d)$  to  $(X/\cong, \tilde{d})$
4.  $(X/\cong, \tilde{d})$  is complete if and only if  $(X, d)$  is **Pseudometric-Complete**.

*Proof of 01.* First we show that  $\tilde{d}$  is well defined as a mapping, that is, that if  $x_0, y_0 \in X$  and  $x_1 \cong x_0$  and  $y_1 \cong y_0$ , then we should have

$$\tilde{d}([x_0], [y_0]) = \tilde{d}([x_1], [y_1]) \quad (2.37)$$

This is easy, as

$$\begin{aligned} d(x_0, y_0) &\leq d(x_0, x_1) + d(x_1, y_1) + d(y_1, y_0) \\ &= d(x_1, y_1) \\ &\leq d(x_1, x_0) + d(x_0, y_0) + d(y_0, y_1) \\ &= d(x_0, y_0) \end{aligned}$$

Nonnegativity falls directly from the nonnegativity of  $d$ . Proving that  $\tilde{d}$  is a **Symmetric Map** is equally trivial

$$\tilde{d}([x], [y]) = d(x, y) = d(y, x) = \tilde{d}([y], [x])$$

Proving that  $\tilde{d}$  satisfies the **Triangle Inequality** is similarly simple, letting  $x_0, y_0, z_0 \in X$ , we have

$$\begin{aligned} \tilde{d}([x_0], [z_0]) &= d(x_0, z_0) \\ &\leq d(x_0, y_0) + d(y_0, z_0) \\ &= \tilde{d}([x_0], [y_0]) + \tilde{d}([y_0], [z_0]) \end{aligned}$$

All that remains is to show positivity on nonequal arguments. Let  $x_0, y_0 \in X$  such that  $[x_0] \neq [y_0]$ . Then  $x_0 \not\equiv y_0$ . Hence

$$\tilde{d}([x_0], [y_0]) = d(x_0, y_0) \neq 0$$

□

*Proof of 02.* By 2.1.13, part 9,  $\mathcal{B}_\cong := \{T(B_d(x; \epsilon)) | x \in X, \epsilon > 0\}$  is a basis for  $\mathcal{T}_{X/\cong}$ . By definition,  $\mathcal{B}_{\tilde{d}} := \{B_{\tilde{d}}([x]; \epsilon) | x \in X, \epsilon > 0\}$  is a basis for  $\mathcal{T}_{\tilde{d}}$ .

I claim that for each  $x \in X$  and  $\epsilon > 0$ ,

$$T(B_d(x; \epsilon)) = B_{\tilde{d}}([x]; \epsilon) \quad (2.38)$$

To see this, suppose  $\tilde{y} \in T(B_d(x; \epsilon))$ . Then  $\tilde{y} = T(y)$  for some  $y \in B_d(x; \epsilon)$ . Hence

$$\begin{aligned} \tilde{d}(\tilde{y}, [x]) &= \tilde{d}(T(y), [x]) \\ &= \tilde{d}([y], [x]) \\ &= d(y, x) \\ &< \epsilon \end{aligned}$$

Hence  $\tilde{y} \in B_{\tilde{d}}([x]; \epsilon)$ , and so

$$T(B_d(x; \epsilon)) \subset B_{\tilde{d}}([x]; \epsilon) \quad (2.39)$$

Suppose  $[y] \in B_{\tilde{d}}([x]; \epsilon)$ . Then  $d(x, y) = \tilde{d}([x], [y]) < \epsilon$ , so  $y \in B_d(x; \epsilon)$ . Hence  $[y] = T(y) \in T(B_d(x; \epsilon))$ , so the reverse inclusion also holds, and so the above claim holds. This, paired with the fact that

$$\{[x] | x \in X\} = X/\cong \quad (2.40)$$

finishes the result.

□

*Proof of 03.* Falls directly from the definition  $T(x) = [x]$ , hence

$$d(x, y) = \tilde{d}([x], [y]) = \tilde{d}(T(x), T(y)) \quad (2.41)$$

$T$  is surjective by 2.1.1.

□



*Proof of 04.* Let  $(X, d)$  be **Pseudometric-Complete**. Let  $\{[x_i]\}_{i \in \mathbb{N}} \subset (X/\cong, \tilde{d})$  be a **Pseudometric Cauchy Sequence**. Let  $\epsilon > 0$ . Then there exists  $N \in \mathbb{N}$  such that for  $m, n > N$ , we have

$$d(x_m, x_n) = \tilde{d}(Tx_m, Ty_m) = \tilde{d}([x_m], [x_n]) < \epsilon \quad (2.42)$$

So the sequence  $\{x_i\}_{i \in \mathbb{N}} \subset (X, d)$  is **Pseudometric Cauchy Sequence**. Since  $(X, d)$  is **Pseudometric-Complete**, this sequence has a limit, say  $x_i \rightarrow x \in (X, d)$ . But, we have  $[x_i] = Tx_i \rightarrow Tx = [x]$ , so  $\{[x_i]\}$  is convergent, and since that sequence was arbitrary,  $(X/\cong, \tilde{d})$  is **Pseudometric-Complete**.

Let  $(X/\cong, \tilde{d})$  be **Pseudometric-Complete**. Let  $\{x_i\} \subset X$  be a **Pseudometric Cauchy Sequence**. Let  $\epsilon > 0$ . Then there exist  $N \in \mathbb{N}$  such that for  $m, n > N$ , we have

$$\tilde{d}([x_m], [x_n]) = \tilde{d}(Tx_m, Tx_n) = d(x_m, x_n) < \epsilon \quad (2.43)$$

so that  $\{[x_i]\}_{i \in \mathbb{N}}$  is also a **Pseudometric Cauchy Sequence**. Since  $(X/\cong, \tilde{d})$  is **Pseudometric-Complete**, this sequence has a limit, say  $[x_i] \rightarrow y \in X/\cong$ . Since  $T$  is surjective, for some  $x \in X$ ,  $Tx \in y$ , and so

$$d(x, x_i) = \tilde{d}(Tx, Tx_i) = \tilde{d}(y, [x_i]) \rightarrow 0 \quad (2.44)$$

meaning  $x_i \rightarrow x$  and we are done. □

**Remark 2.1.32** (Metric Space Correspondence). *Note that in the case of a metric space, the condition of being **Pseudometric-Complete** is equivalent to the condition being Complete, and A sequence is a **Pseudometric Cauchy Sequence** if and only if it is a cauchy sequence.*

**Definition 2.1.33** ((Pseudo)Metriizable). *Let  $(X, \mathcal{T})$  be a topological space.*

1. We say that  $(X, \mathcal{T})$  (Or  $\mathcal{T}$  or  $X$  which it wouldn't cause confusion) is **Pseudometrizable** if there exists a pseudometric  $d$  on  $X$  such that  $\mathcal{T}$  is the **Pseudometric Topology** on  $(X, d)$ .
2. We say that  $(X, \mathcal{T})$  (Or  $\mathcal{T}$  or  $X$  when it wouldn't cause confusion) is **Metriizable** if there exists a metric  $d$  on  $X$  such that  $\mathcal{T}$  is the metric topology on  $(X, d)$ .

**Proposition 2.1.34** (Pseudometrizable Prequotient). *Let  $(X, \mathcal{T}_X)$  be a topological space with **Relation Of Equal Neighborhood Filters** on  $\cong$ , and with **Quotient Topological Space**  $(X/\cong, \mathcal{T}_{X/\cong})$  and **Quotient Map**  $T$ . Let  $(X/\cong, \mathcal{T}_{X/\cong})$  be **Pseudometrizable** with **Pseudometric**  $\tilde{d}$ .*

The following hold.

1.  $(X, \mathcal{T}_X)$  is **Pseudometrizable** with a pseudometric  $d : X \times X \rightarrow [0, \infty)$  defined by

$$d(x, y) = \tilde{d}([x], [y]).$$

2.  $\tilde{d}$  is a Metric  $(X/\cong, \mathcal{T}_{X/\cong})$ , and so this space is **Metriizable**.

3. If  $T$  is injective, then  $d$  as defined above is a metric on  $X$ , so that  $(X, \mathcal{T}_X)$  is **Metrisable**.

*Proof Of One.* First, observe that

$$d(x, y) = \tilde{d}([x], [y]) \in [0, \infty)$$

so that  $d$  is well defined.

Also,

$$d(x, y) = \tilde{d}([x], [y]) = \tilde{d}([y], [x]) = d(y, x)$$

, so  $d$  is a **Symmetric Map**.

Also,

$$\begin{aligned} d(x, z) &= \tilde{d}([x], [z]) \\ &\leq \tilde{d}([x], [y]) + \tilde{d}([y], [z]) \\ &= d(x, y) + d(y, z) \end{aligned}$$

so  $d$  satisfies the **Triangle Inequality**. Also,

$$d(x, x) = \tilde{d}([x], [x]) = 0 \tag{2.45}$$

and so  $d$  is a **Pseudometric** on  $X$ .

Let  $\mathcal{T}_d$  denote the **Pseudometric Topology** on  $(X, d)$ . What remains to show is that  $\mathcal{T}_X = \mathcal{T}_d$ .

Since  $d(x, y) = \tilde{d}([x], [y]) = \tilde{d}(Tx, Ty)$ ,  $T$  is an isometry.

Let  $x \in U \in \mathcal{T}_X$ . Then  $[x] \in T(U) \in \mathcal{T}_{X/\cong}$ . Hence, there is an  $\epsilon > 0$  such that  $B_{\tilde{d}}([x], \epsilon) \subset T(U)$ . By 2.1.13, part 4,  $T^{-1}(B_{\tilde{d}}([x], \epsilon)) \subset T^{-1}(T(U)) = U$ , where by part 6 of that same result,  $T^{-1}(B_{\tilde{d}}([x], \epsilon)) \in \mathcal{T}_X$ . Since  $T$  is an isometry  $B_d(x, \epsilon) = T^{-1}(B_{\tilde{d}}([x], \epsilon)) \subset U$ . Thus we have found an open ball contained in  $U$  containing an arbitrary point of  $U$ . Hence,  $\mathcal{T}_X \subset \mathcal{T}_d$ . As part of the preceding argument we also showed that an arbitrary **d-Open Ball** was in  $\mathcal{T}_X$ , so  $\mathcal{T}_d \subset \mathcal{T}_X$ , and so equality holds and we're done.  $\square$

*Proof of Two.* Let  $x, y \in X$  with  $[x] \neq [y]$ . Then  $x \not\sim y$ . By 2.1.29,  $x \not\sim_d y$ . Hence  $\tilde{d}([x], [y]) = d(x, y) > 0$ .  $\square$

*Proof of Three.* Let  $T$  be injective, and suppose  $x, y \in X$  with  $x \neq y$ . Then  $[x] = Tx \neq Ty = [y]$ , so by part 2 of this result,  $d(x, y) = \tilde{d}([x], [y]) > 0$ .  $\square$

### 2.1.3 Topological Vector Spaces

**Definition 2.1.35** (Topological Vector Space). Let  $(V, +, \cdot)$  be a vector space over a field  $\mathbb{F} \in \{\mathbb{R}, \mathbb{C}\}$ . Let  $\mathcal{T}$  be a topology on  $V$  with respect to which, the operations  $+: V \times V \rightarrow V$  and  $\cdot: \mathbb{F} \times V \rightarrow V$  are each continuous. Then we call  $(V, \mathcal{T})$  a **Topological Vector Space**.

**Definition 2.1.36** (TVS Bounded Set). *Let  $(V, \mathcal{T})$  be a topological vector space. Let  $A \subset V$ . We say that  $A$  is **TVS-Bounded** with respect to  $\mathcal{T}$ , or when confusion is unlikely we simply say that  $A$  is **TVS-Bounded** if for every  $U \in \mathcal{U}_{\mathcal{T}}(0)$ , there exists an  $\alpha \in \mathbb{F}$ ,  $\alpha > 0$ , such that  $A \subset \alpha U$ .*

**Definition 2.1.37** (TVS Bounded Linear Operator). *Let  $(V_i, \mathcal{T}_i)$  be a **Topological Vector Space** over  $\mathbb{F} \in \{\mathbb{R}, \mathbb{C}\}$  for  $i \in \{0, 1\}$ . We say that a linear operator  $T : (V_1, \mathcal{T}_1) \rightarrow (V_2, \mathcal{T}_2)$  is a **Bounded Linear Operator** if for each  $U \in V_1$  with  $U$  **TVS-Bounded** with respect to  $\mathcal{T}_0$ ,  $TU$  is **TVS-Bounded** with respect to  $\mathcal{T}_1$ .*

**Proposition 2.1.38** (Bounded Linear Operator Continuous). *Let  $(V_i, \mathcal{T}_i)$  be a **Topological Vector Space** over a field  $\mathbb{F} \in \{\mathbb{R}, \mathbb{C}\}$  for  $i \in \{0, 1\}$ . Let  $T : V_0 \rightarrow V_1$  be a **Bounded Linear Operator**. Then  $T$  is continuous.*

*Proof.* Let  $0_{V_1} \in U \in \mathcal{T}_1$ . □

## 2.1.4 Seminormed Spaces

**Definition 2.1.39** (Subadditive). *Let  $G$  be a Magma and  $H$  be a Totally ordered Magma. Represent the operation of  $g$  and  $h$  both with  $+$ . We call a mapping  $p : G \rightarrow H$  **Subadditive** if, for every  $x, y \in G$ , we have*

$$p(x + y) \leq p(x) + p(y) \quad (2.46)$$

Under these circumstances, we may also say that the operator  $p$  possesses **Subadditivity**.

**Definition 2.1.40** (Scalar Homogeneous). *Let  $V$  be a vector space over a field  $\mathbb{F} \in \{\mathbb{R}, \mathbb{C}\}$ . We say that a map  $p : V \rightarrow V$  is **Scalar Homogeneous**, if, for each  $\alpha \in \mathbb{F}$  and each  $x \in V$ , we have*

$$p(\alpha x) = |\alpha|p(x) \quad (2.47)$$

Under these circumstances, we may instead say that the operator  $p$  possesses **Scalar Homogeneity**.

**Remark 2.1.41** (Scalar Homogeneous operator at 0 is 0). *If  $V$  is a vector space over  $\mathbb{F} \in \{\mathbb{R}, \mathbb{C}\}$ , then for each  $x \in V$ ,  $0x = 0$ . Hence, if  $p$  is a **Scalar Homogeneous** operator on  $v$ , then for any  $x \in V$*

$$p(0) = p(0x) = |0|p(x) = 0p(x) = 0 \quad (2.48)$$

that is,  $p(0)=0$ .

**Definition 2.1.42** (Seminorm). *Let  $V$  be a vector space over a field  $\mathbb{F} \in \{\mathbb{R}, \mathbb{C}\}$ . We say that a map  $\|\cdot\| : V \rightarrow [0, \infty)$  is a **Seminorm** on  $V$  if it is both **Subadditive** and **Scalar Homogeneous**. In this case, we refer to  $(V, \|\cdot\|)$  as a **Seminormed Space**. We say that  $\|\cdot\|$  is **Non-Degenerate** if there is at least one  $v \in V$  with  $\|v\| > 0$ . We say that  $\|\cdot\|$  is **Degenerate** if it is not **Non-Degenerate**. We may also refer to the **Seminormed Space**  $(V, \|\cdot\|)$  as being **Degenerate** or **Non-Degenerate**.*

**Definition 2.1.43** (Norm). *Let  $(V, \|\cdot\|)$  be a **Seminormed Space** . If the following implication is true for  $x \in V$ , then we refer to  $\|\cdot\|$  as a **Norm** on  $V$ , and we call  $(V, \|\cdot\|)$  a **Normed Space** .*

$$x \neq 0 \implies \|x\| \neq 0 \quad (2.49)$$

**Proposition 2.1.44** (Subadditive Operator On a Group Induces a Metric). *Let  $(G, +, e)$  be a group and let  $(H, +, \leq)$  be a totally ordered magma. Let  $p : G \rightarrow H$  be **Subadditive** . define  $d : G \times G \rightarrow H$  by setting, for each  $x, y \in G$ ,*

$$d(x, y) = p(x + (-y)) \quad (2.50)$$

Then  $d$  satisfies the triangle inequality.

*Proof.* let  $x, y, z \in G$ . Then

$$\begin{aligned} d(x, z) &= p(x + (-z)) \\ &= p(x + e + (-z)) \\ &= p(x + (-y) + y + (-z)) \\ &\leq p(x + (-y)) + p(y + (-z)) \\ &= d(x, y) + d(y, z) \end{aligned}$$

completing the proof. □

**Definition 2.1.45** (Seminorm Topology). *Let  $(X, \|\cdot\|)$  be a **Seminormed Space** . define  $d_{\|\cdot\|} : V \times V \rightarrow [0, \infty)$  by setting, for  $x, y \in X$ ,*

$$d_{\|\cdot\|}(x, y) = \|x - y\| \quad (2.51)$$

Observe the following:

1. 2.1.4 guarantees that  $d_{\|\cdot\|}(x, x) = 0$  for  $x \in X$ .
2. 2.1.44 guarantees that  $d$  satisfies the **Triangle Inequality** .
3.  $d$  is a **Symmetric Map** , as we have

$$d(x, y)_{\|\cdot\|} = \|x - y\| = |-1| \|x - y\| = \|y - x\| = d(y, x) \quad (2.52)$$

Hence,  $d_{\|\cdot\|}$  is a **Pseudometric** on  $X$ , which we call the **Pseudometric induced by the Seminorm** on  $X$ . We refer to  $(X, d_{\|\cdot\|})$  as the **Pseudometric Space induced by the Seminormed Space**  $(X, \|\cdot\|)$ . We refer to the **Pseudometric Topology** induced by  $d_{\|\cdot\|}$  as the **Seminorm Topology** induced by  $\|\cdot\|$ , and unless otherwise specified, when we reference  $(X, \|\cdot\|)$ , we consider it to be endowed with this topology.

**Definition 2.1.46** (Seminorm Kernel). *Let  $(V, \|\cdot\|)$  be a **Seminormed Space** . Define the set  $\mathcal{K}_{(V, \|\cdot\|)}^{\text{ernel}}$  by*

$$\mathcal{K}_{(V, \|\cdot\|)}^{\text{ernel}} = \{x \in V \mid \|x\| = 0\} \quad (2.53)$$

We call this set the **Seminorm Kernel** of the space  $\mathcal{K}_{(V, \|\cdot\|)}^{\text{ernel}}$ . When confusion is unlikely, we may denote this set with  $\mathcal{K}^{\text{ernel}}$ ,  $\mathcal{K}_V^{\text{ernel}}$ , or even  $\mathcal{K}_{\|\cdot\|}^{\text{ernel}}$ , or we may just refer to it as the **Seminorm Kernel** , the **Seminorm Kernel** of  $V$ , or the **Seminorm Kernel** of  $\|\cdot\|$ .

**Proposition 2.1.47** (Seminorm Kernel is a vector Subspace). *Let  $(X, \|\cdot\|)$  be a **Seminormed Space** over a field  $\mathbb{F} \in \{\mathbb{R}, \mathbb{C}\}$  with corresponding **Seminorm Kernel**  $\mathcal{K}^{\text{ernel}}$ . Then the following are true.*

1.  $\mathcal{K}^{\text{ernel}}$  is a vector subspace of  $X$ .
2.  $\mathcal{K}^{\text{ernel}}$  is closed in the **Seminorm Topology** on  $X$ .
3.  $\mathcal{K}^{\text{ernel}} = X$  if and only if  $X$  is **Degenerate** .

*Proof of One.* **Subadditivity** implies that, if  $x, y \in \mathcal{K}^{\text{ernel}}$ , then  $\|x + y\| \leq \|x\| + \|y\| = 0$ . By **Scalar Homogeneity** , if  $x \in \mathcal{K}^{\text{ernel}}$  and  $\alpha \in \mathbb{F}$ ,  $\|\alpha x\| = |\alpha| \|x\| = 0$  so  $\mathcal{K}^{\text{ernel}}$  is in fact a vector subspace of  $X$ .  $\square$

*Proof of Two.* If  $x \in X \setminus \mathcal{K}^{\text{ernel}}$  then  $\|x\| = \alpha > 0$  for some positive  $\alpha$ . Hence  $B(x; \alpha/2)$  is an open set containing  $x$  disjoint from  $\mathcal{K}^{\text{ernel}}$ . We can then write  $X \setminus \mathcal{K}^{\text{ernel}}$  as the union of all such open sets to see that  $\mathcal{K}^{\text{ernel}}$  is closed.  $\square$

*Proof of Three.* Direct application of the definitions of the **Seminorm Kernel** and **Degenerate Seminorm** .  $\square$

**Definition 2.1.48** (Quotient Space Mod Kernel). *Let  $(X, \|\cdot\|)$  be a **Seminormed Space** over a field  $\mathbb{F} \in \{\mathbb{R}, \mathbb{C}\}$ . with **Seminorm Kernel**  $\mathcal{K}^{\text{ernel}}$ . By 2.1.47, part 1,  $\mathcal{K}^{\text{ernel}}$  is a vector subspace of  $X$ 's algebraic structure, and so if we define  $\cong_{\mathcal{K}^{\text{ernel}}} \subset X \times X$  by setting, for  $x, y \in X$*

$$x \cong_{\mathcal{K}^{\text{ernel}}} y \iff x - y \in \mathcal{K}^{\text{ernel}} \quad (2.54)$$

Then one recognizes  $\cong_{\mathcal{K}^{\text{ernel}}}$  as **Equivalence MOD- $\mathcal{K}^{\text{ernel}}$**  as would be commonly spoken of in Module or Vector Space theory. From this, alot of nice properties fall out. We list them here, without proof just to nail down notation. For proof, see any undergraduate algebra text.

1. If  $x \cong_{\mathcal{K}^{\text{ernel}}} y$ , then we say that  $x$  and  $y$  are **Equivalent MOD- $\mathcal{K}^{\text{ernel}}$**  .
2. For  $x \in X$  , we denote the **Equivalence Class**  $[x]_{\cong_{\mathcal{K}^{\text{ernel}}}}$  with  $[x]_{\mathcal{K}^{\text{ernel}}}$  or with  $x + \mathcal{K}^{\text{ernel}}$ , or when confusion is unlikely, simply  $[x]$ .
3. We denote  $X / \cong_{\mathcal{K}^{\text{ernel}}}$  with  $X / \mathcal{K}^{\text{ernel}}$ .
4. If we define  $\oplus : X / \mathcal{K}^{\text{ernel}} \times X / \mathcal{K}^{\text{ernel}} \rightarrow X / \mathcal{K}^{\text{ernel}}$  by setting , for  $x, y \in X$ ,  $[x]_{\mathcal{K}^{\text{ernel}}} \oplus [y]_{\mathcal{K}^{\text{ernel}}} = [x + y]_{\mathcal{K}^{\text{ernel}}}$  , then  $\oplus$  is well defined and endows  $X / \mathcal{K}^{\text{ernel}}$  with a group structure.

5. If we further define  $\odot : \mathbb{F} \times X/\mathcal{K}^{\text{ernel}} \rightarrow X/\mathcal{K}^{\text{ernel}}$  by  $\alpha[x]_{\mathcal{K}^{\text{ernel}}} = [\alpha x]_{\mathcal{K}^{\text{ernel}}}$ , then  $(X/\mathcal{K}^{\text{ernel}}, \oplus, \odot, [0]_{\mathcal{K}^{\text{ernel}}})$  is a Vector space over  $\mathbb{F}$ .
6. Unless otherwise specified, when referring to the set  $X/\mathcal{K}^{\text{ernel}}$ , we endow it with the above vector space structure, and we call this space the **Seminorm Kernel Quotient Vector Space** of the seminormed space  $(X, \|\cdot\|)$ .

**Proposition 2.1.49** (Equivalence Mod Kernel is Pseudometric Equivalence). *Let  $(X, \|\cdot\|)$  be a seminormed space. with **Seminorm Kernel**  $\mathcal{K}^{\text{ernel}}$ . Let  $d$  denote the **Pseudometric induced by the Seminorm**.*

Then  $\cong_{\mathcal{K}^{\text{ernel}}} = \cong_d$ .

