Real Numbers

• The least upper bound

- Let B be any subset of $\mathbf{R}$. B is *bounded above* if there is a $k \in \mathbf{R}$ such that $x \le k$ for all $x \in B$.
- A real number, $k \in \mathbf{R}$ is a unique *least upper bound* of B, i.e. $k = \text{LUB}(B)$, if
  (1) k is an upper bound of B.
  (2) For every $y < k$, y is not an upper bound of B.
- *LUB axiom* says that every nonempty subset of $\mathbf{R}$ that is bounded above has a least upper bound.
- LUB(B) may or may not belong to B. (Ex; $B = \{ y : y = -1/x, x \in \mathbf{R}+ \}$)
- Note that $A \subset B \Rightarrow \text{LUB}(A) \le \text{LUB}(B)$.

• The greatest lower bound

- Let B be any subset of $\mathbf{R}$. If B is *bounded below*, the greatest lower bound, GLB(B) is similarly defined.

• Supremum and infimum

- For any subset B of $\mathbf{R}$, the supremum is defined as

$$\sup B := \begin{cases} \text{LUB}(B), & B \ne \varnothing \text{ and bounded above} \\ +\infty, & B \ne \varnothing \text{ and not bounded above} \\ -\infty, & B = \varnothing \end{cases}.$$

- For any subset C of $\mathbf{R}$, the infimum is defined as

$$\inf C := \begin{cases} \text{GLB}(C), & C \ne \varnothing \text{ and bounded below} \\ -\infty, & C \ne \varnothing \text{ and not bounded below} \\ +\infty, & C = \varnothing \end{cases}.$$

• Bolzano-Weierstrass theorem

- If x_n is a bounded sequence of real numbers, i.e. $-\infty < a \le x_n \le b < +\infty$, then there is a converging subsequence, x_{n_k} whose limit lies in [a, b].

Vector Space

• Field

- A *field* is a set F on which two operations of addition and multiplication are defined with the **usual** properties.
- An *ordered field* is a field F with a relation $<$.
- Example: rational numbers, real numbers, complex numbers

• Vector space and subspace

- A nonempty set V is a *vector space* over a field F if the following properties hold:

  There is an operation called vector addition, + such that

  (1) Closure: $\forall \mathbf{u}, \mathbf{v} \in V, \mathbf{u}+\mathbf{v} \in V$

  (2) Commutative law: $\forall \mathbf{u}, \mathbf{v} \in V, \mathbf{u}+\mathbf{v} = \mathbf{v}+\mathbf{u}$

  (3) Associative law: $\forall \mathbf{u}, \mathbf{v}, \mathbf{w} \in V, (\mathbf{u}+\mathbf{v})+\mathbf{w} = \mathbf{u}+(\mathbf{v}+\mathbf{w})$

  (4) Additive identity: $\exists \mathbf{0} \in V \ni \forall \mathbf{u} \in V, \mathbf{u}+\mathbf{0} = \mathbf{u}$

  (5) Additive inverse: $\forall \mathbf{u} \in V, \exists(-\mathbf{u}) \ni \mathbf{u}+(-\mathbf{u}) = \mathbf{0}$ and $(-\mathbf{u})$ is unique.

  There is an operation called scalar multiplication such that

  (1) Closure: $\forall a \in F$ and $\forall \mathbf{u} \in V, a\mathbf{u} \in V$

  (2) Associative law: $\forall a, b \in F$ and $\forall \mathbf{u} \in V, a(b\mathbf{u}) = (ab)\mathbf{u}$

  (3) First distributive law: $\forall a \in F$ and $\forall \mathbf{u}, \mathbf{v} \in V, a(\mathbf{u}+\mathbf{v}) = a\mathbf{u}+a\mathbf{v}$

  (4) Second distributive law y: $\forall a, b \in F$ and $\forall \mathbf{u} \in V, (a+b)\mathbf{u} = a\mathbf{u}+b\mathbf{u}$

  (5) Multiplicative identity of F: $\forall \mathbf{u} \in V, 1\mathbf{u} = \mathbf{u}$.