*Proof.* Let  $x, y \in X$  and let  $x \cong_{\mathcal{K}^{\text{ernel}}} y$ . Then, since  $x - y \in \mathcal{K}^{\text{ernel}}$ , Then  $d(x, y) := \|x - y\| = 0$ , so  $x \cong_d y$ . Hence  $\cong_{\mathcal{K}^{\text{ernel}}} \subset \cong_d$

Now let  $x, y \in X$  with  $x \cong_d y$ . Then  $\|x - y\| = d(x, y) = 0$ , so  $x - y \in \mathcal{K}^{\text{ernel}}$ , and therefore  $x \cong_{\mathcal{K}^{\text{ernel}}} y$ . Hence,  $\cong_d \subset \cong_{\mathcal{K}^{\text{ernel}}}$ .

Since inclusion goes both directions,  $\cong_{\mathcal{K}^{\text{ernel}}} = \cong_d$ .

□

**Definition 2.1.50** (Quotient Norm Space). *Let  $(X, \|\cdot\|)$  be a **Seminormed Space** with **Pseudometric induced by the Seminorm**  $d$ , **Seminorm Kernel**  $\mathcal{K}^{\text{ernel}}$ , and **Seminorm Kernel Quotient Vector Space**  $X/\mathcal{K}^{\text{ernel}}$ . Let  $\tilde{d} : X/\mathcal{K}^{\text{ernel}} \times X/\mathcal{K}^{\text{ernel}} \rightarrow [0, \infty)$  be the **Metric Induced By The Pseudometric**.*

Define  $\|\cdot\|_{\mathcal{K}^{\text{ernel}}} : X/\mathcal{K}^{\text{ernel}} \rightarrow [0, \infty)$  by

$$\|[x]\|_{\mathcal{K}^{\text{ernel}}} = \tilde{d}([x], [0]) \quad (2.55)$$

By 2.1.51,  $(X/\mathcal{K}^{\text{ernel}}, \|\cdot\|_{\mathcal{K}^{\text{ernel}}})$  is a normed space which we call the **Quotient Normed Space** of  $(X, \|\cdot\|)$ , and we call  $\|\cdot\|_{\mathcal{K}^{\text{ernel}}}$  the **Quotient Norm**. Whenever we refer to  $X/\mathcal{K}^{\text{ernel}}$ , unless otherwise specified, we endow it with this norm and the topology generated by this norm. Furthermore, whenever we consider  $X/\mathcal{K}^{\text{ernel}}$ , unless otherwise specified, we consider it as possessing the topology generated by the norm  $\|\cdot\|_{\mathcal{K}^{\text{ernel}}}$ .

**Proposition 2.1.51** (Quotient Normed Space). *Let  $(X, \|\cdot\|)$  be a **Seminormed Space** with **Pseudometric induced by the Seminorm**  $d$ , **Seminorm Kernel**  $\mathcal{K}^{\text{ernel}}$ , and **Seminorm Kernel Quotient Vector Space**  $X/\mathcal{K}^{\text{ernel}}$ . Let  $\tilde{d} : X/\mathcal{K}^{\text{ernel}} \times X/\mathcal{K}^{\text{ernel}} \rightarrow [0, \infty)$  be the **Metric Induced By The Pseudometric**. Let  $T : X \rightarrow X/\mathcal{K}^{\text{ernel}}$  denote the **Quotient Map** of  $X$  into  $X/\mathcal{K}^{\text{ernel}}$  (Recalling that the **Relation Of Equal Neighborhood Filters** on  $e$  equals the **Relation Of Zero Distance** equals the relation of **Equivalence MOD- $\mathcal{K}^{\text{ernel}}$** ), so they would all produce the same quotient map) Let  $\|\cdot\|_{\mathcal{K}^{\text{ernel}}}$  denote the **Quotient Norm**.*

The following are true.

1.  $\|\cdot\|_{\mathcal{K}^{\text{ernel}}}$  is a norm on  $X/\mathcal{K}^{\text{ernel}}$ .
2.  $\tilde{d}$  is the **Pseudometric induced by the Seminorm**  $\|\cdot\|_{\mathcal{K}^{\text{ernel}}}$ , and thus they produce the same topology.

3.  $T$  has all of the properties described in 2.1.13.
4.  $T$  is Linear.
5.  $T$  is Surjective.
6.  $T$  is an isometry.
7.  $T$  is injective if and only if  $\|\cdot\|$  is a norm.

*Proof of 1.* First, note that  $\text{Range}(\|\cdot\|_{\mathcal{K}^{\text{ernel}}}) \subset \text{Range}(\tilde{d}) \subset [0, \infty)$ , so that  $\|\cdot\|_{\mathcal{K}^{\text{ernel}}}$  has the correct domain and codomain. For **Subadditivity**, let  $[x], [y] \in X/\mathcal{K}^{\text{ernel}}$ . Then

$$\begin{aligned}
 \|[x] + [y]\|_{\mathcal{K}^{\text{ernel}}} &= \|[x + y]\|_{\mathcal{K}^{\text{ernel}}} \\
 &= \tilde{d}([x + y], [0]) \\
 &= d(x + y, 0) \\
 &= \|x + y\| \\
 &\leq \|x\| + \|y\| \\
 &= d(x, 0) + d(y, 0) \\
 &= \tilde{d}([x], [0]) + \tilde{d}([y], [0]) \\
 &= \|[x]\|_{\mathcal{K}^{\text{ernel}}} + \|[y]\|_{\mathcal{K}^{\text{ernel}}}
 \end{aligned}$$

For **Scalar Homogeneity**, let  $\alpha \in \mathbb{F}$  and  $[x] \in X/\mathcal{K}^{\text{ernel}}$ . Then,

$$\begin{aligned}
 \|\alpha[x]\|_{\mathcal{K}^{\text{ernel}}} &= \tilde{d}([\alpha x], [0]) \\
 &= d(\alpha x, 0) \\
 &= \|\alpha x\| \\
 &= |\alpha| \|x\| \\
 &= |\alpha| \|[x]\|_{\mathcal{K}^{\text{ernel}}}
 \end{aligned}$$

Finally, suppose  $[x] \neq 0$ . Then, since the additive identity of  $X/\mathcal{K}^{\text{ernel}}$  is  $\mathcal{K}^{\text{ernel}}$ ,  $x \notin \mathcal{K}^{\text{ernel}}$ . Hence  $\|[x]\|_{\mathcal{K}^{\text{ernel}}} = \tilde{d}([x], 0) = d(x, 0) = \|x\| > 0$ .

□

*Proof of 2.* Let  $D$  denote the **Pseudometric induced by the Seminorm**  $\|\cdot\|_{\mathcal{K}^{\text{ernel}}}$ . Then, for  $[x], [y] \in X/\mathcal{K}^{\text{ernel}}$ ,

$$\begin{aligned}
 \tilde{d}([x], [y]) &= d(x, y) \\
 &= \|x - y\| \\
 &= \|x - y - 0\| \\
 &= d(x - y, 0) \\
 &= \tilde{d}([x - y], 0) \\
 &= \|[x - y]\|_{\mathcal{K}^{\text{ernel}}} \\
 &= \|[x] - [y]\|_{\mathcal{K}^{\text{ernel}}} &= D([x], [y])
 \end{aligned}$$

Since these two **Pseudometric** 's are equal, they produce the same topology. Furthermore, by applying 2.1.31, we see that the topology generated by  $||\cdot||_{\mathcal{K}^{\text{ernel}}}$  is also the **Quotient Topology** on  $X/\mathcal{K}^{\text{ernel}}$ .  $\square$

*Proof of 3.*  $T$  is the topological **Quotient Map** and the norm topology is the **Quotient Topology**, so the assumptions of 2.1.13 are satisfied.  $\square$

*Proof of 4.* Let  $x, y \in X$  and  $\alpha \in \mathbb{F}$ . Then

$$\begin{aligned} T(\alpha x + y) &= [\alpha x + y] \\ &= (\alpha x + y) + \mathcal{K}^{\text{ernel}} \\ &= \alpha (x + \mathcal{K}^{\text{ernel}}) + (y + \mathcal{K}^{\text{ernel}}) \\ &= \alpha[x] + [y] \\ &= \alpha T(x) + T(y) \end{aligned}$$

$\square$

*Proof of 5.* Direct consequence of 2.1.1  $\square$

*Proof of 6.* Consequence of part 2 of this result combined with  $\square$

*Proof of 7.* If  $||\cdot||$  is a **Norm**, then  $\mathcal{K}^{\text{ernel}} = 0$ , so  $Tx = Ty \implies T(x - y) = 0 \implies x - y \in \mathcal{K}^{\text{ernel}} \implies x - y = 0 \implies x = y$ .  $\square$

**Remark 2.1.52** (Quotient Normed Space). *If  $(X, ||\cdot||_X)$  is a **Normed Space** then by parts 4, 5, 6, and 7 of 2.1.51,  $T : X \rightarrow \mathcal{K}_X^{\text{ernel}}$  is an isomorphism of **Normed Spaces** whose definition is literally*

$$Tx = \{x\} \tag{2.56}$$

For this reason, as an admitted abuse of notation, later in this document, I may not distinguish between the quotient  $X/\mathcal{K}_X^{\text{ernel}}$  and the space  $X$  if  $X$  is a **Normed Space**, and similarly, I may not distinguish between  $x \in X$  and  $\{x\} \in X/\mathcal{K}_X^{\text{ernel}}$ .

**Proposition 2.1.53.** *Let  $(X, ||\cdot||)$  be a **Seminormed Space** with **Quotient Normed Space**  $(X/\mathcal{K}^{\text{ernel}}, ||\cdot||_{\mathcal{K}^{\text{ernel}}})$ .*

*Then  $X$  is **Pseudometric-Complete** if and only if  $X/\mathcal{K}^{\text{ernel}}$  is complete.*

*Proof.* Let  $X$  be **Pseudometric-Complete**. Let  $\{[x_i]\}_{i \in \mathbb{N}} \subset X/\mathcal{K}^{\text{ernel}}$  be a **Pseudometric Cauchy Sequence**. Let  $\epsilon > 0$ . Then there is an  $N \in \mathbb{N}$  such that for  $m, n > N$  we have

$$||[x_m - x_n]||_{\mathcal{K}^{\text{ernel}}} < \epsilon \tag{2.57}$$

For this  $N$ , we have

$$||x_m - x_n|| = ||[x_m - x_n]||_{\mathcal{K}^{\text{ernel}}} < \epsilon \tag{2.58}$$



so that  $\{x_i\}_{i \in \mathbb{N}}$  is a **Pseudometric Cauchy Sequence**. Since  $X$  is **Pseudometric-Complete**, there is a  $x \in X$  such that  $\|x_i - x\| \rightarrow 0$ , but since  $T$  is an isometry,

$$\|[x] - [x_i]\| = \|[x_i - x]\|_{\mathcal{K}^{\text{ernel}}} \rightarrow 0 \quad (2.59)$$

and so  $[x_i] \rightarrow [x]$ . so that  $X/\mathcal{K}^{\text{ernel}}$  is complete.

Now suppose instead that  $X/\mathcal{K}^{\text{ernel}}$  is complete and suppose  $\{x_i\}_{i \in \mathbb{N}}$  is a **Pseudometric Cauchy Sequence** in  $X$ . Since  $\|[x_i - x_j]\|_{\mathcal{K}^{\text{ernel}}} = \|x_i - x_j\|$ ,  $\{[x_i]\}_{i \in \mathbb{N}}$  is a **Pseudometric Cauchy Sequence** in  $X/\mathcal{K}^{\text{ernel}}$ , which therefore has a limit  $y \in X/\mathcal{K}^{\text{ernel}}$ . Since  $T$  is surjective,  $y = [x]$  for some  $x \in X$ , and it is easy to see that  $x_i \rightarrow x$  so that  $X$  is **Pseudometric-Complete**.

□

**Definition 2.1.54** (Space of Continuous Linear Operators From a Seminormed Space into a Normed Space). *Let  $(X, \|\cdot\|_X)$  be a **Non-Degenerate Seminormed Space**. Let  $(Y, \|\cdot\|_Y)$  be a **Seminormed Space**. We denote with  $BL((X, \|\cdot\|_X), (Y, \|\cdot\|_Y))$  the collection of linear continuous functions  $T : (X, \|\cdot\|_X) \rightarrow (Y, \|\cdot\|_Y)$ . When the topologies on  $X$  and  $Y$  are understood, we denote this set with  $BL(X, Y)$ . We refer to  $BL(X, Y)$  as the **Space of Bounded Linear Operators** from  $(X, \|\cdot\|_X)$  to  $(Y, \|\cdot\|_Y)$ , or when  $\|\cdot\|_X$  and  $\|\cdot\|_Y$  are understood, from  $X$  to  $Y$ .*

We endow  $BL(X, Y)$  with the algebraic operations of pointwise scalar multiplication and pointwise addition, making  $BL(X, Y)$  a vector space.

We define  $\|\cdot\| : BL(X, Y) \rightarrow [0, \infty)$  by defining, for  $T \in BL(X, Y)$

$$\|T\| = \sup_{\|x\|_X \neq 0} \frac{\|Tx\|_Y}{\|x\|_X} \quad (2.60)$$

As will be proven in 2.1.55,  $\|\cdot\|$  is a **Seminorm** on  $BL(X, Y)$ , which we refer to as the **Operator Seminorm** on  $BL(X, Y)$ . induced by the **Seminorm**  $\|\cdot\|_X$  on  $X$  and the **Seminorm**  $\|\cdot\|_Y$  on  $Y$ .

In the case that  $\|\cdot\|_Y$  is a **Norm**, rather than just a **Seminorm**, by 2.1.55,  $\|\cdot\|$  is a **Norm** on  $BL(X, Y)$ , which we instead call the **Operator Norm**.

**Proposition 2.1.55** (Space of Bounded Linear Operators On Seminormed Spaces). *Let  $(X, \|\cdot\|_X)$  be a **Seminormed Space**. Let  $(Y, \|\cdot\|_Y)$  be a **Seminormed Space**. Let  $BL(X, Y)$  denote the **Space of Bounded Linear Operators** from  $X$  to  $Y$ . Let  $\|\cdot\|$  denote the **Operator Seminorm**.*

The following are true.

1.  $\|\cdot\|$  is in fact a well-defined **Seminorm** on  $BL(X, Y)$ .
2. If  $\|\cdot\|_Y$  is a **Norm**, then so is  $\|\cdot\|$ .
3. If  $T \in BL(X, Y)$  and  $\alpha \in (0, \infty)$ , then  $\|T\| = \sup_{\|x\|_X = \alpha} \frac{\|Tx\|_Y}{\|x\|_X}$ .
4. If  $T \in BL(X, Y)$  and  $\alpha \in (0, \infty)$ , then  $\|T\| = \sup_{0 < \|x\|_X \leq \alpha} \frac{\|Tx\|_Y}{\|x\|_X} = \sup_{0 < \|x\|_X < \alpha} \frac{\|Tx\|_Y}{\|x\|_X}$ .

5. If  $T \in BL(X, Y)$  and  $x \in X$ , then  $\|Tx\|_Y \leq \|T\| \|x\|_X$ .
6.  $S : X \rightarrow Y$  is linear,  $S(\mathcal{K}_X^{\text{ernel}}) \subset \mathcal{K}_Y^{\text{ernel}}$ , and  $\sup_{\|x\|_X \neq 0} \frac{\|Sx\|_Y}{\|x\|_X} < \infty$ , if and only if  $S \in BL(X, Y)$ .
7. A sequence  $\{T_i\}_{i \in \mathbb{N}}$  is a **Pseudometric Cauchy Sequence** if and only if there exists an  $\alpha > 0$  such that the collection of sequences  $\{\{T_i x\}_{i \in \mathbb{N}} | x \in B_X(0; \alpha)\}$  is **Uniformly Cauchy** if and only if for every  $\beta > 0$ , the collection of sequences  $\{\{T_i x\}_{i \in \mathbb{N}} | x \in B_X(0; \beta)\}$  is **Uniformly Cauchy**.
8. If  $T_i \rightarrow T$  with respect to  $\|\cdot\|$ , then  $T_i x \rightarrow Tx$  with respect to  $\|\cdot\|_Y$  for each  $x \in X$ .
9. A sequence  $\{T_i\}_{i \in \mathbb{N}} \subset BL(X, Y)$  converges with respect to  $\|\cdot\|$  if and only if it is a **Pseudometric Cauchy Sequence** and for each  $x_\alpha$  in some Hamel basis  $\{x_\alpha\}_{\alpha \in A} \subset X$ , the sequence  $\{T_i x_\alpha\}_{i \in \mathbb{N}}$  converges with respect to  $\|\cdot\|_Y$ .
10. Let  $X$  be **Non-Degenerate**. Then  $BL(X, Y)$  is complete if  $Y$  is complete.
11. If  $BL(X, Y)$  is **Non-Degenerate** then  $Y$  is **Non-Degenerate**.

*Proof of 1.* Since  $X$  is **Non-Degenerate**, there exists an  $x \in X$  with  $\|x\|_X \neq 0$ , so for each  $T \in BL(X, Y)$ , the set that the supremum is being taken over is nonempty. Also, it is clear that  $\text{Range}(\|\cdot\|) \subset [0, \infty)$ ,

For **Subadditivity**, let  $T_i \in BL(X, Y)$  for  $i \in \{0, 1\}$ . and  $x \in X$  with  $\|x\|_X > 0$ . Then, since  $\|\cdot\|_Y$  is **Subadditive**,

$$\frac{\|(T_0 + T_1)x\|_Y}{\|x\|_X} \leq \frac{\|T_0 x\|_Y}{\|x\|_X} + \frac{\|T_1 x\|_Y}{\|x\|_X}$$

Since this is true for each  $x$  with  $\|x\|_X \neq 0$ , taking the supremum of each side yields

$$\begin{aligned} \sup_{\|x\|_X \neq 0} \left( \frac{\|(T_0 + T_1)x\|_Y}{\|x\|_X} \right) &\leq \sup_{\|x\|_X \neq 0} \left( \frac{\|T_0 x\|_Y}{\|x\|_X} + \frac{\|T_1 x\|_Y}{\|x\|_X} \right) \\ &\leq \sup_{\|x\|_X \neq 0} \left( \frac{\|T_0 x\|_Y}{\|x\|_X} \right) + \sup_{\|x\|_X \neq 0} \left( \frac{\|T_1 x\|_Y}{\|x\|_X} \right) \end{aligned}$$

Hence,  $\|T_0 + T_1\| \leq \|T_0\| + \|T_1\|$  so that  $\|\cdot\|$  is **Subadditive**. For **Scalar Homogeneity**, let  $T \in BL(X, Y)$ ,  $\alpha \in \mathbb{F}$ , and  $x \in X$  with  $\|x\|_X \neq 0$ . Then

$$\frac{\|(\alpha T)x\|_Y}{\|x\|_X} = \frac{\|\alpha(Tx)\|_Y}{\|x\|_X} = |\alpha| \frac{\|Tx\|_Y}{\|x\|_X}$$

Hence taking the supremum finishes the proof. □

*Proof of 2.* Let  $T \neq 0 \in BL(X, Y)$ . Then for some  $x \in X$ ,  $Tx \neq 0$ . Then  $Tx$  has a neighborhood  $U$  disjoint from  $0_Y$ , Hence  $x \in T^{-1}(U)$  but not  $0_X \in T^{-1}(U)$ , since  $T0_X = 0_Y$ . Since  $U$  is a neighborhood of  $x$  disjoint from  $0$ , there is an  $\epsilon > 0$  such that  $0_X \subset \mathbb{C}U \subset \mathbb{C}\overline{B_X}(x; \epsilon)$ , and therefore  $\|x\|_X > \epsilon$ . Since  $\|x\|_X > 0$ , it is ranged over in the supremum defining  $\|T\|$ , and so

$$0 < \frac{\|Tx\|_Y}{\|x\|_X} \leq \sup_{\|x\|_X \neq 0} \frac{\|Tx\|_Y}{\|x\|_X} = \|T\| \quad (2.61)$$

□

*Proof of 3.* Let  $\alpha \in (0, \infty)$  Let  $T \in BL(X, Y)$ . Then, there is a sequence  $\{x_i\} \subset X$  with each  $\|x_i\|_X \neq 0$  such that

$$\frac{\|Tx_i\|_Y}{\|x_i\|_X} \rightarrow \|T\| \quad (2.62)$$

For each  $i \in \mathbb{N}$ , define  $y_i = \alpha x_i / \|x_i\|_X$ . then each  $\|y_i\|_X = \alpha$ , and by **Scalar Homogeneity** of  $T$ , we have

$$\frac{\|Ty_i\|_Y}{\|y_i\|_X} = \frac{\|Tx_i\|_Y}{\|x_i\|_X} \rightarrow \|T\| \quad (2.63)$$

, completing the proof. □

*Proof of 4.* If we define, for  $T \in BL(X, Y)$ ,  $f(T) = \sup_{0 < \|x\|_X \leq \alpha} \frac{\|Tx\|_Y}{\|x\|_X}$ , then since  $\|\cdot\|^{-1}((0, \alpha)) \subset \|\cdot\|^{-1}((0, \infty))$ , we have  $f(T) \leq \|T\|$  and since  $\|\cdot\|^{-1}(\{\alpha\}) \subset \|\cdot\|^{-1}((0, \alpha))$ , we have  $\|T\| \leq f(T)$ . proving the first equality. The second is found by applying the same argument to  $\alpha/2$  and realizing that  $(0, \alpha/2] \subset (0, \alpha)$ . □

*Proof of 5.* Let  $T \in BL(X, Y)$  and  $x \in X$ . If  $\|Tx\|_Y \neq 0$ , then  $B_Y(Tx, \frac{\|Tx\|_Y}{2})$  is a neighborhood of  $Tx$  disjoint from  $0$ . Continuity of  $T$  implies  $x$  then has a neighborhood disjoint from  $0 \in T^{-1}(0)$ , implying that  $\|x\|_X \neq 0$ .

Hence if  $\|x\|_X = 0$ , then we know  $\|Tx\|_Y = 0$ , so that the relation

$$\|Tx\|_Y \leq \|T\| \|x\|_X \quad (2.64)$$

If  $\|x\|_X \neq 0$ , then by definition of supremum,

$$\frac{\|Tx\|_Y}{\|x\|_X} \leq \|T\|$$

so that  $\|Tx\|_Y \leq \|T\| \|x\|_X$ . □

*Proof of 6.* I assume the first 3 conditions and show that  $S \in BL(X, Y)$ . It is necessary and sufficient to show that  $S$  is continuous. Let  $F = \sup_{\|x\|_X \neq 0} \frac{\|Sx\|_Y}{\|x\|_X}$ . If  $F = 0$ , then  $S(X) \subset \mathcal{K}_Y^{\text{ernel}}$ .

Every neighborhood of every point in  $\mathcal{K}_Y^{\text{ernel}}$  contains  $\mathcal{K}_Y^{\text{ernel}}$ , so in that case continuity holds. Suppose  $F \neq 0$ . By translation invariance of the topology, it is sufficient to consider neighborhoods of  $0_Y \in Y$ . Let  $\epsilon > 0$ . Define  $V = B_X(0; \frac{\epsilon}{F})$ . Let  $x_0 \in V$ . If  $\|x_0\|_X = 0$ , then  $S(x_0) \in S(\mathcal{K}_X^{\text{ernel}}) \subset \mathcal{K}_Y^{\text{ernel}} \subset B_Y(0; \epsilon)$ . If  $\|x_0\|_X \neq 0$ , then  $\|Sx_0\|_Y \leq F \|x_0\|_X < \epsilon$ , so

$s(x_0) \in B_Y(0; \epsilon)$ . Hence  $S(B_X(0; \frac{\epsilon}{F})) \subset B_Y(0; \epsilon)$ . so  $S$  is continuous, and this direction for the proof is complete.

Suppose conversely that  $S \in BL(X, Y)$ . Then  $S$  is linear by definition, and the supremum expression is finite by part 1 of this result. Since  $S$  is linear,  $S0_X = 0_Y$ . Since  $S$  is continuous,

$$\begin{aligned} S(\mathcal{K}_X^{\text{ernel}}) &= S(\overline{\{0_X\}}) \\ &\subset \overline{S(\{0_X\})} \\ &= \overline{\{0_Y\}} \\ &= \mathcal{K}_Y^{\text{ernel}} \end{aligned}$$

□

*Proof of 7.* (3  $\implies$  2) is trivial, as is (2  $\implies$  3).

I now prove (1  $\implies$  3). Let  $\{T_i\}_{i \in \mathbb{N}}$  be a **Pseudometric Cauchy Sequence**. Let  $\beta > 0$ . Let  $\epsilon > 0$ . Then there exists  $N \in \mathbb{N}$  such that for  $m, n > N$ ,

$$\|T_n - T_m\| < \frac{\epsilon}{\beta}$$

Let  $x \in B_X(0; \beta)$ . Then

$$\begin{aligned} \|T_m x - T_n x\|_Y &= \|(T_m - T_n)x\|_Y \\ &\leq \|T_m - T_n\| \|x\|_X \\ &< \epsilon \end{aligned}$$

Since  $x \in B_X(0; \beta)$  was arbitrary,  $\{\{T_i x\}_{i \in \mathbb{N}} | x \in B_X(0; \beta)\}$  is **Uniformly Cauchy**.

I now prove (3  $\implies$  1). Let  $\epsilon > 0$ . Then there is an  $N \in \mathbb{N}$  such that for  $m, n > N$ , for each  $x \in B_X(0; 2)$ ,

$$\|T_m x - T_n x\| < \epsilon$$

In particular, if  $\|x\| = 1$ , then

$$\frac{\|(T_m - T_n)x\|_Y}{\|x\|_X} = \|(T_m - T_n)x\|_Y < \epsilon \quad (2.65)$$

Hence, by taking the supremum over such  $x$  and applying part 3 of this result,  $\|T_m - T_n\| < \epsilon$ . □

*Proof of 8.* Let  $T_i \rightarrow T$ . Let  $x \in X$ . If  $x \in \mathcal{K}_X^{\text{ernel}}$ , then  $T_i(x) \in \mathcal{K}_Y^{\text{ernel}}$  for  $i \in \mathbb{N}$  and  $T_x \in \mathcal{K}_Y^{\text{ernel}}$ , so convergence is obvious. Suppose  $\|x\|_X > 0$ . Let  $\epsilon > 0$ . Then there exists  $N \in \mathbb{N}$  such that for  $n > N$ ,  $\|T_n - T\| < \frac{\epsilon}{\|x\|_X}$ . For such  $n$ ,

$$\|T_i x - T x\|_Y \leq \|T_i - T\| \|x\|_X < \epsilon$$

□

*Proof of 9.* ( $\implies$ ) Suppose  $T_i \rightarrow T$ . Then, by 2.1.20,  $\{T_i\}_{i \in \mathbb{N}}$  is a **Pseudometric Cauchy Sequence**. An application of part 8 of this result implies the pointwise convergence on a hamel basis.

( $\impliedby$ ) Let  $\{x_\alpha\}_{\alpha \in A}$  be a Hamel basis for  $X$ . Let  $T_i x_\alpha \rightarrow y_\alpha$  for  $\alpha \in A$ . Define  $T : X \rightarrow Y$  by setting, for  $x \in X$ , for any  $\{\alpha_i\}_{i=1}^n \subset A$   $\{\beta_i\}_{i=1}^n \subset \mathbb{F}$ ,

$$T \left( \sum_{i=1}^n \beta_i x_{\alpha_i} \right) = \sum_{i=1}^n \beta_i y_{\alpha_i} \quad (2.66)$$

The uniqueness of a hamel basis representation implies that  $T$  is well defined. It is clear also that  $T$  is linear, and that  $T(\mathcal{K}_X^{\text{ernel}}) \subset \mathcal{K}_Y^{\text{ernel}}$ .

Let  $x \in X$ . Then we can find a unique representation,  $x = \sum_{j=1}^n \beta_j x_{\alpha_j}$  where  $x_{\alpha_j} \in A$  and  $\beta_j \in \mathbb{F}$  for every  $j$ . For each  $j \in \{1, \dots, n\}$ , there is an  $N_j$  such that if  $n_j > N_j$ , the

$$\|T_{n_j} x_{\alpha_j} - y_{\alpha_j}\| < \frac{\epsilon}{n(|\beta_j| + 1)} \quad (2.67)$$

Let  $N = \max\{N_j\}_{j=1}^n$ . Let  $m > N$ . Then, we have

$$\begin{aligned} \|T_m x - T x\| &= \left\| T_m \left( \sum_{j=1}^n \beta_j x_{\alpha_j} \right) - T \left( \sum_{j=1}^n \beta_j x_{\alpha_j} \right) \right\| \\ &= \left\| \sum_{j=1}^n \beta_j (T_m x_{\alpha_j} - T x_{\alpha_j}) \right\| \\ &= \sum_{j=1}^n |\beta_j| \|T_m x_{\alpha_j} - T x_{\alpha_j}\| \\ &< \epsilon \end{aligned}$$

Since  $m > N$  was arbitrary,  $T_i x \rightarrow T x$  for  $x \in X$ .

Since  $T_i x \rightarrow T x$  for  $x \in B_X(0; 2)$ , and since part 7 of this result, paired with the assumption that  $\{T_i\}_{i \in \mathbb{N}}$  is a **Pseudometric Cauchy Sequence**,  $\{\{T_i x\}_{i \in \mathbb{N}}\}_{x \in B_X(0; 2)}$  is **Uniformly Convergent** to  $\{T x\}_{x \in B_X(0; 2)}$ .

Let  $\epsilon > 0$ . By **Uniform Convergence**, there is an  $N \in \mathbb{N}$  such that for  $n > N$ ,  $x \in B_X(0; 2)$ , we have

$$\|T_n x - T x\| < \epsilon \quad (2.68)$$

In particular, if  $\|x\| = 1$ ,

$$\frac{\|(T_n - T)x\|_Y}{\|x\|_X} < \epsilon \quad (2.69)$$

Implying first through part 6 of this result that  $T \in BL(X, Y)$ , and second that Hence  $T_i \rightarrow T$  with respect to  $\|\cdot\|$ .  $\square$

*Proof of 10.* Let  $Y$  be Pseudometric Complete. and let  $X$  be **Non-Degenerate**. Let  $\{T_\alpha\}_{\alpha \in A} \subset BL(X, Y)$  be a **Pseudometric Cauchy Sequence**. Let  $\{x_\alpha\}_{\alpha \in A}$  be a Hamel basis for  $X$ . Let  $\alpha \in A$ . If  $x_\alpha \in \mathcal{K}_X^{\text{ernel}}$ , then  $T_i x_\alpha \in \mathcal{K}_Y^{\text{ernel}}$  for  $i \in \mathbb{N}$ , and so  $T_i x_\alpha \rightarrow 0$ .

Otherwise,  $\|x_\alpha\|_X > 0$ , so for  $\epsilon > 0$ , there exists  $N \in \mathbb{N}$  such that for  $m, n > N$ , we have  $\|T_m - T_n\| < \frac{\epsilon}{\|x_\alpha\|}$ . For such  $m$  and  $n$ ,

$$\begin{aligned} \frac{\|T_m x_\alpha - T_n x_\alpha\|_Y}{\|x_\alpha\|_X} &= \frac{\|(T_m - T_n) x_\alpha\|_Y}{\|x_\alpha\|_X} \\ &\leq \|T_m - T_n\| \\ &< \frac{\epsilon}{\|x_\alpha\|} \end{aligned}$$

By multiplying by  $\|x_\alpha\|_X$ , we see that  $\{T_i x_\alpha\}_{i \in \mathbb{N}}$  is a **Pseudometric Cauchy Sequence**. Since  $Y$  is **Complete**, these sequences converge, say  $T_i x_\alpha \rightarrow y_\alpha$ . This allows us apply part 9 of this result to claim that  $\{T_i\}_{i \in \mathbb{N}}$  converges in  $\|\cdot\|$ .  $\square$

*Proof of 11.* If  $BL(X, Y)$  is nondegenerate, then for some  $T \in BL(X, Y)$ , for some  $x \in X$ ,  $\|Tx\|_Y \neq 0$ .  $\square$

**Remark 2.1.56** (Converses). *The converses to parts 10 and 11 of 2.1.55 are true, but their proof relies upon the Hahn Banach theorem for Seminormed spaces, and so their official claim is delayed until later in the narrative.*

**Definition 2.1.57** (Codomain Quotient Operator). *Let  $X$  and  $Y$  be Seminormed Spaces. Define  $\mathcal{Q}_Y : BL(X, Y) \rightarrow BL(X, Y/\mathcal{K}_Y^{\text{ernel}})$  by setting, for each  $x \in X$ ,*

$$\mathcal{Q}_Y T x = [Tx]$$

Let  $T \in BL(X, Y)$ . We call  $\mathcal{Q}_Y$  the **Codomain Quotient Map** of  $X$  and  $Y$  and we call  $\mathcal{Q}_Y T$  the **Codomain Quotient Operator** of  $T$ .

**Proposition 2.1.58** (Codomain Quotient Operator). *Let  $X$  and  $Y$  be Seminormed Spaces with Codomain Quotient Map  $\mathcal{Q}_Y$ . The following are true.*

1.  $\mathcal{Q}_Y$  is a well defined continuous linear surjective isometry.
2. If  $Y$  is a **Normed Space**, then  $\mathcal{Q}_Y$  is invertible with a continuous inverse.

*Proof Of 1.* Since  $Tx \in Y$  for any  $x \in X$ ,  $[Tx]_Y$  is defined for any  $x \in X$ . Furthermore, if  $q_y : Y \rightarrow Y/\mathcal{K}^{\text{ernel}}$  is the **Quotient Map** of  $Y$  under **Equivalence MOD- $\mathcal{K}^{\text{ernel}}$** , then  $\mathcal{Q}_Y T = q_y \circ T$ . By 2.1.51,  $q_y$  is linear and an isometry, and hence continuous. Therefore,  $q_y \in BL(Y, Y/\mathcal{K}^{\text{ernel}})$ . Hence  $\mathcal{Q}_Y$  is well defined.

For linearity, let  $\alpha \in \mathbb{F}$  and  $S, T \in BL(X, Y)$ . Let  $x \in X$ . Then,

$$\begin{aligned} \mathcal{Q}_Y (\alpha T + S) x &= [(\alpha T + S) x]_Y \\ &= [\alpha T x + S x]_Y \\ &= [\alpha T x]_Y + [S x]_Y \\ &= \alpha [T x]_Y + [S x]_Y \\ &= \alpha \mathcal{Q}_Y T x + \mathcal{Q}_Y S x \\ &= (\alpha \mathcal{Q}_Y T + \mathcal{Q}_Y S) x \end{aligned}$$

For being an isometry, let  $T \in BL(X, Y)$  and let  $x \in X$ . Then, since  $\|[Tx]_Y\|_{Y/\mathcal{K}^{\text{ernel}}} = \|Tx\|_Y$ ,

$$\begin{aligned} \frac{\|\mathcal{Q}Tx\|_{Y/\mathcal{K}^{\text{ernel}}}}{\|x\|_X} &= \frac{\|[Tx]_Y\|_{Y/\mathcal{K}^{\text{ernel}}}}{\|x\|_X} \\ &= \frac{\|Tx\|_Y}{\|x\|_X} \end{aligned}$$

and thus taking the norm over  $x$  with  $\|x\|_X \neq 0$  will yield the same result. Hence  $\|T\| = \|\mathcal{Q}_Y T\|$ .

For surjectivity, let  $\tilde{T} \in BL(X, Y/\mathcal{K}_Y^{\text{ernel}})$ . Let  $\{x_\alpha\}_{\alpha \in A}$  be a hamel basis for  $X$ . For each  $\alpha \in A$ , let  $y_\alpha \in \tilde{T}x_\alpha$ . Define  $T : X \rightarrow Y$  by

$$T \left( \sum_{i=1}^n \beta_{\alpha_i} x_{\alpha_i} \right) = \sum_{i=1}^n \beta_{\alpha_i} y_{\alpha_i} \quad (2.70)$$

$T$  is obviously linear and has the property  $[Tx] = \tilde{T}x$ . and since  $\tilde{T} \in BL(X, Y/\mathcal{K}^{\text{ernel}})$ ,  $\tilde{T}\mathcal{K}_X^{\text{ernel}} \subset \mathcal{K}_{(Y/\mathcal{K}_Y^{\text{ernel}})}^{\text{ernel}} = 0$ . Hence  $T\mathcal{K}_X^{\text{ernel}} \subset \mathcal{K}_Y^{\text{ernel}}$ . Furthermore, if  $x \in X$  with  $\|x\|_X \neq 0$ , then

$$\begin{aligned} \frac{\|Tx\|_Y}{\|x\|_X} &= \frac{\|[Tx]_Y\|_{Y/\mathcal{K}^{\text{ernel}}}}{\|x\|_X} \\ &= \frac{\|\tilde{T}x\|_{Y/\mathcal{K}^{\text{ernel}}}}{\|x\|_X} \end{aligned}$$

Therefore  $T$  is bounded. Hence  $T \in BL(X, Y)$ , and  $\mathcal{Q}_Y T = \tilde{T}$ . Thus we have surjectivity, and are done.  $\square$

*Proof Of 2.* If  $Y$  is a **Normed Space**, a linear isometric homeomorphism by 2.1.51. In particular, in this case,  $q_Y$  is injective, meaning that if  $T, S \in BL(X, Y)$  where  $T \neq S$ , then  $Tx_0 \neq Sx_0$  for some  $x_0 \in X$ . For this  $x_0$ ,  $q_Y Tx_0 \neq q_Y Sx_0$ , so  $\mathcal{Q}_Y T \neq \mathcal{Q}_Y S$ . Therefore  $\mathcal{Q}_Y$  is injective, and therefore a bijection. The inverse of an isometry is also an isometry and therefore continuous, finishing this proof.  $\square$

**Definition 2.1.59** (Quotient Operator). Let  $X, Y$  be **Seminormed Spaces** with **Seminorm Kernels**  $\mathcal{K}_X^{\text{ernel}}, \mathcal{K}_Y^{\text{ernel}}$ . Define  $Q : BL(X, Y) \rightarrow BL(X/\mathcal{K}_X^{\text{ernel}}, Y/\mathcal{K}_Y^{\text{ernel}})$  by setting, for  $T \in BL(X, Y)$ , for  $x \in X$ ,

$$QT[x]_X = [Tx]_Y \quad (2.71)$$

We call  $Q$  the **Operator Quotient Map** of  $X$  and  $Y$  and we call  $QT$  the **Quotient Operator** of  $T$ .

**Proposition 2.1.60** (Quotient Operator). Let  $X, Y$  be **Seminormed Spaces** with **Seminorm Kernels**  $\mathcal{K}_X^{\text{ernel}}, \mathcal{K}_Y^{\text{ernel}}$  and **Operator Quotient Map**  $Q$ . Then  $Q$  is a well-defined linear surjective isometry.

*Proof.* We first show that  $Q$  is well defined. Let  $T \in BL(X, Y)$  and let  $x_0, x_1 \in X$  such that  $[x_0] = [x_1]$ . Then  $\|x_0 - x_1\|_X = 0$ , so since  $T$  is continuous,  $\|Tx_0 - Tx_1\|_Y = 0$ . Hence  $Tx_0 \cong Tx_1$ , so  $[Tx_0] = [Tx_1]$ .

For linearity, let  $\alpha \in \mathbb{F}$ , and let  $T, S \in BL(X, Y)$ . Let  $x \in X$ . Then

$$\begin{aligned} Q(\alpha T + S)[x]_X &= [(\alpha T + S)x]_Y \\ &= \alpha [Tx]_Y + [Sx]_Y \\ &= \alpha QT[x]_X + QS[x]_X \\ &= (\alpha QT + QS)[x]_X \end{aligned}$$

Since  $x \in X$  was arbitrary,  $Q$  is linear.

As for being an isometry, let  $T \in BL(X, Y)$  and let  $x \in X$ . Since  $\|[x]\| = \|x\|$  and  $\|Tx\| = \|[Tx]\|$ , we have

$$\begin{aligned} \frac{\|QT[x]_{X/\mathcal{K}_X^{\text{ernel}}}\|_{Y/\mathcal{K}_Y^{\text{ernel}}}}{\|[x]\|_{X/\mathcal{K}_X^{\text{ernel}}}} &= \frac{\|[Tx]\|_{Y/\mathcal{K}_Y^{\text{ernel}}}}{\|[x]\|_{X/\mathcal{K}_X^{\text{ernel}}}} \\ &= \frac{\|Tx\|_Y}{\|x\|_X} \end{aligned}$$

and so taking the supremum over  $\|x\| \neq 0$  gives us that this is an isometry.

For surjectivity, let  $\tilde{T} \in BL(X/\mathcal{K}_X^{\text{ernel}}, Y/\mathcal{K}_Y^{\text{ernel}})$ . Let  $\{x_\alpha\}_{\alpha \in A}$  be a Hamel basis for  $X$ . For each  $\alpha \in A$ , let  $y_\alpha \in \tilde{T}[x_\alpha]_X$ . Now define

$$T \sum_{i=1}^n \beta_i x_{\alpha_i} = \sum_{i=1}^n \beta_i y_{\alpha_i} \quad (2.72)$$

Then  $T : X \rightarrow Y$  is obviously linear, and  $Tx \in \tilde{T}[x]_X$  for  $x \in X$ . Hence,

$$\frac{\|Tx\|_Y}{\|x\|_X} = \frac{\|\tilde{T}[x]_X\|_{Y/\mathcal{K}_Y^{\text{ernel}}}}{\|[x]_X\|_{X/\mathcal{K}_X^{\text{ernel}}}} \quad (2.73)$$

so  $T$  is bounded, and hence  $T \in BL(X, Y)$ , but that also implies that by definition,  $QT = \tilde{T}$ , so we have proven surjectivity.  $\square$

**Definition 2.1.61** (Canonical Isomorphism Of The Quotient Space Of Continuous Linear Operators). Let  $X, Y$  be **Seminormed Spaces** with **Seminorm Kernels**  $\mathcal{K}_X^{\text{ernel}}, \mathcal{K}_Y^{\text{ernel}}$ . Let  $\mathcal{K}^{\text{ernel}}$  denote the **Seminorm Kernel** of  $BL(X, Y)$ . Let  $Q$  denote the **Operator Quotient Map** of  $X$  and  $Y$ . Define  $\Theta_{(X,Y)} : BL(X, Y)/\mathcal{K}^{\text{ernel}} \rightarrow BL(X/\mathcal{K}_X^{\text{ernel}}, Y/\mathcal{K}_Y^{\text{ernel}})$  by setting, for each  $T \in BL(X, Y)$ .

$$\Theta_{(X,Y)}([T]) = QT \quad (2.74)$$

We call  $\Theta_{(X,Y)}$  the **Canonical Isomorphism Of The Quotient Space Of Continuous Linear Operators** from  $X$  to  $Y$ . When  $X$  and  $Y$  are understood, we may denote the **Canonical Isomorphism Of The Quotient Space Of Continuous Linear Operators** simply with  $\Theta$ . By 2.1.62,  $\Theta_{(X,Y)}$  is an isomorphism of **Normed Spaces**. That is,  $\Theta$  is Linear, Bijective, Bicontinuous, and an isometry.



**Proposition 2.1.62** (Canonical Isomorphism Of The Quotient Space Of Continuous Linear Operators). *Let  $X, Y$  be Seminormed Spaces . Let  $\Theta$  denote the Canonical Isomorphism Of The Quotient Space Of Continuous Linear Operators from  $X$  to  $Y$ . Then  $\Theta$  is a bijective, bicontinuous, linear, isometry.*

*Proof.* By 2.1.51, part 1,  $Y/\mathcal{K}_Y^{\text{ernel}}$  is a Normed Space , Hence by 2.1.55, part 2,  $BL(X/\mathcal{K}_X^{\text{ernel}}, Y/\mathcal{K}_Y^{\text{ernel}})$  is a Normed Space . Similarly, by 2.1.51, part 1,  $BL(X, Y)/\mathcal{K}^{\text{ernel}}$  is a normed space. Hence, it is sufficient to show that  $\Theta$  is a well-defined surjective linear isometry.

For well definedness, let  $T, S \in BL(X, Y)$  with  $[T] = [S]$ . Then,  $\|T - S\| = 0$ , so if  $x \in X$ ,  $\|Tx - Sx\| = 0$ . Hence  $Tx \cong Sx$  and since  $x$  was arbitrary,  $QT = QS$ .

Let  $q$  denote the Quotient Map  $q : BL(X, Y) \rightarrow BL(X, Y)/\mathcal{K}^{\text{ernel}}$ . By parts 4, 5, and 6 of 2.1.51,  $q$  is a linear surjective isometry. Also, by definition,  $\Theta \circ q = Q$ . Since  $Q$  is surjective,  $\Theta$  is surjective. Since  $Q$  is an isometry, and  $q$  is a surjective isometry,  $\Theta$  is an isometry. Since  $Q$  is linear, and since  $q$  is surjective and linear,  $\Theta$  is linear.  $\square$

**Definition 2.1.63** (Seminorm Topological Dual Space). *Let  $(X, \|\cdot\|)$  be a Seminormed Space over a field  $\mathbb{F}$ . We denote with  $X^*$  Normed Space  $BL(X, \mathbb{F})$ , and we call  $X^*$  the Topological Dual Space of  $X$ . If  $x^* \in X^*$ , then we may denote, for  $x \in X$ ,  $x^*(x)$  with  $\langle x, x^* \rangle$ .*

Since  $\mathbb{F}$  is a Normed Space , by 2.1.55, part 02,  $X^*$  is as well.

Since  $X^*$  is a normed space

Also,  $q : \mathbb{F} \rightarrow \mathbb{F}/\mathcal{K}_{\mathbb{F}}^{\text{ernel}}$  is a linear bijective isometry by 2.1.51, so if  $Q : X^* \rightarrow BL(X/\mathcal{K}_X^{\text{ernel}}, \mathbb{F}/\mathcal{K}_{\mathbb{F}}^{\text{ernel}})$  is the Operator Quotient Map and if  $\Theta : BL(X, \mathbb{F})/\mathcal{K}^{\text{ernel}} \rightarrow BL(X/\mathcal{K}_X^{\text{ernel}}, \mathbb{F}/\mathcal{K}_{\mathbb{F}}^{\text{ernel}})$  is the Canonical Isomorphism Of The Quotient Space Of Continuous Linear Operators , then we have

$$\Theta = Q \circ q^{-1} \quad (2.75)$$

**Definition 2.1.64** (Dual Space). *Let  $(X, \|\cdot\|)$  be a Seminormed Space . We call  $BL(X, \mathbb{F})$  the Topological Dual Space of  $(X, \|\cdot\|)$ , and we denote  $BL(X, \mathbb{F})$  with the symbol  $X^*$ . If  $x^* \in X^*$ , then we use the notational convention of writing, for  $x \in X$ .*

$$\langle x, x^* \rangle := x^*(x) \quad (2.76)$$

**Remark 2.1.65** ( Topological Dual Space is a Normed Space ). *Let  $X$  be a Seminormed Space . Then, using 2.1.55, since  $\mathbb{F}$  is a Normed Space , so is  $X^*$ .*

**Theorem 2.1.66** ( Topological Dual Space Isomorphism). *Let  $X$  be a Seminormed Space . Define  $\Omega : X^* \rightarrow (X/\mathcal{K}_X^{\text{ernel}})^*$  by setting, for  $x^* \in X^*$ , and for  $x \in X$ ,*

$$\langle x, x^* \rangle = \langle [x], \Omega x^* \rangle \quad (2.77)$$

Then  $\Omega$  is a Linear, Bijective, Isometric, Bicontinuous operator. That is,  $X^*$  and  $(X/\mathcal{K}_X^{\text{ernel}})^*$  are isomorphic, and that isomorphism is explicitly given by  $\Omega$ .