- A subset W of a vector space V over F is a *subspace* of V iff $\forall a \in F$ and $\forall \mathbf{u}, \mathbf{v} \in W, a\mathbf{u}+\mathbf{v} \in W$. W itself is a vector space.

• Span, linear independence, and basis

- Let V be a vector space over a field F. Suppose $G \subset V$ and G may not be a subspace and may not be a finite set. The set of all linear combinations of elements of G is denoted by span G, i.e.,

$$\text{span } G := \left\{ \sum_{k=1}^{n} a_k \mathbf{v}_k : n \text{ is any positive integer}, \forall \mathbf{v}_k \in G, \text{ and } \forall a_k \in F \right\}.$$

  Note that

  (1) $G \subset$ span G.

  (2) span G is a subspace of V.

  (3) If a subspace W contains G, then W contains span G.

- For an arbitrary subset G of V, G is *linearly independent* if

$$\forall \mathbf{v}_k \in G,\ \sum_{k=1}^{n} a_k \mathbf{v}_k = \mathbf{0} \text{ implies } a_1 = a_2 = \cdots = a_n = 0 .$$

  If G is not linearly independent, G is *linearly dependent*. Note that if $\mathbf{0} \in G$, G is linearly dependent.

- If $\{\mathbf{v}_k\}_{k=1}^{n}$ are linaerly independent, no vector $\mathbf{v}_k$ can be expressed as a linear combination of other vectors in the set.
- Let W be a subspace of V. If there exists a finite subset $G \subset W$, such that span $G = W$, then W is *finite-dimensional*. If span $G = W$ and G is linearly independent, G is a *basis* for W.
- If $G = \{\mathbf{v}_k\}_{k=1}^{n}$ is a basis for W, $\mathbf{x} = \sum_{k=1}^{n} a_k \mathbf{v}_k \, \forall \mathbf{x} \in W$ and $\{a_k\}_{k=1}^{n}$ is unique.
- If W is finite-dimensional, then any basis of W contains the same number, n of linearly independent vectors. We say that n is the *dimension* of W (i.e. dim$W = n$). If dim$W = n$ and $\{\mathbf{t}_1, \mathbf{t}_2, \cdots, \mathbf{t}_n\} \subset W$ are linearly independent, then span $\{\mathbf{t}_1, \mathbf{t}_2, \cdots, \mathbf{t}_n\} = W$.

Mapping

• Function and mapping

- A *function* is a triple (X, Y, f), also denoted by f: $X \to Y$, where X and Y are specified sets of inputs and outputs, respectively.
- f is a rule or *mapping* that associates to each $x \in X$, a *unique* element $f(x) \in Y$.
- The set X is the *domain* of f and the set Y is the *co-domain* of f.
- The *range* of f is the set $\{ f(x) : x \in X \}$.
- Two functions (X_1, Y_1, f_1) and (X_2, Y_2, f_2) are equal iff

  $X_1 = X_2, Y_1 = Y_2$, and $f_1(x) = f_2(x) \forall x \in X_1 = X_2$.

• Vector space of mappings

Let V be a vector space over F and U be an arbitrary set.

- x: $U \to V$ is a *mapping* if there is a rule that assigns to each $u \in U$, an element $x(u) \in V$.
- We let X be the set of all mappings from U into V. Two mappings, x and y in X are equal iff $x(u) = y(u) \forall u \in U$.
- X is itself a vector space with the following definitions

  (1) Addition of mappings is defined as

  $(x + y)(u) := x(u) + y(u) \forall x, y \in X$ and $\forall u \in U$,

  (2) Additive identity, $z(u) := \mathbf{0}\ \forall u \in U$,

  (3) Additive inverse, $(-x)(u) := -x(u)\ \forall u \in U$,

  (4) Scalar multiplication, $(ax)(u) := a \cdot x(u)\ \forall u \in U$ and $a \in F$.