*Proof.* Consider the following

$$BL(X, \mathbb{F}) \xrightarrow{q} BL(X, \mathbb{F})/\mathcal{K}_{BL(X/\mathbb{F})}^{\text{ernel}} \xrightarrow{\Theta} BL(X/\mathcal{K}_X^{\text{ernel}}, \mathbb{F}/\mathcal{K}_{\mathbb{F}}^{\text{ernel}}) \xrightarrow{\mathcal{Q}_{\mathbb{F}}^{-1}} BL(X/\mathcal{K}_X^{\text{ernel}}, \mathbb{F}) \quad (2.78)$$

where  $q$  is the **Quotient Map**, which is an linear bijective bicontinuous isometry in this case by parts 4, 5, 6, and 7 of 2.1.51,  $\Theta$  is the **Canonical Isomorphism Of The Quotient Space Of Continuous Linear Operators**, which is a linear bijective bicontinuous isometry by 2.1.62 and  $\mathcal{Q}_{\mathbb{F}}$  is the **Codomain Quotient Map**, which is in this case a linear, bijective, bicontinuous isometry by 2.1.58

Since  $\Omega = \mathcal{Q}_{\mathbb{F}}^{-1} \circ \Theta \circ q$ , and since each of the described properties are preserved under composition,  $\Omega$  is also a linear bijective bicontinuous isometry.  $\square$

**Theorem 2.1.67** (Hahn Banach Theorem For Seminormed Spaces). *Let  $(X, \|\cdot\|)$  be a Seminormed Space, let  $x_i \in X$  for  $i \in \{0, 1\}$  such that  $\|x_0 - x_1\|_X \neq 0$ , and let  $X^*$  denote  $X$ 's Topological Dual Space. The following are true.*

1. If  $Z \subset X$  is a subspace and  $z^* \in Z^*$ , then there is an extension  $x^*$  of  $z^*$ ,  $x^* \in X^*$  such that

$$\|z^*\|_{Z^*} = \|x^*\|_{X^*} \quad (2.79)$$

2. If  $x \in X$ , with  $\|x\| \neq 0$ , then there exists an  $x^* \in X^*$  with  $\|x^*\| = 1$  and  $\langle x, x^* \rangle = \|x\|_X$ .
3. If  $x \in X$ , then

$$\|x\|_X = \sup_{0 \neq x^* \in X^*} \frac{\langle x, x^* \rangle}{\|x^*\|} \quad (2.80)$$

*Proof of 01.* For  $\alpha \in \{Z, X\}$ , let  $\Omega_\alpha : \alpha^* \rightarrow (\alpha/\mathcal{K}_\alpha^{\text{ernel}})^*$  denote the isomorphism defined in 2.1.66. Let  $q$  denote the quotient operator  $q : X \rightarrow X/\mathcal{K}_X^{\text{ernel}}$ . Define  $T : Z/\mathcal{K}_Z^{\text{ernel}} \rightarrow q(Z)$  by  $T([z]_{\cong_Z}) = [z]_{\cong_X}$ . Since  $Z$  is endowed with the subspace Topology,  $T$  is obviously a Linear Bijective Bicontinuous Isometry.

Define  $\Gamma_Z : (Z/\mathcal{K}_Z^{\text{ernel}})^* \rightarrow q(Z)^*$  by setting, for  $\phi^* \in (Z/\mathcal{K}_Z^{\text{ernel}})^*$ , for  $[z]_Z \in Z/\mathcal{K}_Z^{\text{ernel}}$ ,

$$\langle T[z]_Z, \Gamma_Z \phi^* \rangle = \langle [z]_Z, \phi^* \rangle \quad (2.81)$$

Then  $\Gamma_Z$  is a Linear Bijective Isometry. Hence  $\Gamma_Z \circ \Omega_Z z^* \in q(Z)^*$  with  $\|\Gamma_Z \circ \Omega_Z z^*\|_{q(Z)^*} = \|z^*\|_{Z^*}$ .

Thus we can apply the Hahn Banach theorem for **Normed Spaces** to claim the existence of  $x_q^* \in (X/\mathcal{K}_X^{\text{ernel}})^*$  where  $x_q^*$  is an extension of  $\Gamma_Z \circ \Omega_Z z^*$  and

$$\|x_q^*\|_{(X/\mathcal{K}_X^{\text{ernel}})^*} = \|\Gamma_Z \circ \Omega_Z z^*\|_{(q(Z))^*} = \|z^*\|_{Z^*} \quad (2.82)$$

Finally, letting  $x^* = \Omega_X^{-1} x_q^*$ , we have  $x^* \in X^*$ ,  $\|x^*\|_{X^*} = \|x_q^*\|_{(X/\mathcal{K}_X^{\text{ernel}})^*} = \|z^*\|_{Z^*}$ , and if  $z \in Z$ , then

$$\begin{aligned} \langle z, x^* \rangle &= \langle [z]_X, x_q^* \rangle \\ &= \langle [z]_X, \Gamma_Z \circ \Omega_Z z^* \rangle \\ &= \langle [z]_Z, \Omega_Z z^* \rangle \\ &= \langle z, z^* \rangle \end{aligned}$$

$\square$

*Proof of 2.* Let  $Z = \text{span}(x)$ . Define  $z^* \in Z^*$  by  $\langle \alpha x, z^* \rangle = \alpha \|x\|$ . Then  $\|z^*\| = 1$ . Also, by part 1 of this result, it has an extension  $x^* \in X^*$  with  $\|x^*\| = \|z^*\| = 1$  and  $\langle x, x^* \rangle = \|x\|$ .  $\square$

*Proof of 3.* If  $\|x\| = 0$ , then for every  $x^* \in X$ ,  $\langle x, x^* \rangle = 0$ . Hence

$$\|x\|_X = \sup_{0 \neq x^* \in X^*} \frac{\langle x, x^* \rangle}{\|x^*\|} = \sup_{x^* \in \partial B_{X^*}(0;1)} \frac{\langle x, x^* \rangle}{\|x^*\|} = 0 \quad (2.83)$$

Otherwise, let  $x^* \in X^*$  guaranteed to exist by part 2 which satisfies  $\|x^*\| = 1$ ,  $\langle x, x^* \rangle = \|x\|$ . Then

$$\begin{aligned} \|x\| &= \frac{\langle x, x^* \rangle}{\|x^*\|} \\ &\leq \sup_{x^* \in \partial B_{X^*}(0;1)} \frac{\langle x, x^* \rangle}{\|x^*\|} \\ &\leq \sup_{0 \neq x^* \in X^*} \frac{\langle x, x^* \rangle}{\|x^*\|} \end{aligned}$$

The other direction of the inequality falls directly from the definition of the norm on  $X^*$ , and is trivial, so we are done.  $\square$

Further, since  $X/K$  can be embedded into  $X$ , several existence results, such as Helly's theorem, can also be generalized to the case of a seminormed space. In the context of a seminormed space, the canonical embedding  $c : X \rightarrow X^{**}$  ceases to be injective but remains a linear isometry, and we shall continue to use the nomenclature that  $X$  is **reflexive** if  $c$  is surjective. Since  $X^{**} = (X/\|\cdot\|^{-1}\{0\})^{**}$ , it is no surprise that  $c(X) = c(X/\|\cdot\|^{-1}\{0\})$ . Hence, a seminormed space is reflexive if and only if its induced normed space is reflexive. The weak topology on a set  $X$  induced by set of mappings  $\{\phi_\alpha : X \rightarrow Y_\alpha\}$  where each  $Y_\alpha$  is a topological space is the coarsest topology on  $X$  which makes each  $\phi_\alpha$  continuous. Similar to in the context of a normed space, if  $X$  is a seminormed space, we define the weak topology on  $X$  to be the topology on  $X$  generated by  $X^*$ , and the *weak\** topology on  $X^*$  to be the topology generated by  $c(X)$ . Before moving on to the classical theory revamped, I present on more useful result about weak topologies of seminormed spaces.

**Proposition 2.1.68** (Weak Quotients). *Let  $X$  be a seminormed space and  $\{Y_\alpha\}_{\alpha \in A}$  be a collection of topological spaces. For each  $\alpha \in A$  let  $\phi_\alpha : X \rightarrow Y_\alpha$  have the property that for every  $x, y \in X$ , for every  $\alpha \in A$ ,  $\|x - y\| = 0 \implies \phi_\alpha(x) = \phi_\alpha(y)$ . For each  $\alpha \in A$ , define  $\tilde{\phi}_\alpha : X/\|\cdot\|^{-1}\{0\} \rightarrow Y_\alpha$  by  $\tilde{\phi}_\alpha[x] = \phi_\alpha x$ . Let  $\mathcal{T}_w$  denote the weak topology on  $X$  induced by  $\{\phi_\alpha\}_{\alpha \in A}$ , and  $\mathcal{T}_{\tilde{w}}$  denote the weak topology on  $X/\|\cdot\|^{-1}\{0\}$  induced by  $\{\tilde{\phi}_\alpha\}_{\alpha \in A}$ . Then*

$$(X, \mathcal{T}_w)/\|\cdot\|^{-1}\{0\} = (X/\|\cdot\|^{-1}\{0\}, \mathcal{T}_{\tilde{w}}) \quad (2.84)$$

*Proof.*  $\square$

Finally, before we move on, recall that if  $X, Y$  are Topological vector spaces, we can topologize the set of continuous linear operators from  $X$  to  $Y$ , denoted  $BL(X, Y)$  by saying that  $\{T_\alpha\}_{\alpha \in A} \subset BL(X, Y)$  converges to  $T \in BL(X, Y)$  if there is a neighborhood  $U$  of 0 in  $X$  such that  $T_\alpha x \rightarrow Tx$  uniformly for  $x \in U$ .

## 2.2 Classical Results With A Twist

By ?? and 2.1.68, many of the classical theorems relating a normed space and its duals still hold in the context of a seminormed space without too much alteration of the proofs. Since the author has not seen these results presented in this context, they are presented with proof below.

### 2.2.1 Helly

In this subsection, we develop Helly's theorem in the context of a seminormed space, which will serve as valuable lemma throughout this document. Its location here is due to the fact that it is a generalization of a lemma commonly used to prove the Goldstine Theorem.

**Theorem 2.2.1** (Helly's Theorem). *Let  $(X, \|\cdot\|)$  be a seminormed space  $M > 0$ ,  $\{\alpha_i\}_{i=1}^n \subset \mathbb{R}$ , and  $\{x_i^*\}_{i=1}^n \subset X^*$ . Then the following are equivalent.*

1. *For every  $\epsilon > 0$ , there is an  $x_\epsilon \in X$  such that  $\|x_\epsilon\| < M + \epsilon$  and  $\langle x, x_i^* \rangle = \alpha_i$  for  $1 \leq i \leq n$ .*
2. *For every  $\epsilon > 0$ , there is an  $x_\epsilon \in X$  such that  $\|x_\epsilon\| \leq M$  and  $|\langle x_\epsilon, x_i^* \rangle - \alpha_i| < \epsilon$  for  $1 \leq i \leq n$ .*
3. *For each  $\{\beta_i\}_{i=1}^n \subset \mathbb{C}$ ,*

$$\left| \sum_{i=1}^n \beta_i \alpha_i \right| \leq M \left\| \sum_{i=1}^n \beta_i x_i^* \right\| \quad (2.85)$$

*Proof.* (1  $\implies$  2) Obvious since  $\{x_i^*\}_{i=1}^n \subset X^*$ . □

*Proof.* (2  $\implies$  3) Let  $\{\beta_i\}_{i=1}^n \subset \mathbb{C}$  and choose  $\epsilon > 0$ . Then

$$\begin{aligned} \left| \sum_{i=1}^n \beta_i \alpha_i \right| &= \left| \sum_{i=1}^n \beta_i (\alpha_i - \langle x_\epsilon, x_i^* \rangle + \langle x_\epsilon, x_i^* \rangle) \right| \\ &< \sum_{i=1}^n \epsilon |\beta_i| + \left| \left\langle x_\epsilon, \sum_{i=1}^n \beta_i x_i^* \right\rangle \right| \\ &\leq \epsilon \sum_{i=1}^n |\beta_i| + M \left\| \sum_{i=1}^n \beta_i x_i^* \right\| \end{aligned} \quad (2.86)$$

Since  $\epsilon$  was arbitrary, the desired inequality holds. □

*Proof.* (3  $\implies$  1) If each  $x_i^* = 0$ , then by 2.85, each  $\alpha_i = 0$ , so  $x = 0$  works for any  $\epsilon$ . Otherwise, we without loss of generality reorder  $\{x_i^*\}_{i=1}^n$  so that  $\{x_i^*\}_{i=1}^m$  is linearly independent and  $\text{span}\{x_i\}_{i=1}^m = \text{span}\{x_i\}_{i=1}^n$ . Define  $S : X \rightarrow \mathbb{C}^m$  by  $Sx = [\langle x, x_1^* \rangle, \dots, \langle x, x_m^* \rangle]$ , and recognize that linear independence of  $\{x_i\}_{i=1}^m$  guarantees that  $S$  is surjective, so there exists  $\tilde{x} \in S^{-1}\{\alpha_1, \dots, \alpha_m\}$  and furthermore

$$S^{-1}\{\alpha_1, \dots, \alpha_m\} = \tilde{x} + \bigcap_{i=1}^m \text{kern}(x_i^*) = \tilde{x} + \bigcap_{i=1}^n \text{kern}(x_i^*) := \tilde{x} + K \quad (2.87)$$

If  $m < j \leq n$ , then  $x_j^* \in \text{span}(x_1^*, \dots, x_n^*)$  so  $x_j = \sum_{i=1}^n \gamma_i x_i^*$ . Now we choose  $\beta_i = \gamma_i$  for  $1 \leq i \leq m$ ,  $\beta_j = -1$ , and other  $\beta_k = 0$ .

$$|\langle \tilde{x}, x_j^* \rangle - \alpha_j| = \left| \left\langle \tilde{x}, \sum_{i=1}^m \beta_i x_i^* \right\rangle - \alpha_j \right| = \left| \left( \sum_{i=1}^m \beta_i \langle \tilde{x}, x_i^* \rangle \right) + (-1)\alpha_j \right| \quad (2.88)$$

$$= \left| \sum_{i=1}^n \beta_i \alpha_i \right| \quad (2.89)$$

$$\leq M \left\| \sum_{i=1}^n \beta_i x_i^* \right\| \quad (2.90)$$

$$= M \left\| \sum_{i=1}^m \gamma_i x_i^* + (-1)x_j^* \right\| \quad (2.91)$$

Hence  $\langle x, x_i^* \rangle = \alpha_i$  for  $1 \leq i \leq n$  and any  $x \in \tilde{x} + K$ . By the Hahn Banach Theorem applied to the semi norm on  $X$  induced by the seminorm on the quotient space  $X/K$ , there is an  $x^* \in X^*$  such that  $\sup_{\|x\| \neq 0} \frac{|\langle x, x^* \rangle|}{\|x\|} = 1$ ,  $\langle \tilde{x}, x^* \rangle = d(\tilde{x}, K)$ , and  $K \subset \ker(x^*)$ . Since  $K \subset \ker(x^*)$ ,  $x^* \in \text{span}\{x_i^*\}_{i=1}^n$ , say  $x^* = \sum_{i=1}^n \mu_i x_i^*$ . Hence,

$$\begin{aligned} d(\tilde{x}, K) &= \langle \tilde{x}, x^* \rangle = \sum_{i=1}^n \mu_i \langle \tilde{x}, x_i^* \rangle \\ &= \sum_{i=1}^n \mu_i \alpha_i \\ &\leq M \left\| \sum_{i=1}^n \mu_i x_i^* \right\| = M \end{aligned} \quad (2.92)$$

Thus, given  $\epsilon > 0$ , we find an  $z_\epsilon \in K$  such that  $\|\tilde{x} - z_\epsilon\| < M + \epsilon$  and let  $x_\epsilon = \tilde{x} - z_\epsilon$ . □

**Corollary 2.2.2.** *Let  $X$  be a seminormed space,  $x^{**} \in X^{**}$ ,  $\{x_i^*\}_{i=1}^n \subset X^*$ , and  $\epsilon > 0$ . Then there exists the following.*

1. An  $x_1 \in X$  such that  $\|x_1\| \leq \|x^{**}\| + \epsilon$  and for  $1 \leq i \leq n$ ,  $\langle x_1, x_i^* \rangle = \langle x_i^*, x^{**} \rangle$ .
2. An  $x_2 \in X$  such that  $\|x_2\| \leq \|x^{**}\|$  and for  $1 \leq i \leq n$ ,  $|\langle x_1, x_i^* \rangle - \langle x_i^*, x^{**} \rangle| < \epsilon$ .

*Proof.* For  $1 \leq i \leq n$ , let  $\alpha_i = \langle x_i^*, x^{**} \rangle$ , and let  $\{\beta_i\}_{i=1}^n \subset \mathbb{C}$ . Then

$$\left| \sum_{i=1}^n \beta_i \alpha_i \right| = \left| \left\langle \sum_{i=1}^n \beta_i x_i^*, x^{**} \right\rangle \right| \leq \|x^{**}\| \left\| \sum_{i=1}^n \beta_i x_i^* \right\| \quad (2.93)$$

An application of 2.2.1 completes the proof. □

### 2.2.2 Goldstine

**Theorem 2.2.3** (Goldstine). *Let  $X$  be a seminormed space,  $c : X \rightarrow X^{**}$  denote the canonical embedding,  $B$  denote the closed unit ball of  $X$ , and  $B_1$  denote the closed unit ball of  $X^{**}$ . Then  $c(B)$  is weak\* dense in  $B_1$ .*

*Proof.* Note that the weak\* topology on  $X^{**}$  has as a basis sets of the form

$$U(x^{**}, \epsilon, \{x_i^*\}_{i=1}^n) := \{y^{**} \in X^{**} : (\forall 1 \leq i \leq n) (|\langle x_i^*, x^{**} - y^{**} \rangle| < \epsilon)\} \quad (2.94)$$

where we range over all  $x^{**} \in X^{**}$ ,  $\epsilon > 0$ , and finite subsets  $\{x_i^*\}_{i=1}^n$  of  $X^*$ . Let  $x^{**} \in B_1$ ,  $\epsilon > 0$ , and  $\{x_i^*\}_{i=1}^n \subset X^*$ . Let  $\epsilon > 0$ . Then by 2.2.2, there exists an  $x \in B$  such that for  $1 \leq i \leq n$ ,  $|\langle x_i^*, x^{**} - c(x) \rangle| = |\langle x_i^*, x^{**} \rangle - \langle x, x_i^* \rangle| < \epsilon$ , from which the desired result follows.  $\square$

### 2.2.3 Banach Alaoglu

The following well known result concerning the weak\* compactness of the unit ball of a Banach space was first proven in the separable case by Banach, and then generalized in 1940 by Alaoglu [1] to Banach spaces. Generalizations of this result in a general TVS satisfying sufficient conditions have also been shown but the form presented here comes from [2], who drops the assumption of completeness for one direction of the implication.

**Theorem 2.2.4** (Banach-Alaoglu-Morales). *Let  $X$  be a normed space and define  $B = \{x^* \in X^* : \|x^*\| \leq 1\}$ . Then  $B$  is weak\* compact.*

*Proof.* Let  $\mathbb{F}$  denote  $X$ 's field, and for  $x \in X$ , define  $D_x = \{y \in \mathbb{F} : |y| \leq \|x\|\}$ . Then each  $D_x$  is Hausdorff and compact so by Tychonoff's theorem,  $D := \prod_{x \in X} D_x$  is compact and Hausdorff when endowed with the product topology. If  $T \in D$ , then  $T : X \rightarrow \mathbb{F}$  and  $|Tx| \leq \|x\|$  for each  $x \in X$ , so  $D \cap X^* \subset B$ . It is also clear that  $B \subset D$ , so  $D \cap X^* = B$ . Let  $\{\gamma_\alpha\}_{\alpha \in A}$  be a net in  $B$  converging to  $\gamma \in D$  in  $D$ 's product topology. Then, letting  $\pi_x$  denote the  $x^{th}$  projection, for each  $x \in X$ ,

$$\gamma_\alpha(x) = \pi_x(\gamma_\alpha) \rightarrow \pi_x(\gamma) = \gamma(x) \quad (2.95)$$

If  $\alpha \in \mathbb{F}$  and  $x, y \in X$ , then

$$\langle \alpha x + y, \gamma_\alpha \rangle \rightarrow \langle \alpha x + y, \gamma \rangle \quad (2.96)$$

and also

$$\langle \alpha x + y, \gamma_\alpha \rangle = \alpha \langle x, \gamma_\alpha \rangle + \langle y, \gamma_\alpha \rangle \rightarrow \alpha \langle x, \gamma \rangle + \langle y, \gamma \rangle \quad (2.97)$$

which implies  $\gamma$  is linear since  $D$  is Hausdorff, and hence  $\gamma \in B$ . Thus  $B$  is closed in  $D$ . What remains to be shown is that the weak\* topology on  $B$  is the subspace topology on  $B$  induced by  $D$ 's topology, since a Closed subset of a compact Hausdorff space is compact. For notation, denote with  $\mathcal{T}_D$  the subspace topology on  $B$  induced by  $D$ 's topology, and denote with  $\mathcal{T}_w$  the subspace topology on  $B$  induced by the weak\* topology on  $X^*$ . To see that  $\mathcal{T}_w \subset \mathcal{T}_D$ , let  $\{\gamma_\alpha\}_{\alpha \in A} \subset B$  such that  $\gamma_\alpha \xrightarrow{\mathcal{T}_D} \gamma$ . For each  $x \in X$ , letting  $c$  be the canonical embedding,

$$\langle \gamma_\alpha, c(x) \rangle = \langle x, \gamma_\alpha \rangle = \pi_x(\gamma_\alpha) \rightarrow \pi_x(\gamma) = \langle x, \gamma \rangle = \langle \gamma, c(x) \rangle \quad (2.98)$$

Hence  $\gamma_\alpha \xrightarrow{\mathcal{T}_w} \gamma$ , so  $\mathcal{T}_w \subset \mathcal{T}_D$ . To see that  $\mathcal{T}_D \subset \mathcal{T}_w$ , fix  $x \in X$  and let  $\{\gamma_\alpha\}_{\alpha \in A} \subset B$  such that  $\gamma_\alpha \xrightarrow{\mathcal{T}_w} \gamma$ . Then  $\pi_x(\gamma_\alpha) = \langle x, \gamma_\alpha \rangle \rightarrow \gamma(x) = \pi_x(\gamma)$ , so by definition of the product topology  $\gamma_\alpha \xrightarrow{\mathcal{T}_D} \gamma$ , implying  $\mathcal{T}_D \subset \mathcal{T}_w$ . Hence  $B$  is *weak\** compact.  $\square$

**Corollary 2.2.5** (Banach Alaoglu Seminorm). *Let  $X$  be a seminormed space and define  $B = \{x^* \in X^* : \|x^*\| \leq 1\}$ . Then  $B$  is *weak\** compact.*

*Proof.* This is a consequence of the fact that the *weak\** topology on  $X^*$  is identical to the *weak\** topology on the dual space of  $X/\|\cdot\|^{-1}\{0\}$ .  $\square$

This gives us the useable result

**Corollary 2.2.6** (Banach-Alaoglu-Morales). *Let  $X$  be a seminormed space and  $C \subset X^*$*

1. *If  $X$  is complete and  $C$  *weak\** compact, then  $C$  is *weak\** closed and bounded.*
2. *If  $C$  is *weak\** closed and bounded, then  $C$  is *weak\** compact.*

*Proof.* (1) Since  $C$  is *weak\** compact, it is *weak\** closed since the *weak\** topology is Hausdorff. Since  $c(x) : (X, \mathcal{T}_w) \rightarrow \mathbb{C}$  is continuous for each  $x \in X$ , for each  $x \in X$ ,  $c(x)(C)$  is compact and therefore bounded. Hence, for every  $x \in X$ ,  $\{|\langle x, c \rangle| : c \in C\}$  is bounded, so by the Banach Steinhaus,  $C$  is bounded.  $\square$

*Proof.* (2) Since  $C$  is bounded, it is contained in some closed ball  $B$  which we know to be *weak\** compact by 2.2.4. Since the *weak\** topology on  $B$  is compact and Hausdorff and  $C$  is closed in this topology, it is compact in this topology. Since the subspace topology on  $C$  induced by the *weak\** topology on  $X^*$  equals this topology, we are done.  $\square$

## 2.2.4 Eberlein-Smulian

The purpose of this section is to provide a characterization of weakly compact subsets of a complete seminormed space  $X$ , which will serve to increase the applicability of the results regarding weakly compactly generated spaces covered later in this document. The first main result of this section, 2.2.9, serves to show that even though weak topologies of Banach Spaces are not in general metrizable, an equivalence between weak compactness and sequential compactness exists. From this result (1  $\implies$  2) was first presented in the case of normed spaces in [3], and then (2  $\implies$  1) was proven in the case of normed spaces in [4]. Several different proofs have been given in the years since, and the one present here is based on that present in [5], which is also followed in [6]. We begin with a few lemmas.

**Lemma 2.2.7** (Metrizable Weak). *If  $X$  is a seminormed space and  $X^*$  contains a countable set that separates points mod  $K := \|\cdot\|^{-1}\{0\}$ , then subspace topology induced by the weak topology on any weakly compact subset  $A$  of  $X$  is pseudometrizable.*

*Proof.* As a consequence of 2.1.34 and 2.1.68, it is sufficient to let  $X$  be a normed space and  $\{x_i^*\}_{i \in \mathbb{N}}$  separate points in  $X$ . Let  $M = 2 \sup_{x \in A} \|x\|$ , and define  $d$  to be the metric on  $A$  defined by, for  $x, y \in A$ ,

$$d(x, y) = \sum_{k \in \mathbb{N}} \frac{|\langle x - y, x_k^* \rangle|}{\|x_k^*\| 2^k} \quad (2.99)$$

Let  $x \in A$ ,  $\epsilon > 0$  be arbitrary, and define

$$n = \left\lceil 2 + \log_2 \left( \frac{M}{\epsilon} \right) \right\rceil \quad U = A \cap \bigcap_{k=1}^n \left\{ y \in X : |\langle x - y, x_k^* \rangle| < \frac{\|x_k^*\| 2^{k-1} \epsilon}{n} \right\} \quad (2.100)$$

The  $U$  is open in the subspace topology on  $A$  induced by  $X$ 's weak topology. Furthermore, if  $y \in U$ , then

$$\begin{aligned} d(x, y) &= \sum_{k \in \mathbb{N}} \frac{|\langle x - y, x_k^* \rangle|}{\|x_k^*\| 2^k} \\ &\leq \sum_{k=1}^n \frac{|\langle x - y, x_k^* \rangle|}{\|x_k^*\| 2^k} + \sum_{k=n+1}^{\infty} \frac{2M}{2^k} \\ &< \sum_{k=1}^n \frac{\epsilon}{2^n} + \frac{M}{2^{n-1}} < \epsilon \end{aligned} \quad (2.101)$$

So that  $U \subset B_d(x; \epsilon)$ . This implies  $Id : (A, \mathcal{T}_w) \rightarrow (A, \mathcal{T}_d)$  is continuous. Since a continuous injection from a compact space into a Hausdorff space is a homeomorphism, the subspace topology on  $A$  induced by the weak topology equals the topology on  $A$  induced by  $d$ , and so  $A$ 's weak topology is metrizable.  $\square$

**Lemma 2.2.8.** *Let  $X$  be a seminormed space and  $Y \subset X^{**}$  be a finite dimensional vector subspace. Then there exists a finite set  $Z \subset \partial B_{X^*}(0; 1)$  such that for each  $y^{**} \in Y$ ,*

$$\|y^{**}\| \leq 2 \max_{z^* \in Z} |\langle z^*, y^{**} \rangle| \quad (2.102)$$

*Proof.* Let  $S = \partial B_{X^{**}}(0; 1) \cap Y$ . Then, since  $Y$  is finite dimensional,  $S$  is compact, and therefore permits a  $\frac{1}{4}$ -net  $\{s_i\}_{i=1}^n$ . Now let  $\{z_k^*\}_{k=1}^n \subset \partial B_{X^*}(0; 1)$  such that for each  $k$ ,  $\langle z_k^*, s_i \rangle > \frac{3}{4}$ . Let  $s \in S$  then there is a  $k$  such that  $\|s - s_k\| < \frac{1}{4}$ . for this  $k$ , we have

$$\langle z_k^*, s \rangle = \langle z_k^*, s_k \rangle + \langle z_k^*, s - s_k \rangle \geq \frac{3}{4} - \frac{1}{4} = \frac{1}{2} \quad (2.103)$$

$\square$

**Theorem 2.2.9** (Eberlein-Smulian). *Let  $X$  be a seminormed space and  $A \subset X$ . Then the following are equivalent.*

1.  $A$  is weakly compact.
2.  $A$  is weakly sequentially compact.

*Proof.* (1  $\implies$  2) Let  $A \subset X$  be weakly compact, and let  $\{x_i\}_{i \in \mathbb{N}} \subset A$ . Define  $S = \overline{\text{span}\{x_i : i \in \mathbb{N}\}}$ . Since  $S$  is closed and convex, it is weakly closed, and so  $A \cap S$  is weakly compact as well. By construction,  $S$  is separable, and so contains a countable dense set  $\{y_i\}_{i \in \mathbb{N}}$ . By Hahn-Banach, for each  $i \in \mathbb{N}$ , there exists  $y_i^* \in S^*$  such that  $\langle y_i, y_i^* \rangle = 1$ , and continuity of each  $y_i^*$  implies  $\{y_i^*\}_{i \in \mathbb{N}}$  separates points in  $S \text{ mod } \|\cdot\|^{-1}\{0\}$ . Hence we can apply 2.2.7 to claim that the subspace topology on  $A \cap S$  induced by  $S'$ 's weak topology is



metrizable, and therefore  $\{x_i\}_{i \in \mathbb{N}}$  has a sub-sequence  $\{x_{n_i}\}_{i \in \mathbb{N}}$  which is weakly S-convergent, and therefore weakly X-convergent since subspace topologies are no less fine than the topologies that induce them. Since  $A \subset X$  is weakly closed, this sequence converges within A, and so A is weakly sequentially compact.  $\square$

*Proof.* (2  $\implies$  1). Let  $A \subset X$  be weakly sequentially compact, let  $c$  denote the canonical embedding of  $X$  into  $X^{**}$ , and let  $x^{**}$  in the *weak\** closure of  $c(A)$ . Let  $x_1^1 \in X^*$  have norm 1. By assumption, there exists  $a_1^{**} \in c(A)$  such that  $|\langle x_1^1, x^{**} - a_1^{**} \rangle| < 1$ . By 2.2.8, there exists  $\{x_1^2, \dots, x_{n_2}^2\} \subset \partial B_{X^*}(0; 1)$  such that for each  $y^{**} \in \text{span}\{x^{**}, x^{**} - a_1^{**}\}$ ,

$$\|y^{**}\| \leq 2 \max_{1 \leq k \leq n_2} |\langle x_k^2, y^{**} \rangle| \quad (2.104)$$

Also, since  $x^{**}$  is in the *weak\** closure of  $c(A)$ , there exists  $a_2^{**} \in c(A) \cap U_2$  where

$$U_2 = \{y^{**} \in X^{**} : (\forall 1 \leq j \leq 2)(\forall 1 \leq k \leq n_j)(|\langle x_k^j, x^{**} - y^{**} \rangle| < \frac{1}{2})\} \quad (2.105)$$

Continuing inductively, we construct a sequence  $\{a_n^{**}\}_{n \in \mathbb{N}} \subset c(A)$  such that for each  $j \in \mathbb{N}$ ,  $\{x_k^j\}_{k=1}^{n_j} \subset \partial B_{X^*}(0; 1)$  such that for every  $y^{**} \in \text{span}\{x^{**}, x^{**} - a_1^{**}, \dots, x^{**} - a_{j-1}^{**}\}$ , we have

$$\|y^{**}\| \leq 2 \max_{1 \leq k \leq n_j} |\langle x_k^j, x^{**} - y^{**} \rangle| \quad (2.106)$$

and  $a_j^{**} \in c(A) \cap U_j$  where  $U_j$  is the  $\{x_k^m\}_{1 \leq m \leq j, 1 \leq k \leq n_m}$  *weak\** neighborhood about  $x^{**}$  of radius  $\frac{1}{j}$ . For each  $k \in \mathbb{N}$ , let  $a_k = c^{-1}(c(a_k))$ . Since A is sequentially weakly compact,  $\{a_k\}_{k \in \mathbb{N}}$  has a weak cluster point  $x \in A$ . Also,  $x \in \overline{\text{span}\{a_i\}_{i \in \mathbb{N}}}$  because this is a weakly closed set, implying  $c(x) \in \overline{\text{span}\{a_i^{**}\}_{i \in \mathbb{N}}}$ , which then implies  $c(x) \in \overline{\text{span}\{x^{**}, x^{**} - a_1^{**}, x^{**} - a_2^{**}, \dots\}}$ . By continuity of the norm and each element of  $\{x_i^k\}_{k \in \mathbb{N}, 1 \leq i \leq n_k}$ , we conclude that for each element  $y^{**}$  of  $\overline{\text{span}\{x^{**}, x^{**} - a_1^{**}, x^{**} - a_2^{**}, \dots\}}$ ,

$$\|y^{**}\| \leq 2 \sup_{k \in \mathbb{N}, 1 \leq i \leq n_k} |\langle x_i^k, y^{**} \rangle| \quad (2.107)$$

This is useful, because for each  $k \in \mathbb{N}$ ,  $1 \leq i \leq n_k$ , we have, for large enough j,

$$\begin{aligned} |\langle x_i^k, x^{**} - c(x) \rangle| &\leq |\langle x_i^k, x^{**} - a_j^{**} \rangle| + |\langle a_j^{**} - c(x), x_i^k \rangle| \\ &\leq \frac{1}{j} + |\langle x_i^k, a_j - x \rangle| \end{aligned} \quad (2.108)$$

which can be made arbitrarily small, and so  $|\langle x_i^k, x^{**} - c(x) \rangle| = 0$ , implying that

$$\|x^{**} - c(x)\| \leq 2 \sup_{k \in \mathbb{N}, 1 \leq i \leq n_k} |\langle x_i^k, x^{**} - x \rangle| = 0 \quad (2.109)$$

So  $x^{**} = c(x)$ , and therefore  $c(A)$  is *weak\** closed. Since A is weakly-sequentially compact,  $c(A)$  is *weak\** sequentially compact and therefore bounded by Banach Steinhaus. By 2.2.4, bounded *weak\** closed sets are compact, and so  $c(A)$  is *weak\** compact. Since the weak topology on  $A/\|\cdot\|^{-1}\{0\}$  is the same as the *weak\** topology on  $c(A)$ ,  $A/\|\cdot\|^{-1}\{0\}$  is weakly compact. To see that A is weakly compact, apply ??  $\square$

### 2.2.5 Bishop-Phelps

In this subsection, I develop a result due to [7] which will prove useful throughout this document. I begin by presenting the concept of a convex cone and a trio of lemmas which are commonly utilized in the proof of this result.

**Definition 2.2.10** (Convex Cone). Let  $X$  be a seminormed space over  $\mathbb{R}$ . If  $K \subset X$  is convex and closed under positive scalar multiples, then we call it a **convex cone**. If  $J$  is a convex cone in  $X$ ,  $C \subset X$ ,  $x_0 \in C$ , and  $(J + x_0) \cap C = \{x_0\}$ , then we say that  $J$  **supports**  $C$  at  $x_0$ . If  $x^* \in \partial B_{X^*}(0; 1)$  and  $\alpha > 0$  then we define

$$K(x^*, \alpha) := \{x \in X : \|x\| \leq \alpha \langle x, x^* \rangle\} \quad (2.110)$$

**Remark 2.2.11.** Let  $X$  be a seminormed space,  $x^* \in \partial B_{X^*}(0; 1)$ , and  $\alpha > 0$ . The following are true.

1.  $K(x^*, \alpha)$  is a closed convex cone.
2. If  $\alpha > 1$ ,  $\text{Int}(K(x^*, \alpha)) \neq \emptyset$ .

*Proof.* (1) If  $\{x_n\} \subset K(x^*, \alpha)$  converges, say  $x_n \rightarrow x$ , then continuity of  $x^*$  implies  $\langle x_n, x^* \rangle \rightarrow \langle x, x^* \rangle$ . Hence, given  $\epsilon > 0$ , there exists  $N > 0$  such that for  $n > N$  we have  $\max(\|x\| - \|x_n\|, |\langle x - x_n, x^* \rangle|) < \epsilon$ , so that for all  $n > N$ ,

$$\|x\| \leq \|x_n\| + \epsilon < \alpha \langle x_n, x^* \rangle + \epsilon < \alpha \langle x, x^* \rangle + (\alpha + 1)\epsilon \quad (2.111)$$

So  $x \in K(x^*, \alpha)$  closedness is verified. It is obvious that  $K(x^*, \alpha)$  is closed under positive scalar multiples, and for convexity, if  $x, y \in K(x^*, \alpha)$  and  $t \in [0, 1]$ , then

$$\|tx + (1 - t)y\| \leq t\|x\| + (1 - t)\|y\| \leq t\alpha \langle x, x^* \rangle + (1 - t)\alpha \langle y, x^* \rangle = \alpha \langle tx + (1 - t)y, x^* \rangle \quad (2.112)$$

□

*Proof.* (2) By definition of the norm on  $X^*$ , there is an  $x \in \overline{B_X(0; 1)}$  such that  $2 / (\alpha (1 + \frac{1}{\alpha})) < \langle x, x^* \rangle$ , implying by linearity that  $1/\alpha < \langle \frac{1 + (1/\alpha)}{2} x, x^* \rangle$ . By continuity of  $x^*$  we find a neighborhood  $U$  of  $(1 + \frac{1}{\alpha})/2$  contained in  $B_X(0; 1)$  such that for each  $y \in U$ ,  $1/\alpha < \langle y, x^* \rangle$ . This implies  $\|y\| \leq 1 < \alpha \langle y, x^* \rangle$ , so  $U \subset K(x^*, \alpha)$ . □

**Lemma 2.2.12** (Bishop-Phelps Lemma). Let  $X$  be a complete seminormed space,  $x^*, y^* \in \partial B_{X^*}(0; 1)$ ,  $C \subset X$  closed and convex,  $1 > \epsilon > 0$ , and  $k > 1 + \frac{2}{\epsilon}$ . The following are true.

1. If  $x^*$  is bounded on  $C$ , then for each  $z \in C$ , there is an  $x_0 \in X$  such that  $K(x^*, \epsilon)$  supports  $C$  at  $x_0$  and  $x_0 \in K(x^*, \epsilon) + z$ .
2. If  $|\langle x, y^* \rangle| \leq \frac{\epsilon}{2}$  for each  $x \in \text{Kern}(x^*) \cap \overline{B_X(0; 1)}$ , then

$$\min(\|x^* + y^*\|, \|x^* - y^*\|) \leq \epsilon \quad (2.113)$$

3. If  $y^*$  is nonnegative on  $K(x^*, k)$ , then  $\|x^* - y^*\| \leq \epsilon$ .

*Proof.* (1) Let  $x^*$  be bounded on  $C$  and define, for  $x, y \in X$ ,  $y \lesssim x$  if and only if  $x - y \in K(x^*, \epsilon)$ . Fix  $z \in C$ . Define  $Z = C \cap (K(x^*, \epsilon) + z)$ . Since  $C$  and  $K(x^*, \epsilon)$  are closed, so is  $Z$ . Let  $\mathcal{C} = \{x_\alpha\}_{\alpha \in A}$  be a chain in where  $(A, \leq)$  is a totally ordered set and  $x_\alpha \lesssim x_\beta \iff \alpha \leq \beta$ . If  $x_\alpha, x_\beta \in \mathcal{C}$ , where  $x_\beta \lesssim x_\alpha$ , then  $x_\alpha - x_\beta \in K(x^*, \epsilon)$ , so  $0 \leq \|x_\alpha - x_\beta\| \leq \epsilon \langle x_\alpha - x_\beta, x^* \rangle$ , implying  $\langle x_\beta, x^* \rangle \leq \langle x_\alpha, x^* \rangle$ . Thus we conclude  $\{\langle x_\alpha, x^* \rangle\}_{\alpha \in A}$  is a monotone bounded net in  $\mathbb{R}$  that is therefore Cauchy, which by the following inequality

$$\|x_\beta - x_\alpha\| \leq \epsilon \langle x_\alpha - x_\beta, x^* \rangle = \epsilon (\langle x_\alpha, x^* \rangle - \langle x_\beta, x^* \rangle) \rightarrow 0 \quad (2.114)$$

implies  $\mathcal{C}$  is a Cauchy net and therefore converges, say  $x_\alpha \rightarrow y_0 \in Z$ . Continuity of the norm and  $x^*$  imply together that  $y_0$  is an upper bound for  $\mathcal{C}$ . Since  $\mathcal{C}$  was an arbitrary chain in  $Z$ ,  $Z$  has a maximal element  $x_0$ . By definition,  $x_0 \in Z := K(x^*, \epsilon) + z$ . Since  $x_0 \in Z \subset C$ ,  $x_0 \in C$ . Further, since  $0 \in K(x^*, \epsilon)$ ,  $x_0 \in K(x^*, \epsilon) \cap C$ . Let  $y \in (K(x^*, \epsilon) + x_0) \cap C$ . Then  $y - x_0 \in K(x^*, \epsilon)$  so that  $z \lesssim x_0 \lesssim y$ , meaning  $y \in Z$  and therefore  $y = x_0$  since  $x_0$  is maximal. Hence  $(K(x^*, \epsilon) + x_0) \cap C = \{x_0\}$ , so we are done.  $\square$

*Proof.* (2) By assumption,  $\|y^*|_{\text{Kern}(x^*)}\| \leq \frac{\epsilon}{2}$ , so by the Hahn-Banach theorem, we can find a  $\tilde{y}^* \in X^*$  extending  $y^*|_{\text{Kern}(x^*)}$  such that  $\|\tilde{y}^*\| \leq \frac{\epsilon}{2}$ . Since  $y^* - \tilde{y}^* \neq 0$ ,  $\text{codim}(\text{Kern}(x^*)) = 1$ , and  $\text{Kern}(x^*) \subset \text{Kern}(y^* - \tilde{y}^*)$ , we conclude  $\text{Kern}(y^* - \tilde{y}^*) = \text{Kern}(x^*)$ . Hence, for some  $\alpha \in \mathbb{R}$ ,  $y^* - \tilde{y}^* = \alpha x^*$ . For this alpha, we have

$$|1 - |\alpha|| = \|y^* - \tilde{y}^*\| \leq \|\tilde{y}^*\| \leq \frac{\epsilon}{2} \quad (2.115)$$

If  $\alpha \geq 0$ ,

$$\|x^* - y^*\| = \|x^* - (\alpha x^* + \tilde{y}^*)\| = \|(1 - \alpha)x^* - \tilde{y}^*\| \leq |1 - \alpha| + \|\tilde{y}^*\| \leq \epsilon \quad (2.116)$$

If  $\alpha \leq 0$ , then

$$\|x^* + y^*\| = \|x^* + (\alpha x^* + \tilde{y}^*)\| = \|(1 + \alpha)x^* + \tilde{y}^*\| \leq |1 + \alpha| + \|\tilde{y}^*\| \leq \epsilon \quad (2.117)$$

$\square$

*Proof.* (3) Since  $\|x^*\| = 1$ , there exists  $x \in \partial B_X(0; 1)$  such that  $\langle x, x^* \rangle > \frac{1}{k} (1 + \frac{2}{\epsilon})$ . If  $y \in \text{Kern}(x^*) \cap \overline{B_X(0; 1)}$ , then

$$\left\|x \pm \frac{2}{\epsilon}y\right\| \leq 1 + \frac{2}{\epsilon} < k \langle x, x^* \rangle = k \left\langle x \pm \frac{2}{\epsilon}y, x^* \right\rangle \quad (2.118)$$

so  $x \pm \frac{2}{\epsilon}y \in K(x^*, k)$ , so by assumption  $\langle x \pm \frac{2}{\epsilon}y, y^* \rangle \geq 0$ . Since this occurs for both positive and negative,  $|\langle y, y^* \rangle| = \frac{\epsilon}{2} \left| \left\langle \frac{2}{\epsilon}y, y^* \right\rangle \right| \leq \frac{\epsilon}{2} \langle y^*, x \rangle \leq \frac{\epsilon}{2} \|x\| = \frac{\epsilon}{2}$ . Hence by part 2, either  $\|x^* - y^*\| \leq \epsilon$ , or  $\|x^* + y^*\| \leq \epsilon$ . Since  $\|x^*\| = 1$ , there exists  $x \in \partial B_X(0; 1)$  such that  $\frac{\|x\|}{k} \leq \max(\epsilon, \frac{1}{k}) < \langle x, x^* \rangle$ , so that  $x \in K(x^*, k)$ , implying  $\langle x, y^* \rangle \geq 0$ , and therefore  $\epsilon < \langle x_0, x^* + y^* \rangle \leq \|x^* + y^*\|$ . Hence we conclude  $\|x^* - y^*\| \leq \epsilon$ .  $\square$

**Theorem 2.2.13** (Bishop-Phelps Theorem). *Let  $X$  be a complete seminormed space,  $C \subset X$  be closed, bounded, and convex, and define  $M := \{f \in X^* | (\exists x_0 \in C)(\langle x_0, f \rangle = \sup_{x \in C} \langle x, f \rangle)\}$ .*

*Then  $\overline{M} = X^*$*

*Proof.* Since  $M$  is a vector subspace independent of translations of  $C$ , we assume without loss of generality that  $0 \in C$  and that it is sufficient to show that  $M$  is dense in  $\partial B_{X^*}(0; 1)$ . Let  $x^* \in \partial B_{X^*}(0; 1)$ . Let  $\epsilon \in (0, 1)$  and let  $1 + \frac{2}{\epsilon} < k$ . by 2.2.11,  $K(x^*, k)$  is a closed convex cone with nonempty interior. Applying 2.2.12, part one, there is  $x_0 \in C$  with  $x_0 \in K(x^*, k)$  and  $(K(x^*, k) + x_0) \cap C = \{x_0\}$ . By Hahn Banach, there exists  $y^* \in \partial B_{X^*}(0; 1)$  satisfying

$$\sup_{x \in C} \langle x, y^* \rangle = \langle x_0, y^* \rangle = \inf_{x \in K(x^*, k) + x_0} \langle x, y^* \rangle = \inf_{\tilde{x} \in K(x^*, k)} \langle \tilde{x}, y^* \rangle + \langle x_0, y^* \rangle \quad (2.119)$$

Hence  $y^*$  is positive on  $K(x^*, k)$ , so by 2.2.12 part 3,  $\|x^* - y^*\| < \epsilon$ , so we are done since  $y^* \in M$  and  $x^*$  was arbitrary.  $\square$

## 2.3 Reflexivity

Recall that a seminormed space  $X$  is said to be **reflexive** if  $c(X) = X^{**}$ . Since  $X^{**}$  is always complete and  $c$  an isometry, any reflexive space is always complete. Due to the Banach-Alaoglu theorem, in reflexive space  $X$ , the closed unit ball of  $X$  is weakly compact. For this reason and others, reflexivity is a condition of interest to many mathematicians. We begin with a basic result.

**Lemma 2.3.1** (Reflexive Separable). *Let  $X$  be a complete seminormed space. Then the following are equivalent.*

1.  $X$  is reflexive.
2. The closed unit ball of  $X$  is weakly compact.
3. Each closed separable subspace of  $X$  is reflexive.
4. All collections of closed, bounded, convex sets in  $X$  have the finite intersection property
5. The closed unit ball of  $X$  is weakly sequentially compact

*Proof.* (1  $\implies$  2) Let  $X$  be reflexive. By 2.2.9 it is sufficient to show that any sequence  $\{x_i\}_{i \in \mathbb{N}} \subset \overline{B_X(0; 1)}$  has a weak cluster point  $x \in \overline{B_X(0; 1)}$ . Since  $\overline{B_{X^{**}}(0; 1)}$  is  $weak^*$  compact,  $\{c(x_i)\}_{i \in \mathbb{N}}$  has a subsequence  $\{c(x_{n_i})\}_{i \in \mathbb{N}}$  such that  $c(x_{n_i}) \xrightarrow{w^*} \tilde{x} \in \overline{B_{X^{**}}(0; 1)}$ . Since  $X$  is reflexive, for some  $x \in \overline{B_X(0; 1)}$ ,  $c(x) = \tilde{x}$ . Let  $x^* \in X^*$ . Then,

$$|\langle x_{n_i} - x, x^* \rangle| = |\langle x^*, c(x_{n_i}) - \tilde{x} \rangle| \rightarrow 0 \quad (2.120)$$

as  $i \rightarrow \infty$ , and so  $x_{n_i} \xrightarrow{w} x$ , completing the proof.  $\square$

*Proof.* (2  $\implies$  3) Suppose the closed unit ball of  $X$  is weakly compact, and let  $x^{**} \in \overline{B_{X^{**}}(0; 1)}$ . By 2.2.3, there is a sequence  $\{x_n\}_{n \in \mathbb{N}} \subset \overline{B_X(0; 1)}$  such that  $c(x_n) \xrightarrow{w^*} x^{**}$ . By assumption, there is a subsequence  $\{x_{n_k}\}_{k \in \mathbb{N}}$  such that  $x_{n_k} \xrightarrow{w} x \in \overline{B_X(0; 1)}$ . This implies  $c(x_{n_k}) \xrightarrow{w^*} c(x)$ , and so since the  $weak^*$  topology is Hausdorff,  $x^{**} = c(x) \in c(\overline{B_X(0; 1)})$ .  $\square$

*Proof.* (2  $\implies$  3). Let  $X$  be reflexive and  $S \subset X$  be a closed separable vector subspace. Let  $\{x_i\}_{i \in \mathbb{N}} \subset \overline{B_X(0;1)}$ . By assumption this sequence has an  $X$ -weakly convergent subsequence,  $x_{n_k} \rightarrow x \in X$ . Since  $S$  is weakly closed,  $x \in S$ , and since the weak topology on  $X$  is finer than that on  $S$ ,  $x_{n_k} \xrightarrow{S-w} x$ . By 2.2.9 and (2  $\implies$  1,  $S$  is reflexive.  $\square$

*Proof.* (3  $\implies$  2) Let  $\{x_n\}_{n \in \mathbb{N}} \subset \overline{B_X(0;1)}$ . Then since  $S := \overline{\text{span}\{x_i\}_{i \in \mathbb{N}}}$  is a closed separable subspace,  $\{x_n\}_{n \in \mathbb{N}}$  has an  $S$ -weakly convergent subsequence,  $x_{n_k} \xrightarrow{S-w} x \in S$ . If  $x^* \in X^*$ , then  $x^*|_S \in S^*$ , so that  $|\langle x - x_{n_k}, x^* \rangle| \rightarrow 0$ , implying  $x_{n_k} \xrightarrow{w} x$ , an application of 2.2.9 finishes the proof.  $\square$

*Proof.* (4  $\iff$  2) Obvious since closed convex sets are weakly closed.  $\square$

*Proof.* (5  $\iff$  2) Apply 2.2.9.  $\square$

### 2.3.1 James

As an easy application of 2.2.4 and 2.2.9, for a reflexive space  $X$ , all  $x^* \in X^*$  attain their norm. The converse of this fact was, for a time, an open question of considerable interest. The converse of this result was, as is traditional in mathematics, proven in a piecemeal manner. The result was first tackled by James in [8] under the added assumption that every space  $Y$  isomorphic to  $X$  has the property that each  $y^* \in Y^*$  attains its norm and that  $X$  permits a Schauder basis. This result was rapidly improved by Klee in [9] who dropped the assumption of a Schauder basis, and then by James again in [10] who proved the result in the case of a separable space  $X$ . The question of the converse in a Banach space was finally answered to the affirmative in [11], building on the arguments in [10]. This paper included generalizations all the way to quasi-complete locally convex TVS's.

**Definition 2.3.2.** If  $X$  is a topological vector space and  $\{x_i^*\}_{i \in \mathbb{N}} \subset X^*$ , then  $\text{CoLim}\{x_i^*\}_{i \in \mathbb{N}}$  is the set of all  $x^* \in X^*$  such that for every  $x \in X$ ,

$$\liminf_{i \rightarrow \infty} \langle x, x_i^* \rangle \leq \langle x, x^* \rangle \leq \limsup_{i \rightarrow \infty} \langle x, x_i^* \rangle \quad (2.121)$$

**Remark 2.3.3** (CoLim Nonempty). Let  $X$  be a complete seminormed space and let  $\{x_i^*\}_{i \in \mathbb{N}} \subset X^*$  be bounded. Then  $\text{CoLim}\{x_i^*\}_{i \in \mathbb{N}} \neq \emptyset$

*Proof.* Since  $\{x_i^*\}_{i \in \mathbb{N}}$  is bounded, it has a subsequence with a  $\text{weak}^*$  limit  $x^*$  who must live in  $\text{CoLim}\{x_i^*\}_{i \in \mathbb{N}}$ .  $\square$

**Lemma 2.3.4.** Let  $X$  be a complete seminormed space,  $\alpha \in (0,1)$ ,  $\{x_i^*\}_{i \in \mathbb{N}} \subset X^*$ , and  $\{\beta_i\}_{i \in \mathbb{N}} \subset (0,1)$  such that  $\sum_{i \in \mathbb{N}} \beta_i = 1$ . Then if (1) or (3) hold below, there are  $\{y_i^*\}_{i \in \mathbb{N}} \subset X^*$  and  $\gamma \geq \alpha$  such that (2) or (4) hold respectively.

1.  $\{x_i^*\}_{i \in \mathbb{N}} \subset \partial B_{X^*}(0;1)$  such that  $d(0, \overline{\text{co}}\{x_i^*\}_{i \in \mathbb{N}}) \geq \alpha$ .

2.  $\gamma \leq 1$ , and for each  $i \in \mathbb{N}$ ,

$$y_i^* \in \overline{\text{co}}\{x_j^*\}_{j \geq i} \quad \left\| \sum_{j \in \mathbb{N}} \beta_j y_j^* \right\| = \gamma \quad \left\| \sum_{j=1}^i \beta_j y_j^* \right\| < \gamma \left( 1 - \alpha \left( \sum_{j=i+1}^{\infty} \beta_j \right) \right) \quad (2.122)$$

3.  $\{x_i^*\}_{i \in \mathbb{N}} \subset \overline{B_{X^*}(0;1)}$  such that  $d(\overline{\text{co}}\{x_i^*\}_{i \in \mathbb{N}} - \text{CoLim}\{x_i^*\}_{i \in \mathbb{N}}, 0) \geq \alpha$ .

4.  $\gamma \leq 2$ ,  $\{y_i^*\}_{i \in \mathbb{N}} \subset \overline{B_{X^*}(0;1)}$ , and for each  $i \in \mathbb{N}$ ,  $y^* \in \text{CoLim}\{y_i^*\}_{i \in \mathbb{N}}$ ,

$$\left\| \sum_{j \in \mathbb{N}} \beta_j (y_j^* - y^*) \right\| = \gamma \quad \left\| \sum_{j=1}^i \beta_j (y_j^* - y^*) \right\| < \gamma \left( 1 - \alpha \left( \sum_{j=i+1}^{\infty} \beta_j \right) \right) \quad (2.123)$$

*Proof.* (1  $\implies$  2) There exists a positive sequence  $\{\delta_i\}_{i \in \mathbb{N}}$  such that

$$\sum_{i \in \mathbb{N}} \frac{\beta_i \delta_i}{\left( \sum_{j=i+1}^{\infty} \beta_j \right) \left( \sum_{j=i}^{\infty} \beta_j \right)} < 1 - \alpha \quad (2.124)$$

Let  $\gamma_1 \in \mathbb{R}$  and choose  $y_1^* \in \overline{\text{co}}\{x_i^*\}_{i \in \mathbb{N}}$  such that  $\gamma_1 = d(0, \overline{\text{co}}\{x_i^*\}_{i \in \mathbb{N}})$  and  $\|y_1^*\| \leq \gamma_1 (1 + \delta_1)$ . From here, for each  $n \geq 1$ , define  $\gamma_{n+1} \in \mathbb{R}$  and choose  $y_{n+1}^* \in \overline{\text{co}}\{x_i^*\}_{i \geq n+1}$  such that

$$\gamma_{n+1} = \inf \left\{ \left\| \left( \sum_{i=1}^n \beta_i y_i^* \right) + \left( 1 - \sum_{i=1}^n \beta_i \right) y^* \right\| : y^* \in \overline{\text{co}}\{x_i^*\}_{i \geq n+1} \right\} \quad (2.125)$$

and

$$\left\| \sum_{i=1}^n \beta_i y_i^* + \left( 1 - \sum_{i=1}^n \beta_i \right) y_{n+1}^* \right\| < \gamma_{n+1} (1 + \delta_{n+1}) \quad (2.126)$$

It is clear that since the set over which we are taking the infimum never gets larger, so  $\{\gamma_i\}_{i \in \mathbb{N}}$  is a nondecreasing sequence. Further, since  $\{x_i^*\}_{i \in \mathbb{N}} \subset \overline{B_{X^*}(0;1)}$  and  $\sum_{i \in \mathbb{N}} \beta_i = 1$ , we have, for every  $i$ ,

$$\alpha \leq \gamma_i \nearrow \gamma = \left\| \sum_{k \in \mathbb{N}} \beta_k y_k^* \right\| \leq 1 \quad (2.127)$$

So what is left to be shown is that for every  $i \in \mathbb{N}$ ,

$$\left\| \sum_{j=1}^i \beta_j y_j^* \right\| < \gamma \left( 1 - \alpha \left( \sum_{j=i+1}^{\infty} \beta_j \right) \right) \quad (2.128)$$

Let  $i \in \mathbb{N}$ . Then,

$$\begin{aligned}
\left\| \sum_{j=1}^i \beta_j (y_j^* - y^*) \right\| &= \left\| \left( \left( \frac{\sum_{j=i}^{\infty} \beta_j}{\sum_{j=i}^{\infty} \beta_j} \right) \left( \sum_{j=1}^{i-1} \beta_j y_j^* \right) \right) + \left( \left( \frac{\sum_{j=i}^{\infty} \beta_j}{\sum_{j=i}^{\infty} \beta_j} \right) (\beta_i y_i^*) \right) \right\| \\
&= \left\| \left( \left( \frac{\lambda_i + \sum_{j=i+1}^{\infty} \beta_j}{\sum_{j=i}^{\infty} \beta_j} \right) \left( \sum_{j=1}^{i-1} \beta_j y_j^* \right) \right) + \left( \left( \frac{\beta_i \sum_{j=i}^{\infty} \beta_j}{\sum_{j=i}^{\infty} \beta_j} \right) (y_i^*) \right) \right\| \\
&\leq \frac{\beta_i}{\sum_{j=i}^{\infty} \beta_j} \left\| \sum_{j=1}^{i-1} \beta_j y_j^* + \left( \sum_{j=i}^{\infty} \beta_j \right) y_i^* \right\| + \frac{\sum_{j=i+1}^{\infty} \beta_j}{\sum_{j=i}^{\infty} \beta_j} \left\| \sum_{j=1}^{i-1} \beta_j y_j^* \right\| \\
&\leq \frac{\beta_i}{\sum_{j=i}^{\infty} \beta_j} \left\| \sum_{j=1}^{i-1} \beta_j y_j^* + \left( 1 - \sum_{j=1}^{i-1} \beta_j \right) y_i^* \right\| + \frac{\sum_{j=i+1}^{\infty} \beta_j}{\sum_{j=i}^{\infty} \beta_j} \left\| \sum_{j=1}^{i-1} \beta_j y_j^* \right\| \\
&< \frac{\beta_i}{\sum_{j=i}^{\infty} \beta_j} (\gamma_i) (1 + \delta_i) + \frac{\sum_{j=i+1}^{\infty} \beta_j}{\sum_{j=i}^{\infty} \beta_j} \left\| \sum_{j=1}^{i-1} \beta_j y_j^* \right\| \\
&= \left( \sum_{j=i+1}^{\infty} \beta_j \right) \left( \left( \frac{\beta_i \gamma_i (1 + \delta_i)}{\left( \sum_{j=i}^{\infty} \beta_j \right) \left( \sum_{j=i+1}^{\infty} \beta_j \right)} \right) + \left( \frac{1}{\sum_{j=i}^{\infty} \beta_j} \right) \left\| \sum_{j=1}^{i-1} \beta_j y_j^* \right\| \right)
\end{aligned} \tag{2.129}$$

Hence, for any  $i \in \mathbb{N}$ ,

$$\begin{aligned}
\left\| \sum_{j=1}^i \beta_j y_j^* \right\| &< \left( \sum_{j=i+1}^{\infty} \beta_j \right) \left( \left( \frac{\beta_i \gamma_i (1 + \delta_i)}{\left( \sum_{j=i}^{\infty} \beta_j \right) \left( \sum_{j=i+1}^{\infty} \beta_j \right)} \right) + \left( \frac{1}{\sum_{j=i}^{\infty} \beta_j} \right) \left\| \sum_{j=1}^{i-1} \beta_j y_j^* \right\| \right) \\
&< \left( \sum_{j=i+1}^{\infty} \beta_j \right) \sum_{j=1}^i \frac{\beta_j \gamma_j (1 + \delta_j)}{\left( \sum_{k=j}^{\infty} \beta_k \right) \left( \sum_{k=j+1}^{\infty} \beta_k \right)} \\
&\leq \gamma \left( \sum_{j=i+1}^{\infty} \beta_j \right) \sum_{j=1}^i \frac{\beta_j (1 + \delta_j)}{\left( \sum_{k=j}^{\infty} \beta_k \right) \left( \sum_{k=j+1}^{\infty} \beta_k \right)} \\
&\leq \gamma \left( \sum_{j=i+1}^{\infty} \beta_j \right) \left( \left( \sum_{j=1}^i \frac{\beta_j}{\left( \sum_{k=j}^{\infty} \beta_k \right) \left( \sum_{k=j+1}^{\infty} \beta_k \right)} \right) + (1 - \alpha) \right) \\
&= \gamma \left( \sum_{j=i+1}^{\infty} \beta_j \right) \left( \left( \sum_{j=1}^i \left( \frac{1}{\sum_{k=j}^{\infty} \beta_k} - \frac{1}{\sum_{k=j+1}^{\infty} \beta_k} \right) \right) + (1 - \alpha) \right) \\
&= \gamma \left( \sum_{j=i+1}^{\infty} \beta_j \right) \left( \frac{1}{\sum_{j=i+1}^{\infty} \beta_j} - \frac{1}{\sum_{j=1}^{\infty} \beta_j} + 1 - \alpha \right) \\
&= \gamma \left( \sum_{j=i+1}^{\infty} \beta_j \right) \left( \frac{1}{\sum_{j=i+1}^{\infty} \beta_j} - \alpha \right) \\
&= \gamma \left( 1 - \alpha \left( \sum_{j=i+1}^{\infty} \beta_j \right) \right)
\end{aligned} \tag{2.130}$$

completing the proof.  $\square$

*Proof.* (3  $\implies$  4) There exists a positive sequence  $\{\delta_i\}_{i \in \mathbb{N}}$  such that

$$\sum_{i \in \mathbb{N}} \frac{\beta_i \delta_i}{\left( \sum_{j=i+1}^{\infty} \beta_j \right) \left( \sum_{j=i}^{\infty} \beta_j \right)} < 1 - \alpha \tag{2.131}$$

Define  $\{x_i^0\}_{i \in \mathbb{N}} = \{x_i^*\}_{i \in \mathbb{N}}$ ,

$$\gamma_1 = \inf \left\{ \sup_{y^* \in \text{CoLim}\{\phi_i\}_{i \in \mathbb{N}}} \{ \|x^* - y^*\| : x^* \in \overline{\text{co}}\{x_i^*\}_{i \in \mathbb{N}}, \phi_k \in \overline{\text{co}}\{x_i^*\}_{i \geq k}, k \in \mathbb{N} \right\} \tag{2.132}$$

and pick  $y_1^* \in \overline{\text{co}}\{x_i^*\}_{i \in \mathbb{N}}$ ,  $\{\phi_i^1\}_{i \in \mathbb{N}} \subset X^*$  such that  $\phi_k^1 \in \overline{\text{co}}\{x_i^*\}_{i \geq k}$  for every  $k$  and  $w' \in \text{CoLim}\{\phi_i^1\}_{i \in \mathbb{N}}$  such that

$$\gamma_1(1 - \delta_1) < \|y_1^* - w'\| < \gamma_1(1 + \delta_1) \tag{2.133}$$



So that there exists  $\tilde{x} \in \overline{B_X(0;1)}$  such that  $\gamma_1(1 - \delta_1) < \langle \tilde{x}, y_1^* - w' \rangle$ , and since  $w' \in \text{CoLim}\{\phi_i^1\}_{i \in \mathbb{N}}$ , we extract a subsequence  $\{x_i^1\}_{i \in \mathbb{N}}$  of  $\{\phi_i^1\}_{i \in \mathbb{N}}$  so that for any  $w \in \text{CoLim}\{x_i^1\}_{i \in \mathbb{N}}$ , we have

$$\langle \tilde{x}, w \rangle = \lim_{i \rightarrow \infty} \langle \tilde{x}, x_i^1 \rangle = \liminf_{i \rightarrow \infty} \langle \tilde{x}, \phi_i^1 \rangle \leq \langle \tilde{x}, w' \rangle \quad (2.134)$$

And so, for any  $w \in \text{CoLim}\{x_i^1\}_{i \in \mathbb{N}}$ , we have

$$\gamma_1(1 - \delta_1) < \langle \tilde{x}, y_1^* - w \rangle \quad (2.135)$$

Continuing inductively, for  $i \in \mathbb{N}$ , set

$$\gamma_{i+1} = \inf \left\{ \sup \left\{ \left\| \left( \sum_{j=1}^i \beta_j y_j^* \right) + \left( \left( \sum_{j=i+1}^{\infty} \beta_j \right) y^* \right) - w \right\| : w \in \text{CoLim}\{\phi_i\}_{i \in \mathbb{N}} \right\} \right\} \quad (2.136)$$

Where the infimum is taken over all  $y^* \in \overline{\text{co}}\{x_j^i\}_{j \geq i+1}$  and all  $\{\phi_i\}_{i \in \mathbb{N}} \subset X^*$  such that  $\phi_k \in \overline{\text{co}}\{x_j^i\}_{j \geq k}$ . Next, pick  $y_{i+1}^* \in \overline{\text{co}}\{x_j^i\}_{j \geq i+1}$  and  $\{\phi_j^{i+1}\}_{j \in \mathbb{N}} \subset X^*$  such that for every  $k$ ,  $\phi_k^{i+1} \in \overline{\text{co}}\{x_j^i\}_{j \geq k}$  and pick  $w' \in \text{CoLim}\{\phi_j^{i+1}\}_{j \in \mathbb{N}}$  such that

$$\gamma_{i+1}(1 - \delta_{i+1}) < \left\| \sum_{j=1}^i \beta_j y_j^* + \left( \sum_{j=i+1}^{\infty} \beta_j \right) y_{i+1}^* - w' \right\| < \gamma_{i+1}(1 + \delta_{i+1}) \quad (2.137)$$

Next, pick  $\tilde{x} \in \overline{B_X(0;1)}$  satisfying

$$\gamma_{i+1}(1 - \delta_{i+1}) < \left\langle \tilde{x}, \sum_{j=1}^i \beta_j y_j^* + \left( \left( \sum_{j=i+1}^{\infty} \beta_j \right) y_j^* \right) - w' \right\rangle \quad (2.138)$$

and apply the fact that since  $\liminf_{j \rightarrow \infty} \langle \tilde{x}, \phi_j^{i+1} \rangle \leq \langle \tilde{x}, w \rangle$ , we can find a subsequence  $\{x_j^{i+1}\}_{j \in \mathbb{N}}$  of  $\{\phi_j^{i+1}\}_{j \in \mathbb{N}}$  such that for every  $w \in \text{CoLim}\{x_j^{i+1}\}_{j \in \mathbb{N}}$  we have

$$\gamma_{i+1}(1 - \delta_{i+1}) < \left\langle \tilde{x}, \sum_{j=1}^i \beta_j y_j^* + \left( \left( \sum_{j=i+1}^{\infty} \beta_j \right) y_j^* \right) - w \right\rangle \quad (2.139)$$

completing our construction. Clearly,  $\text{CoLim}\{y_j^*\}_{j \in \mathbb{N}} \subset \text{CoLim}\{\phi_j^i\}_{j \in \mathbb{N}}$  for every  $i \in \mathbb{N}$ . Hence, for every  $w \in \text{CoLim}\{y_j^*\}_{j \in \mathbb{N}}$ , for every  $i \in \mathbb{N}$ , we have

$$\gamma_i(1 - \delta_i) < \left\| \sum_{j=1}^{i-1} \beta_j y_j^* + \left( \left( \sum_{j=i}^{\infty} \beta_j \right) y_i^* \right) - w \right\| < \gamma_i(1 + \delta_i) \quad (2.140)$$

Also, since  $\{y_j^*\}_{j \in \mathbb{N}} \subset \overline{\text{co}}\{x_j\}_{j \in \mathbb{N}} \subset \overline{B_{X^*}(0;1)}$ ,  $\text{CoLim}\{y_j^*\}_{j \in \mathbb{N}} \subset \overline{\text{co}}\{y_j^*\}_{j \in \mathbb{N}} \subset \overline{B_{X^*}(0;1)}$ . By definition,  $\gamma_1 \geq \alpha$ , and  $\{\gamma_i\}_{i \in \mathbb{N}}$  is a nondecreasing sequence since it is defined by taking the infimum over a set which never gains new elements as  $i$  increases. Further,  $\|w\| \leq 1$  for  $w \in \text{CoLim}\{y_j^*\}_{j \in \mathbb{N}}$  implies that for every  $n$ ,  $\gamma_n \leq 2$ , so by monotone convergence,  $\gamma_i \nearrow \gamma = \left\| \sum_{j \in \mathbb{N}} \beta_j (y_j - w) \right\| \leq 2$ . As for the final estimate, we have, for  $i \in \mathbb{N}$  and  $y^* \in \text{CoLim}\{y_j^*\}_{j \in \mathbb{N}}$ , we have

Let  $i \in \mathbb{N}$ . Then, Hence, for every  $i \in \mathbb{N}$ , we have

$$\begin{aligned}
\left\| \sum_{j=1}^i \beta_j (y_j^* - y^*) \right\| &< \left( \sum_{j=i+1}^{\infty} \beta_j \right) \\
&\quad * \left( \left( \frac{\beta_i \gamma_i (1 + \delta_i)}{\left( \sum_{j=i}^{\infty} \beta_j \right) \left( \sum_{j=i+1}^{\infty} \beta_j \right)} \right) + \left( \frac{1}{\sum_{j=i}^{\infty} \beta_j} \right) \left\| \sum_{j=1}^{i-1} \beta_j (y_j^* - y^*) \right\| \right) \\
&< \left( \sum_{j=i+1}^{\infty} \beta_j \right) \sum_{j=1}^i \frac{\beta_j \gamma_j (1 + \delta_j)}{\left( \sum_{k=j}^{\infty} \beta_k \right) \left( \sum_{k=j+1}^{\infty} \beta_k \right)} \\
&\leq \gamma \left( \sum_{j=i+1}^{\infty} \beta_j \right) \sum_{j=1}^i \frac{\beta_j (1 + \delta_j)}{\left( \sum_{k=j}^{\infty} \beta_k \right) \left( \sum_{k=j+1}^{\infty} \beta_k \right)} \\
&\leq \gamma \left( \sum_{j=i+1}^{\infty} \beta_j \right) \left( \left( \sum_{j=1}^i \frac{\beta_j}{\left( \sum_{k=j}^{\infty} \beta_k \right) \left( \sum_{k=j+1}^{\infty} \beta_k \right)} \right) + (1 - \alpha) \right) \\
&= \gamma \left( \sum_{j=i+1}^{\infty} \beta_j \right) \left( \left( \sum_{j=1}^i \left( \frac{1}{\sum_{k=j}^{\infty} \beta_k} - \frac{1}{\sum_{k=j+1}^{\infty} \beta_k} \right) \right) + (1 - \alpha) \right) \\
&= \gamma \left( \sum_{j=i+1}^{\infty} \beta_j \right) \left( \frac{1}{\sum_{j=i+1}^{\infty} \beta_j} - \frac{1}{\sum_{j=1}^{\infty} \beta_j} + 1 - \alpha \right) \\
&= \gamma \left( \sum_{j=i+1}^{\infty} \beta_j \right) \left( \frac{1}{\sum_{j=i+1}^{\infty} \beta_j} - \alpha \right) \\
&= \gamma \left( 1 - \alpha \left( \sum_{j=i+1}^{\infty} \beta_j \right) \right)
\end{aligned} \tag{2.141}$$

□

It is worth noting that in the following two theorems, the assumption of completeness is necessary, as demonstrated by [12].

**Theorem 2.3.5** (James Separable). *If  $X$  is a separable complete seminormed space then the following are equivalent.*

1.  $X$  is not reflexive.
2. For every  $\alpha \in (0, 1)$  there is some sequence  $\{x_i^*\}_{i \in \mathbb{N}} \subset \overline{B_{X^*}(0; 1)}$  satisfying  $d(0, \overline{\text{co}}\{x_i^*\}_{i \in \mathbb{N}}) \geq \alpha$  and  $x_i^* \xrightarrow{w^*} 0$ .
3. For every  $\alpha \in (0, 1)$  and  $\{\beta_i\}_{i \in \mathbb{N}} \subset (0, 1)$  satisfying  $\sum_{i \in \mathbb{N}} \beta_i = 1$ , there is a  $\gamma \in [0, 1]$

and  $\{y_i^*\}_{i \in \mathbb{N}} \subset X^*$  such that  $y_i^* \xrightarrow{w^*} 0$  and for each  $i \in \mathbb{N}$ ,

$$\left\| \sum_{j \in \mathbb{N}} \beta_j y_j^* \right\| = \gamma \quad \left\| \sum_{j=1}^i \beta_j y_j^* \right\| \leq \gamma \left( 1 - \alpha \left( \sum_{j=i+1}^{\infty} \beta_j \right) \right) \quad (2.142)$$

4. There exists  $x^* \in X^*$  not achieving its norm.

*Proof.* (1  $\implies$  2) Let  $\alpha \in (0, 1)$ . Since  $X$  is nonreflexive and  $c(X)$  is complete, by Riesz's lemma [13], there exists an  $x^{**} \in B_{X^{**}}(0; 1)$  such that  $d(x^{**}, c(X)) > \alpha$ . Since  $X$  is separable it has a countable dense set  $\{x_i\}_{i \in \mathbb{N}}$ . Fix  $i \in \mathbb{N}$ , let  $\alpha_1 = \alpha_2 = \dots = \alpha_{i-1} = 0$ ,  $\alpha_i = \alpha$ , and let  $\{\beta_j\}_{j=1}^i \subset \mathbb{C}$  where  $\beta_i \neq 0$  without loss of generality. Then, since  $c(X)$  is a subspace,

$$\begin{aligned} \left| \sum_{j=1}^i \beta_j \alpha_j \right| &= |\beta_i \alpha_i| = |\beta_i| \alpha \\ &\leq \frac{|\beta_i| \alpha}{d(x^{**}, c(X))} \left\| x^{**} + \sum_{j=1}^{i-1} \frac{\beta_j}{\beta_i} c(x_j) \right\| \\ &= \frac{\alpha}{d(x^{**}, c(X))} \left\| \beta_i x^{**} + \sum_{j=1}^{i-1} \beta_j c(x_j) \right\| \end{aligned} \quad (2.143)$$

Since  $\alpha < d(x^{**}, c(X))$ , for some  $\epsilon > 0$ ,  $\epsilon + \frac{\alpha}{d(x^{**}, c(X))} < 1$ , so by 2.2.1, since  $X^{**} = (X^*)^*$ , there exists an  $x_i^* \in \overline{B_{X^*}(0; 1)}$  such that for  $1 \leq j \leq i-1$  we have  $\langle x_j, x_i^* \rangle = \langle x_i^*, c(x_j) \rangle = 0$  and  $\langle x_i^*, c(x_i) \rangle \geq \alpha$ . Using this method we construct a sequence  $\{x_i^*\}_{i \in \mathbb{N}} \subset \overline{B_{X^*}(0; 1)}$  such that for each  $1 \leq j \leq i-1$ ,  $\langle x_j, x_i^* \rangle = 0$  and  $\langle x_i, x^{**} \rangle \geq \alpha$ . Without loss of generality, we let  $\|x_i^*\| = 1$ . Density of  $\{x_j\}_{j \in \mathbb{N}}$  and the boundedness of  $\{x_j^*\}_{j \in \mathbb{N}}$  implies  $x_j^* \xrightarrow{w^*} 0$ . Furthermore, any convex combination of the  $(x_i^*)'$ s satisfies

$$\alpha \leq \left\langle \sum_{j=1}^n \lambda_j x_{k_j}^*, x^{**} \right\rangle \leq \|x^{**}\| \left\| \sum_{j=1}^n \lambda_j x_{k_j}^* \right\| \leq \left\| \sum_{j=1}^n \lambda_j x_{k_j}^* \right\| \quad (2.144)$$

so that  $d(0, \overline{co}\{x_i^*\}_{i \in \mathbb{N}}) \geq \alpha$ , completing the proof.  $\square$

*Proof.* (2  $\implies$  3). This is a direct application of 2.3.4 part (1  $\implies$  2), paired with the fact that if for every  $i$ ,  $y_i^* \in \overline{co}\{x_j^*\}_{j \geq i}$  and  $x_j^* \xrightarrow{w^*} x$ , then  $y_j^* \xrightarrow{w^*} x$ .  $\square$

*Proof.* (3  $\implies$  4). Let  $x^* = \sum_{j \in \mathbb{N}} \beta_j y_j^*$  and let  $x \in \overline{B_X(0; 1)}$ . Since  $y_j^* \xrightarrow{w^*} 0$ , for some  $N \in \mathbb{N}$ ,

$\langle x, y_j^* \rangle < \gamma\alpha$  for every  $j > \mathbb{N}$ . Then

$$\begin{aligned}
|\langle x, x^* \rangle| &\leq \left| \left\langle x, \sum_{j=1}^N \beta_j y_j^* \right\rangle \right| + \left| \left\langle x, \sum_{j=N+1}^{\infty} \beta_j y_j^* \right\rangle \right| \\
&< \left| \left\langle x, \sum_{j=1}^N \beta_j y_j^* \right\rangle \right| + \alpha\gamma \sum_{j=N+1}^{\infty} \beta_j \\
&\leq \left\| \sum_{j=1}^N \beta_j y_j^* \right\| + \alpha\gamma \sum_{j=N+1}^{\infty} \beta_j \leq \gamma \left( 1 - \alpha \sum_{j=N+1}^{\infty} \beta_j \right) + \gamma\alpha \sum_{j=N+1}^{\infty} \beta_j \\
&= \gamma = \left\| \sum_{j \in \mathbb{N}} \beta_j y_j^* \right\| = \|x^*\|
\end{aligned} \tag{2.145}$$

Since the inequality is strict and  $x \in \overline{B_X(0;1)}$  was arbitrary, we are done.  $\square$

*Proof.* (4  $\implies$  1). If  $X$  is reflexive and  $x^* \in X$ , then there is a sequence  $\{x_n\}_{n \in \mathbb{N}} \subset \overline{B_X(0;1)}$  such that  $\langle x_n, x^* \rangle \rightarrow \|x^*\|$ . By 2.3.1,  $\{x_n\}_{n \in \mathbb{N}}$  has a subsequence  $x_{k_n} \xrightarrow{w} x \in \overline{B_X(0;1)}$ . This  $x$  satisfies  $\langle x, x^* \rangle = \|x^*\|$ .  $\square$

**Theorem 2.3.6** (James). *If  $X$  is a complete seminormed space, then the following are equivalent.*

1.  $X$  is non-reflexive.
2. For each  $\alpha \in (0, 1)$ , there exists an  $\{x_i^*\}_{i \in \mathbb{N}} \subset \overline{B_{X^*}(0;1)}$  and a subspace  $Y \subset X$  such that  $d(\overline{\text{co}}\{x_i^*\}_{i \in \mathbb{N}} - Y^\perp, 0) \geq \alpha$  and that  $\langle y, x_i^* \rangle \rightarrow 0$  for each  $y \in Y$ .
3. For every  $\alpha \in (0, 1)$  and  $\{\beta_i\}_{i \in \mathbb{N}} \subset [0, \infty)$  such that  $\sum_{i \in \mathbb{N}} \beta_i = 1$ , there is a  $\gamma \in [0, 2]$  and  $\{y_i^*\}_{i \in \mathbb{N}} \subset \overline{B_{X^*}(0;1)}$  such that for each  $y^* \in \text{CoLim}\{y_i^*\}_{i \in \mathbb{N}}$ , each  $i \in \mathbb{N}$ ,

$$\left\| \sum_{j \in \mathbb{N}} \beta_j (y_j^* - y^*) \right\| = \gamma \quad \left\| \sum_{j=1}^i \beta_j (y_j^* - y_j) \right\| < \gamma \left( 1 - \alpha \left( \sum_{j=i+1}^{\infty} \beta_j \right) \right) \tag{2.146}$$

4. There exists  $x^* \in X^*$  which doesn't achieve its norm.

*Proof.* (1  $\implies$  2) If  $X$  is non-reflexive, then  $X$  contains a non-reflexive closed separable subspace  $S$ . An application of 2.3.5 implies the existence of a sequence  $\{x_i\}_{i \in \mathbb{N}} \subset \overline{B_{S^*}(0;1)}$  such that

$$d_s(0, \overline{\text{co}}\{x_i\}_{i \in \mathbb{N}}) \geq \alpha \quad x_i \xrightarrow{S-w^*} 0 \tag{2.147}$$

If  $y^\perp \in X^*$  such that  $Y \subset \text{kern}(y^*)$ , then letting for each  $i \in \mathbb{N}$   $x_i^*$  be a Hahn-Banach extension living in  $\overline{B_{X^*}(0;1)}$ , and let  $x^* \in \overline{\text{co}}\{x_i^*\}_{i \in \mathbb{N}}$ . Then  $x := x^*|_S \in \overline{\text{co}}\{x_i\}_{i \in \mathbb{N}}$ . If  $y \in Y$ , then  $\langle y, x_i^* \rangle = \langle y, x \rangle \rightarrow 0$ . If  $y^\perp \in Y^\perp$ , then

$$\|x^* - y^\perp\| \geq \|x - (y^\perp|_S)\|_S = \|x\| \geq \alpha \tag{2.148}$$

so  $d(\overline{\text{co}}\{x_i^*\}_{i \in \mathbb{N}} - Y^\perp, 0) \geq \alpha$   $\square$

*Proof.* (2  $\implies$  3) Since  $CoLim\{x_i^*\}_{i \in \mathbb{N}} \subset Y^\perp$  from the previous part, this is an easy application of 2.3.4 (3  $\implies$  4).  $\square$

*Proof.* (3  $\implies$  4) Define  $\eta = \frac{\alpha^2}{4}$ , and then let  $\lambda_1 \in [0, \infty)$  such that for every natural  $n$ ,  $\lambda_{n+1} < \eta\lambda_n$  and  $\sum_{k \in \mathbb{N}} \lambda_k = 1$ . Let  $y^* \in CoLim\{y_i^*\}_{i \in \mathbb{N}}$  where  $\{y_i^*\}_{i \in \mathbb{N}}$  are as in part (3) of this theorem. Let  $x \in \overline{B_X(0; 1)}$ . Since  $y^* \in Colim\{y_i^*\}_{i \in \mathbb{N}}$ , and since  $\alpha \leq \gamma$ , there exists  $i \in \mathbb{N}$  such that

$$\langle x, y_{i+1}^* - y^* \rangle < \alpha^2 - 2\eta \leq \alpha\gamma - 2\eta \quad (2.149)$$

For this  $x$ , we have

$$\begin{aligned} \left\langle x, \sum_{j \in \mathbb{N}} \beta_j (y_j^* - y^*) \right\rangle &< \sum_{j=1}^i \beta_j \langle x, y_j^* - y^* \rangle + \beta_{i+1} (\alpha\gamma - 2\eta) + \sum_{j=i+2}^{\infty} \beta_j \langle x, y_j^* - y^* \rangle \\ &\leq \left\| \sum_{j=1}^i \beta_j (y_j^* - y^*) \right\| + \beta_{i+1} (\alpha\gamma - 2\eta) + 2 \sum_{j=i+2}^{\infty} \beta_j \\ &\leq \gamma \left( 1 - \alpha \left( \sum_{j=i+1}^{\infty} \beta_j \right) \right) + \beta_{i+1} (\alpha\gamma - 2\eta) + 2 \sum_{j=i+2}^{\infty} \beta_j \\ &= \gamma - \gamma\alpha \sum_{j=i+2}^{\infty} \beta_j - 2\eta\beta_{i+1} + 2 \sum_{j=i+1}^{\infty} \eta\beta_j \\ &\leq \gamma - (\gamma\alpha - 2\eta) \sum_{j=i+1}^{\infty} \beta_j < \gamma = \left\| \sum_{j \in \mathbb{N}} \beta_j (y_j^* - y^*) \right\| \end{aligned} \quad (2.150)$$

Since  $x \in \overline{B_X(0; 1)}$  was arbitrary, we are done.  $\square$

*Proof.* (4  $\implies$  1) If  $X$  is reflexive and  $x^* \in X$ , then there is a sequence  $\{x_n\}_{n \in \mathbb{N}} \subset \overline{B_X(0; 1)}$  such that  $\langle x_n, x^* \rangle \rightarrow \|x^*\|$ . By 2.3.1,  $\{x_n\}_{n \in \mathbb{N}}$  has a subsequence  $x_{k_n} \xrightarrow{w} x \in \overline{B_X(0; 1)}$ . This  $x$  satisfies  $\langle x, x^* \rangle = \|x^*\|$ .  $\square$

**Corollary 2.3.7.** *Let  $X$  be a complete seminormed space. Then the following are equivalent.*

1.  $X$  is reflexive.
2. Each element of  $X^*$  attains its norm.

*Proof.* Direct consequence of 2.3.6.  $\square$

## 2.3.2 Lindenstrauss On Nonseparable Reflexive Banach Spaces

If  $\Gamma \neq \emptyset$ , then  $c_0(\Gamma)$  denotes the space of mappings  $f : \Gamma \rightarrow \mathbb{C}$  such that for every  $\epsilon > 0$ ,  $\text{card}\{x \in \Gamma : |f(x)| > \epsilon\} \in \mathbb{N}$ .

## 2.4 Convexity Of Functions And Sets

**Definition 2.4.1** (Convex Functions). *Let  $X$  be a vector space,  $Y$  a topological vector space,  $\mathcal{U}$  the set of neighborhoods of 0 in  $Y$  except  $Y$  itself,  $f : X \rightarrow (-\infty, \infty]$ , and  $g : Y \rightarrow (-\infty, \infty]$ . Let  $x, y \in X$ .*

1. We call  $D(f) := f^{-1}(\mathbb{R})$  the **effective domain** of  $f$ .
2. If  $D(f) \neq \emptyset$ , then we call  $f$  **proper**.
3. We call  $\text{Epi}(f) := \{(x, t) \in X \times \mathbb{R} : f(x) \leq t\}$  the **Epigraph** of  $f$ .
4. We denote  $[x, y] = \{tx + (1 - t)y : t \in [0, 1]\}$ .
5. We denote  $(x, y) = \{tx + (1 - t)y : t \in (0, 1)\}$ .
6. We say that  $C \subset X$  is **convex** if  $[x, y] \subset C$  for each  $x, y \in C$ .
7. We say that  $C \subset X$  is **strictly convex** if for each  $x, y \in C$ , for each  $z_0 \in (x, y)$ , and for each  $z_1 \in X$ , there is a  $t > 0$  such that  $[z_0, z_0 + tz_1] \subset C$ .
8. We say that  $f$  is **convex** if for each  $x, y \in X$ ,  $f\left(\frac{x+y}{2}\right) \leq \frac{f(x)+f(y)}{2}$ .
9. We say that  $f$  is **strictly convex** if for each  $x, y \in X$ ,  $f\left(\frac{x+y}{2}\right) < \frac{f(x)+f(y)}{2}$ .
10. If  $g$  is a convex function, then then we define the **modulus of local uniform convexity** of  $g$ ,  $\tilde{\Delta} : \mathcal{U} \times Y \rightarrow \mathbb{R}$  by

$$\tilde{\Delta}(U, x) = \frac{1}{2} \inf_{y \in Y \setminus (x+U)} \left\{ f(x) + f(y) - 2f\left(\frac{x+y}{2}\right) \right\} \quad (2.151)$$

11. If  $g$  is a convex function, then we define the **modulus of uniform convexity** of  $g$ ,  $\Delta : \mathcal{U} \rightarrow \mathbb{R}$  by  $\Delta(U) = \inf_{g(x)=1} \tilde{\Delta}(U, x)$ .
12. If  $g$  is a convex function, then we say that  $g$  is **locally uniformly convex at  $x \in Y$**  if for each  $U \in \mathcal{U}$ ,  $\tilde{\Delta}(U, x) > 0$ .
13. We say that  $g$  is **locally uniformly convex** if it is **locally uniformly convex** at each of its points.
14. We say that  $g$  is **uniformly convex** if for each  $U \in \mathcal{U}$ ,  $\Delta(U) > 0$ .
15. We say that  $g$  is **lower semi-continuous**, or LSC if it is continuous with respect to the topology on  $(-\infty, \infty]$  generated by sets of the form  $(-\infty, \alpha)$  where  $\alpha \in \mathbb{R}$ , along with  $(-\infty, \infty]$  itself.

**Remark 2.4.2** (Basis Independence). *It is easy to see that a mapping is locally uniform convex at a point (locally uniformly convex) [uniformly convex] if we define  $\Delta$ ,  $\tilde{\Delta}$  in terms of a single neighborhood basis of  $Y$  at 0 instead of all neighborhoods of 0 in  $Y$ .*

**Remark 2.4.3** (Strictly Convex Real Valued). *If  $X$  is a vector space and  $f : X \rightarrow (-\infty, \infty]$  is strictly convex, and  $f$  is finite everywhere.*

*Proof.* If  $f(x) = \infty$  where  $x \in X$  and  $f$  is strictly convex, then we must have  $\infty = f(x) < \frac{f(0)+f(2x)}{2}$ , a contradiction.  $\square$

**Proposition 2.4.4.** *Let  $X$  be a vector space and  $T : X \rightarrow (-\infty, \infty]$ . Then the following are equivalent.*

1.  $T$  is (strictly) convex.
2. For each  $x_1 \neq x_2 \in X$  and  $\lambda \in (0, 1)$ .

$$T(\lambda x_1 + (1 - \lambda)x_2)(<) \leq \lambda T x_1 + (1 - \lambda)T x_2 \quad (2.152)$$

3. For each  $\{\lambda_i\}_{i=1}^n \subset (0, 1)$  which sums to 1, for each  $\{x_i\}_{i=1}^n \subset X$ ,

$$T\left(\sum_{j=1}^n \lambda_j x_j\right)(<) \leq \sum_{j=1}^n \lambda_j T x_j \quad (2.153)$$

4. If  $x_1 \neq x_3 \in X$  and  $x_2 \in (x_1, x_3)$ , say  $x_2 = \lambda x_1 + (1 - \lambda)x_3$  then

$$\frac{T x_2 - T x_1}{\lambda}(<) \leq T x_3 - T x_1(<) \leq \frac{T x_3 - T x_2}{1 - \lambda} \quad (2.154)$$

5.  $\text{Epi}(T)$  is (strictly) convex

*Proof.* (1  $\implies$  2)

$\square$

*Proof.* (2  $\implies$  3) I utilize induction on  $n$ . Since  $f$  is assumed to be (strictly) convex, the proposition holds for  $n = 1$  and  $n = 2$ . Let  $k \in \mathbb{N}$ . Suppose that for any  $(\psi_1, \dots, \psi_k) \in [0, 1]^k$  such that  $\sum_{j=1}^k \psi_j = 1$ , and for each  $(x_1, \dots, x_k) \in X^k$ , we have

$$f\left(\sum_{j=1}^k \lambda_j x_j\right)(<) \leq \sum_{j=1}^k \lambda_j f(x_j) \quad (2.155)$$

Let  $(\lambda_1, \dots, \lambda_{k+1}) \in [0, 1]^{k+1}$ . Let  $(x_1, \dots, x_{k+1}) \in X^{k+1}$ . Without loss of generality, we assume  $\lambda_{k+1} \neq 0$ . Then

$$\sum_{j=1}^k \frac{\lambda_j}{1 - \lambda_{k+1}} = 1 \quad \left(\frac{\lambda_1}{1 - \lambda_{k+1}}, \dots, \frac{\lambda_k}{1 - \lambda_{k+1}}\right) \in [0, 1]^k \quad (2.156)$$

Hence, because  $f$  is (strictly) convex,

$$\begin{aligned}
 f\left(\sum_{j=1}^{k+1} \lambda_j x_j\right) &= f\left(\lambda_{k+1} x_{k+1} + (1 - \lambda_{k+1}) \sum_{j=1}^k \frac{\lambda_j}{1 - \lambda_{k+1}} x_j\right) \\
 &\leq \lambda_{k+1} f(x_{k+1}) + (1 - \lambda_{k+1}) f\left(\sum_{j=1}^k \frac{\lambda_j}{1 - \lambda_{k+1}} x_j\right) \\
 &\leq \sum_{j=1}^{k+1} \lambda_j f(x_j)
 \end{aligned} \tag{2.157}$$

□

*Proof.* (3  $\implies$  4) □

*Proof.* (4  $\implies$  1). □

*Proof.* (2  $\iff$  5) □

The epigraph of a function provides us with a nice characterization of lower semi-continuity.

**Proposition 2.4.5** (Convex Continuity). *Let  $X$  be a locally convex space and  $f : X \rightarrow (-\infty, \infty]$ . The following conditions are equivalent.*

1.  $f$  is LSC on  $X$ .
2.  $\text{Epi}(f)$  is closed in  $X \times \mathbb{R}$ .

*Proof.* Define  $F : X \times \mathbb{R} \rightarrow \tilde{\mathbb{R}}$  by  $F(x, \alpha) = f(x) - \alpha$ . Then  $f$  is (weakly) LSC on  $X$  if and only if  $F$  is (weakly) LSC on  $X \times \mathbb{R}$ . Suppose  $f$  is (weakly) LSC. Then  $F$  is (weakly) LSC, so  $F^{-1}((-\infty, 0]) = \text{Epi}(f)$  is (weakly) closed, so we're done. Suppose  $\text{Epi}(f)$  is (weakly) closed. Then  $F^{-1}((-\infty, 0])$  is (weakly) closed. Further, for any  $\beta \in \mathbb{R}$ ,  $F^{-1}((-\infty, \beta]) = F^{-1}((-\infty, 0]) - (0, \beta)$ , and so is also closed. Hence  $F$  is (weakly) LSC, and so  $f$  is too. □

In the case of a convex function, the above proposition allows us to equate weak and strong lower semicontinuity.

**Corollary 2.4.6** (Weak To Strong Convex). *Let  $X$  be locally convex Hausdorff space and  $f : X \rightarrow (-\infty, \infty]$  be convex. Then  $f$  is LSC if and only if it is weakly LSC.*

*Proof.* Since  $\text{Epi}(f)$  is convex, it is closed if and only if it is weakly closed, allowing us to apply 2.4.5. □

**Theorem 2.4.7** (Point Continuous). *Let  $X$  be a locally convex space and  $f : X \rightarrow (-\infty, \infty]$  be convex and proper. Then  $f$  is bounded on some open set if and only if  $f$  is continuous on the interior of its domain.*



*Proof. (implies)* Without loss of generality, we assume that  $f$  is bounded from above by  $M$  on a (weakly) open set  $\mathcal{U}$  which is symmetric and contains 0. Further, we can also suppose  $f(0) = 0$ . For each  $\epsilon \in (0, 1)$  and each  $x \in \epsilon\mathcal{U}$ , we have

$$f(x) = f\left(\epsilon \frac{x}{\epsilon} + (1 - \epsilon)0\right) \leq \epsilon f\left(\frac{x}{\epsilon}\right) \leq \epsilon M \quad (2.158)$$

and since  $0 = \frac{x}{1+\epsilon} + \left(1 - \frac{1}{1+\epsilon}\right)\left(\frac{-x}{\epsilon}\right)$ ,

$$0 = f(0) = f\left(\frac{x}{1+\epsilon} + \left(1 - \frac{1}{1+\epsilon}\right)\left(\frac{-x}{\epsilon}\right)\right) \leq \frac{f(x)}{1+\epsilon} + \frac{\epsilon f\left(\frac{-x}{\epsilon}\right)}{1+\epsilon} \quad (2.159)$$

so, since  $\frac{-x}{\epsilon} \in \mathcal{U}$ ,

$$-\epsilon M \leq -\epsilon f\left(\frac{x}{\epsilon}\right) \leq f(x) \quad (2.160)$$

Hence,  $|f(x)| \leq \epsilon M$  for  $x \in \epsilon\mathcal{U}$ , and  $f$  is (weakly) continuous at 0. Hence, it is sufficient to show that for any  $y$  in the (weak) interior of  $D(f)$ , there is a (weak) neighborhood of  $y$  on which  $f$  is bounded from above. To see this, let  $y$  in the (weak) interior of  $D(f)$ . Since scalar multiplication is continuous, there is a  $\rho > 1$  such that  $\rho y \in D(f)$ . If  $\mathcal{U}_y = y + \left(1 - \frac{1}{\rho}\right)\mathcal{U}$ , then  $x \in \mathcal{U}_y$  can be written, for some  $z \in \mathcal{U}$ , as

$$x = y + \left(1 - \frac{1}{\rho}\right)z = \frac{1}{\rho}(\rho y) + \left(1 - \frac{1}{\rho}\right)z \quad (2.161)$$

Since  $f$  is convex,  $D(f)$  is convex, and so  $x \in D(f)$ , implying  $\mathcal{U}_y \subset D(f)$ . Since  $f$  is a convex function, we also have that

$$f(x) \leq \frac{1}{\rho}f(\rho y) + \left(1 - \frac{1}{\rho}\right)f(x) \leq \frac{1}{\rho}f(\rho y) + \left(1 - \frac{1}{\rho}\right)M \quad (2.162)$$

so that  $f$  is bounded on  $\mathcal{U}_y$  and is therefore continuous at  $y$ . □

*Proof. ( $\Leftarrow$ )* This is obvious. □

**Corollary 2.4.8.** *Let  $X$  be a locally convex, space and  $f : X \rightarrow (-\infty, \infty]$  be LSC at some point in its effective domain.*

1. *if  $f$  is convex, then it is continuous on the interior of  $D(f)$ .*
2. *If  $f$  is strictly convex, then it is continuous on  $X$ .*

## 2.5 Differentiation And SubDifferentials

**Definition 2.5.1** (Types Of Differentiability). *Let  $X$  be a topological vector space,  $Y$  a Hausdorff topological vector space,  $C \subset X$ ,  $f : C \rightarrow Y$ , and  $x_0 \in C$ .*

1. If  $y \in X$  such that  $x_0$  is an accumulation point of  $[x_0, x_0 + y] \cap C$ , then we say that the **directional derivative in the direction of  $y$**  exists at  $x_0$  and we write

$$\lim_{t \rightarrow 0^+} \frac{f(x_0 + ty) - f(x_0)}{t} = f'_+(x_0, y) \quad (2.163)$$

if the limit above actually exists.

2. If  $f$  is differentiable at  $x_0$  in the direction of  $-y$ , then we denote  $f'_-(x_0, y) := -f'_+(x_0, -y)$ .
3. If there exists  $f'(x_0) \in BL(X, Y)$  such that for every  $y \in X$ ,  $f'_+(x_0, y) = f'(x_0)y$  then we call  $f'(x_0)$  the **Gateaux derivative** of  $f$  at  $x_0$  and we call  $f$  **Gateaux differentiable**.
4. If  $f$  is Gateaux differentiable at  $x_0$  and  $\frac{f(x_0 + ty) - f(x_0)}{t} \rightarrow f'(x_0)y$  uniformly for  $y$  in some neighborhood of 0 in  $X$ , then we say that  $f$  is **Frechet differentiable** at  $x_0$  and we call  $f'(x_0)$  the **Frechet derivative** of  $f$  at  $x_0$ .

5. If  $h : X \rightarrow (-\infty, \infty]$  and there is an  $x^* \in X^*$  such that

$$\langle y - x, x^* \rangle \leq h(y) - h(x) \quad (\forall y \in X) \quad (2.164)$$

then we say that  $h$  is **subdifferentiable** at  $x_0$ , call  $x^*$  a **subgradient** of  $h$  at  $x_0$ , and denote the set of all subgradients of  $h$  at  $x_0$  with  $\partial h(x_0)$ . if  $D$  is the set on which  $h$  is subdifferentiable, then we call  $\partial h : D \rightarrow 2^{X^*}$  the **subdifferential** of  $h$ .

One useful feature of convex functions is how they interact with the various forms of differentiability.

**Proposition 2.5.2** (Gateaux). *Let  $X$  be a topological vector space,  $Y$  a Hausdorff topological vector space,  $f : X \rightarrow Y$  Gateaux differentiable at  $x_0 \in X$ , and  $y \in X$ . The following are true.*

1.  $f'_+(x_0, y) = f'_+(x_0, -y) = f'_-(x_0, y)$ .
2.  $\langle y, f'(x_0) \rangle = \frac{d}{dt} f(x_0 + ty) |_{t=0}$
3. If  $f$  is Gateaux differentiable on a neighborhood of  $x_0$  and  $f' : X \rightarrow BL(X, Y)$  is Gateaux Differentiable at  $x_0$ , then  $f'' : X \rightarrow BL(X, BL(X, Y))$  satisfies

$$\langle y, f''(x)y \rangle = \frac{d^2}{dt^2} f(x_0 + ty) |_{t=0} \quad (2.165)$$

*Proof.* (1) □

*Proof.* (2) □

*Proof.* (3) □

**Proposition 2.5.3** (Convex Differentiable). *Let  $X$  be a seminormed space and  $f : X \rightarrow (-\infty, \infty]$  be convex. Then for each  $y \in X$  and each  $x_0$  in the interior of  $D(f)$ , the directional derivative in the direction of  $y$  at  $x_0$  exists and  $f'_-(x, y) \leq f'_+(x, y)$ , and for any  $t > 0$ ,*

$$f'_+(x, y) \leq \frac{f(x + ty) - f(x)}{t} \leq f'_-(x + ty, y) \quad (2.166)$$

## 2.6 Normalized Duality Mapping

**Definition 2.6.1** (Normalized Duality Mapping). *If  $X$  is a seminormed space, then we call  $J : X \rightarrow 2^{X^*}$  defined by*

$$Jx = \{x^* \in X^* : \langle x, x^* \rangle = \|x\|^2 = \|x^*\|^2\} \quad (2.167)$$

*the normalized duality mapping of  $X$ .*

**Proposition 2.6.2** (Normalized Duality Inequality). *Let  $X$  be a seminormed space and  $J$  be  $X$ 's normalized duality mapping. Then, if  $x, y \in X$  and  $\|x + \lambda y\| \neq 0$  where  $\lambda > 0$ , and  $j_x \in Jx$ ,  $j_{x+\lambda y} \in J(x + \lambda y)$ , then*

$$\frac{\langle y, j_x \rangle}{\|x\|} \leq \frac{\|x + \lambda y\| - \|x\|}{\lambda} \leq \frac{\langle y, j_{x+\lambda y} \rangle}{\|x + \lambda y\|} \quad (2.168)$$

*Proof.*

$$\begin{aligned} \frac{\langle y, j_x \rangle}{\|x\|} &= \frac{\langle x + \lambda y, j_x \rangle - \|x\|^2}{\lambda \|x\|} \leq \frac{|\langle x + \lambda y, j_x \rangle| - \|x\|^2}{\lambda \|x\|} \leq \frac{\|j_x\| \|x + \lambda y\| - \|x\|^2}{\lambda \|x\|} \\ &= \frac{\|x + \lambda y\| - \|x\|}{\lambda} \\ &= \frac{\|x + \lambda y\|}{\|x + \lambda y\|} \frac{\|x + \lambda y\| - \|x\|}{\lambda} \leq \frac{\|x + \lambda y\|^2 - |\langle x, j_{x+\lambda y} \rangle|}{\lambda \|x + \lambda y\|} \\ &= \frac{\lambda \langle y, j_{x+\lambda y} \rangle + \langle x, j_{x+\lambda y} \rangle - |\langle x, j_{x+\lambda y} \rangle|}{\lambda \|x + \lambda y\|} \\ &\leq \frac{\lambda \langle y, j_{x+\lambda y} \rangle}{\lambda \|x + \lambda y\|} = \frac{\langle y, j_{x+\lambda y} \rangle}{\|x + \lambda y\|} \end{aligned} \quad (2.169)$$

□

**Theorem 2.6.3** (Asplund). *[14] Let  $X$  be a seminormed space and  $J$  be its normalized duality mapping. Then for any  $x \in X$ ,  $Jx = \partial(\|x\|^2)$ .*

*Proof.*

□

**Proposition 2.6.4.** *Let  $X$  be a (Possibly Complete, maybe not) seminormed space and let  $J$  be its normalized duality mapping. Then  $J$  is norm to weak\* upper semicontinuous on  $X$ .*

*Proof.*

□

## 2.7 Orthogonality

**Definition 2.7.1** (Orthogonality). *Let  $X$  be a seminormed space and  $x, y \in X$ . We say that  $x$  is **orthogonal** to  $y$  and we write  $x \perp y$  if for each scalar  $\lambda$ , we have*

$$\|x\| \leq \|x + \lambda y\| \quad (2.170)$$

**Proposition 2.7.2** (Orthogonality). *Let  $X$  be a seminormed space,  $x, z \in X$ , and  $x^* \in X^*$ .*

1.  $\langle x, x^* \rangle = \|x\| \|x^*\|$  if and only if for each  $y \in \ker(x^*)$ ,  $x \perp y$ .
2.  $x$  is orthogonal to each element of some hyperplane in  $X$ .
3. For some  $\alpha \neq 0$   $x \perp (\alpha x + z)$ .
4. The mapping  $T : \mathbb{F} \rightarrow \mathbb{R}$  defined by  $T\alpha = \|\alpha x + z\|$  achieves its minimum, and if  $\lambda_0$  is a point at which it achieves this minimum, then  $(\lambda_0 x + y) \perp x$  for any  $\lambda_0$  which minimizes  $T$ . Furthermore, since  $T$  as defined earlier is a convex function, the set of  $\lambda$  for which  $(\lambda x + y) \perp x$  is a convex set.

## 2.8 Convexity Of A Space

**Definition 2.8.1** (Uniform Convexity, Weak Uniform Convexity, Local Uniform Convexity, Weak Local Uniform Convexity, Strict Convexity). *Let  $(X, \|\cdot\|)$  be a seminormed space.*

1. We call the local modulus of uniform convexity of  $\|\cdot\|$ , denoted by the symbol  $\tilde{\Delta}$ , the **local modulus of uniform convexity** of  $X$ .
2. If  $\Delta$  is the modulus of uniform convexity of  $\|\cdot\|$ , then we call  $\Delta$  the **modulus of uniform convexity** of  $X$ .
3. We define  $\tilde{\Delta}_w : (0, \infty) \times \partial B_X(0; 1) \rightarrow (0, \infty)$  by

$$\tilde{\Delta}_w(\epsilon, x) = \inf \{2 - \langle x + y, x^* \rangle : x^* \in \partial B_{X^*}(0; 1), y \in \partial B_X(0; 1), \|x - y\| \geq \epsilon\} \quad (2.171)$$

We call  $\tilde{\Delta}_w$  the **modulus of weak local uniform convexity** of  $X$ .

4. We define  $\Delta_w : (0, \infty) \rightarrow (0, \infty)$  by

$$\Delta_w(\epsilon) = \inf_{x \in \partial B_X(0; 1)} \tilde{\Delta}_w(\epsilon, x) \quad (2.172)$$

We call this the **modulus of weak uniform convexity** of  $X$ .

1. We say that  $X$  is **strictly convex** if for each  $x, y \in X$  such that  $\|x - y\| \neq 0$ ,  $\|x + y\| < \|x\| + \|y\|$ .
2. We say that  $X$  is **uniformly convex at  $x$**  if  $\|\cdot\|$  is uniformly convex at  $x$ .
3. We say that  $X$  is **locally uniformly convex** if  $\|\cdot\|$  is locally uniformly convex.
4. We say that  $X$  is **uniformly convex** if  $\|\cdot\|$  is uniformly convex.
5. We say that  $X$  is **weakly uniformly convex at  $x \in \partial B_X(0; 1)$**  if for each  $\epsilon > 0$ ,  $\tilde{\Delta}_w(\epsilon, x) > 0$ .

6. We say that  $X$  is **locally weakly uniformly convex** if it is weakly uniformly convex at each point on the boundary of  $X$ 's unit sphere.
7. We say that  $X$  is **weakly uniformly convex** if for each  $\epsilon > 0$ ,  $\Delta_w(\epsilon) > 0$ .

**Proposition 2.8.2** (Strictly Convex Spaces). *Let  $X$  be a normed space. and let  $J$  be a duality mapping on  $X$  of weight  $\phi$ . Then the following are equivalent.*

1.  $X$  is strictly convex.
2. If  $x, y \in X$  and  $\|x + y\| = \|x\| + \|y\|$ , then for some  $\alpha \geq 0$ ,  $\|x - \alpha y\| = 0$ .
3. If  $\|x\| = \|y\| = 1$  where  $0 \neq \|x - y\|$ , then  $\|x + y\| < 2$ .
4. If  $x, y, z \in X$  and  $\|x - y\| = \|x - z\| + \|z - y\|$ ,  $\|z - z_0\| = 0$  for some  $z_0 \in [x, y]$ .
5. If  $x^* \in X^*$  and  $\|x\| = \|y\| = 1$  such that  $\langle x, x^* \rangle = \langle y, y^* \rangle = \sup_{\|z\|=1} \langle z, x^* \rangle$ , then  $\|x - y\| = 0$ .
6.  $\|\cdot\|^2$  is strictly convex.
7.  $J$  is strictly monotone. That is, if  $x, y \in X$ ,  $\|x - y\| \neq 0$ ,  $x^* \in Jx$ , and  $y^* \in Jy$ , then

$$\langle x - y, x^* - y^* \rangle > 0 \quad (2.173)$$

8. Orthogonality in  $X$  is left-unique. That is, for  $x, y \in X$ , there is a unique  $\alpha \in \mathbb{F}$  such that  $(\alpha x + y) \perp x$ .

**Proposition 2.8.3** (Locally Uniformly Convex Spaces). *Let  $X$  be a Banach Space. Then the following are equivalent.*

1.  $X$  is locally uniformly convex
2. For each  $\epsilon > 0$  and  $x \in X$  with  $\|x\| = 1$ , there is a  $\delta > 0$  such that if  $y \in X$  satisfies  $\|y\| = 1$  and  $\|x - y\| \geq \epsilon$ , then  $\|x + y\| \leq 2(1 - \delta)$ .
3. If  $x \in \partial B_X(0; 1)$ ,  $\{x_n\}_{n \in \mathbb{N}} \subset \partial B_X(0; 1)$ , and  $\|x + x_n\| \rightarrow 2$ , then  $x_n \rightarrow x$ .
4.  $\frac{1}{2} \|\cdot\|^2$  is locally uniformly convex.

**Proposition 2.8.4** (Uniformly Convex Spaces). *Let  $X$  be a Banach space. The following are equivalent.*

1.  $X$  is uniformly Convex.
2. For each  $\epsilon > 0$ , there is a  $\delta > 0$  such that if  $x, y \in \overline{B_X(0; 1)}$  and  $\|x - y\| \geq \epsilon$ , then  $\|x + y\| \leq 2(1 - \delta)$ .
3. If  $\{x_i\}_{i \in \mathbb{N}}, \{y_i\}_{i \in \mathbb{N}} \subset \overline{B_X(0; 1)}$  and  $\|x_n + y_n\| \rightarrow 2$ , then  $x_n - y_n \rightarrow 0$ .
4.  $\frac{1}{2} \|\cdot\|^2$  is uniformly convex.

**Proposition 2.8.5** (Weakly Locally Uniformly Convex Spaces). *Let  $X$  be a Banach space. The following conditions are equivalent.*

1.  $X$  is weakly locally uniformly convex.
2. For each  $\epsilon > 0$ ,  $x^* \in \partial B_{X^*}(0; 1)$ , and  $x \in \overline{B_X(0; 1)}$  there is a  $\delta > 0$  such that if  $y \in \overline{B_X(0; 1)}$  and  $\langle x - y, x^* \rangle \geq \epsilon$ , then  $\|x + y\| \leq 2(1 - \delta)$ .
3. If  $x \in \overline{B_X(0; 1)}$  and  $\{x_n\}_{n \in \mathbb{N}} \subset \overline{B_X(0; 1)}$  such that  $\|x + x_n\| \rightarrow 2$ , then  $x_n \xrightarrow{w} x$ .

**Proposition 2.8.6** (Weakly Uniformly Convex Spaces). *Let  $X$  be a Banach space. The following conditions are equivalent.*

1.  $X$  is weakly uniformly convex.
2. For each  $\epsilon > 0$  and  $x^* \in \partial B_{X^*}(0; 1)$ , there is a  $\delta > 0$  such that if  $x, y \in \overline{B_X(0; 1)}$  such that  $\langle x - y, x^* \rangle \geq \epsilon$ , then  $\|x + y\| \leq 2(1 - \delta)$ .
3. If  $\{x_n\}_{n \in \mathbb{N}}, \{y_n\}_{n \in \mathbb{N}} \subset \overline{B_X(0; 1)}$  and  $\|x_n + y_n\| \rightarrow 2$ , then  $x_n - y_n \xrightarrow{w} 0$ .

**Proposition 2.8.7** (Degrees Of Convexity). *Let  $X$  be a seminormed space.*

1. If  $X$  is uniformly convex, then  $X$  is weakly uniformly convex.
2. If  $X$  is uniformly convex, then  $X$  is locally uniformly convex.
3. if  $X$  is locally uniformly convex, then  $X$  is weakly locally uniformly convex.
4. if  $X$  is weakly locally uniformly convex, then  $X$  is strictly convex.

**Proposition 2.8.8** (Local Weak To Strong). *If a seminormed space  $X$  is locally uniformly convex and  $\{x_n\} \subset X$  satisfies  $x_n \xrightarrow{w} x$  and  $\|x_n\| \rightarrow \|x\|$ , then  $x_n \rightarrow x$ .*

*Proof.*

□

**Theorem 2.8.9.** (Milman Pettis) *A complete uniformly convex seminormed space  $X$  is reflexive.*

## 2.9 Smoothness Of A Space

Define Moduli Of Smoothness, remark on positiveness

**Definition 2.9.1.** *Let  $X$  be a seminormed space and  $x_0 \in X$ .*

1. We define the **modulus of smoothness** of  $X$  at  $x_0$ ,  $\tilde{\rho} : [0, \infty) \times X \rightarrow \mathbb{R}$  by

$$\tilde{\rho}(\epsilon, x) = \frac{1}{2} \sup_{\|y\| < 1} (\|x + \epsilon y\| + \|x - \epsilon y\| - 2\|x\|) \quad (2.174)$$

2. We define the **modulus of smoothness** of  $X$ ,  $\rho : [0, \infty) \rightarrow \mathbb{R}$  by

$$\rho(\epsilon) = \sup_{\|x\| \geq 1} \rho(\epsilon, x) \quad (2.175)$$

3. We say that  $X$  is **locally uniformly smooth** at  $x_0$  if  $\lim_{\epsilon \rightarrow 0} \frac{\tilde{\rho}(\epsilon, x_0)}{\epsilon} = 0$ .
4. We say that  $X$  is **locally uniformly smooth** if it is locally uniformly smooth at each of its points.
5. We say that  $X$  is **uniformly smooth** if  $\lim_{\epsilon \rightarrow 0} \frac{\rho(\epsilon)}{\epsilon} = 0$ .
6. We say that  $X$  is **smooth** at  $x_0$  if  $Jx_0$  is a singleton.
7. We say that  $X$  is **smooth** if it is smooth at each of its points.
8. 2.9.2 motivates defining  $X$  to be called **very smooth** at  $x_0$  if it is smooth and  $J$  is seminorm to weak continuous at  $x_0$ .
9. We say that  $X$  is **very smooth** if it is very smooth at each of its points.

**Proposition 2.9.2** (Smooth Characterization). *Let  $X$  be a seminormed space,  $x_0 \in X$ , and  $J$  it's normalized duality mapping. The following are equivalent.*

1.  $X$  is a smooth at  $x_0$ .
2. Every selection of  $J$  is norm to weak\* continuous at  $x_0$ .
3. There exists a selection of  $J$  which is norm to weak\* continuous at  $x_0$ .
4.  $\|\cdot\|$  is Gateaux Differentiable at  $x_0$ .
5. For every  $y \in X$ , there is a unique  $\alpha \in \mathbb{C}$  such that  $x \perp (\alpha x + y)$ .
6. For every  $y, z \in X$ , if  $x \perp y$  and  $x \perp z$ , then  $x \perp y + z$ .
7. (NEED TO DEFINE HYPERPLANE) There is a supporting hyperplane for  $\overline{B_X(0; \|x\|)}$  at  $x$ .

**Proposition 2.9.3** (Degrees Of Smoothness). *Let  $X$  be a seminormed space.*

1. If  $X$  is uniformly smooth, then it is locally uniformly smooth.
2. If  $X$  is locally uniformly smooth, then it is very smooth.
3. If  $X$  is very smooth, then it is smooth.

**Proposition 2.9.4** (Very Smooth).

**Proposition 2.9.5** (Local Uniformly Smooth At A Point). *Let  $X$  be a seminormed space,  $x_0 \in X$ , and  $J$  be  $X'$ 's normalized duality mapping. The following conditions are equivalent.*

1.  $X$  is locally uniformly smooth at  $x_0$ .
2.  $J$  is continuous at  $x_0$ .
3.  $\|\cdot\|$  is Frechet differentiable at  $x_0$ .

**Corollary 2.9.6** (Local Uniformly Smooth). *Let  $X$  be a seminormed space and  $J$  be  $X$ 's normalized duality mapping. The following conditions are equivalent.*

1.  $X$  is locally uniformly smooth.
2.  $J$  is continuous.
3.  $\|\cdot\|$  is Frechet differentiable.

**Proposition 2.9.7** (Uniformly Smooth). *Let  $X$  be a seminormed space and  $J$  be  $X$ 's normalized duality mapping. The following are equivalent.*

1.  $X$  is uniformly smooth.
2.  $J$  is uniformly continuous on bounded subsets of  $X$ .
3.  $\|\cdot\|$  is uniformly Frechet differentiable on bounded subsets of  $X$ .



# Chapter 3

## Smoothness And Convexity

### 3.1 Convexity And Smoothness Of A Space

**Proposition 3.1.1** (Smoothness and Strict Convexity). *Let  $X$  be a seminormed space and  $J$  be  $X$ 's normalized duality mapping.*

1. *If  $X^*$  is smooth, then  $X$  is strictly convex.*
2. *If  $X^*$  is strictly convex, then  $X$  is smooth.*
3. *If  $X$  is reflexive, then  $X$  is strictly convex if and only if  $X^*$  is smooth.*
4. *If  $X$  is reflexive, then  $X$  is smooth if and only if  $X^*$  is strictly convex.*
5. *If  $X^*$  is strictly convex, then  $J$  is single valued and norm to weak  $*$  continuous.*
6.  *$X$  is smooth and strictly convex if and only if  $J$  is single valued and strictly monotone.*

**Proposition 3.1.2** (Lindenstrauss Duality Formula).

**Proposition 3.1.3** (Very Smooth and Weak Local convexity).

**Proposition 3.1.4** (Local Uniform Smoothness and Local Uniform Convexity). *Let  $X$  be a seminormed space and  $J$  be  $X$ 's normalized duality mapping.*

**Proposition 3.1.5** (Uniform Smoothness and Convexity). *Let  $X$  be a (possibly complete) seminormed space and  $J$  be  $X$ 's normalized duality mapping.*

1.  *$X$  is uniformly convex if and only if  $X^*$  is uniformly smooth.*
2.  *$X$  is uniformly smooth if and only if  $X^*$  is uniformly convex.*
3.  *$X^*$  is uniformly convex if and only if  $J$  is single valued and uniformly continuous on bounded subsets of  $X$ .*

**Corollary 3.1.6.** *Uniformly Smooth Banach Spaces are Reflexive*

**Proposition 3.1.7** (Normalized Convergence). *Let  $X$  be a smooth locally uniformly convex seminormed space with normalized duality mapping  $J$ . If  $\{x_n\}_{n \in \mathbb{N}} \subset X$ ,  $x \in X$ ,  $j_x \in Jx$ , and  $j_n \in Jx_n$  for each  $n \in \mathbb{N}$ , then*

$$\langle x_n - x, j_n - j \rangle \rightarrow 0 \implies x_n \rightarrow x \quad (3.1)$$

## 3.2 Convexity, Smoothness, and High Order Duals

If you start with a poorly behaved Space, then things can only get worse.

**Theorem 3.2.1.** *If  $X$  is a seminormed space and  $X^*$  is very smooth, then  $X$  is reflexive.*

**Corollary 3.2.2.** *Let  $X$  be a seminormed space.*

1. *If  $X^*$ 's norm is Frechet differentiable, then  $X$  is reflexive.*
2. *If  $X^{**}$  is weakly locally uniformly convex, then  $X$  is reflexive.*
3. *If  $X^{***}$  is smooth, then  $X$  is reflexive.*
4. *If  $X^{****}$  is strictly convex, then  $X$  is reflexive.*

# Chapter 4

## Renorming Theory (Including Results about WCG Spaces)

### 4.1 Representations Of Reflexive Spaces

(Lindenstrauss' Theorem Goes Here)

### 4.2 Local Uniform Convexifiability Of Reflexive Spaces

-Trojanski's Theorem Goes Here

## Chapter 5

# Convexity And Fixed Point Theory

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