• Linear functional

- Let V be a vector spave over F. A mapping β: $V \to F$ is called a linear functional if

  $\beta(a\mathbf{v}_1 + \mathbf{v}_2) = a\beta(\mathbf{v}_1) + \beta(\mathbf{v}_2),\ \forall a \in F, \forall \mathbf{v}_1, \mathbf{v}_2 \in V$.

- Given a set of vectors, $\{\mathbf{t}_1, \mathbf{t}_2, \cdots, \mathbf{t}_n\} \subset V$, if there exists a set of linear functionals, $\{\beta_1, \beta_2, \cdots, \beta_n\}$ such that $\beta_j(\mathbf{t}_i) = \delta_{ij} = \begin{cases} 1, & \text{if } i = j \\ 0, & \text{if } i \neq j \end{cases}$, then $\{\mathbf{t}_1, \mathbf{t}_2, \cdots, \mathbf{t}_n\}$ is linearly independent.

Metric Space

• Metric space

- Let X be a nonempty set and define a mapping ρ: $X \times X \to [0, \infty)$ with the follwoing properties:
  (1) $\rho(x, y) \geq 0$ and $\rho(x, y) = 0$ iff $x = y$
  (2) $\rho(x, y) = \rho(y, x)$
  (3) $\rho(x, z) \leq \rho(x, y) + \rho(y, z)$.
  Then, ρ is called a *metric*. The pair (X, ρ) or X is a *metric space*.
- We define a ball as $B(x,r) = B_r(x) := \{y \in X : \rho(x, y) < r\}$, for some $x \in X$.

• Convergence

- A sequence $x_n \in X$ *converges* to $x \in X$ if $\forall \varepsilon > 0$, $\rho(x_n, x) < \varepsilon$ for all sufficiently large n (i.e., there exists an integer N such that the condition holds for all $n > N$). We denote this as $x_n \to x$ or $\lim_{n\to\infty} x_n = x$.
- A sequence $x_n \in X$ converges to $x \in X$ if $x_n \in B(x, \varepsilon)$, $\forall \varepsilon > 0$ for all sufficiently large n.
- A set E in a metric space is *closed* iff every converging sequence of points in E converges to a point in E.
- (*Approximation*) If $x \in \overline{E}$, there is a sequence $x_n \in E$ and $x_n \to x$. In orther words, if $x \in \overline{E}$, then there is a point $y \in E$ such that $\rho(x, y) < \varepsilon$ for any $\varepsilon > 0$.

• Subsequence

- Let $n_1, n_2, \cdots$ be integers such that $n_k \to \infty$ as $k \to \infty$.
- If $x_n \in X$ is a sequence, x_{n_k} is a subsequence of x_n.

• Sequential compactness

- A subset D is *sequentially compact* if for every sequence $x_n \in D$, there is a converging subsequence x_{n_k} whose limit lies in *D*.

- From Bolzano-Weierstrass, [*a*, *b*] with $-\infty < a < b < \infty$ is sequentially compact.
- Sequentially compact subset of a metric space must be closed.

• Cauchy sequence

- A sequence x_n in a metric space is ***Cauchy*** if $\rho(x_n, x_m) < \varepsilon, \forall \varepsilon > 0$ and for all sufficiently large *n* and *m*.
- In a Cauchy sequence, all the points in the tail of the sequence are close together.
- Every converging sequence is Cauchy. The converse is not true.
- *A Cauchy sequence is bounded*.

• Complete space

- If every Cauchy sequence of a metric space converges to a point in the space, the space is *complete*.
- If x_n is a Cuachy sequence in a metric space, and if x_{n_k} is a converging subsequence of x_n, then x_n converges to the same limit as x_{n_k}.
- The real numbers $\mathbb{R}$ with the metric $\rho(x, y) = |x - y|$ is a complete metric space.
- The space $\mathbb{R}^d$ is complete under the usual Euclidian distance, i.e.

$$\rho(\mathbf{x}, \mathbf{y}) = \sqrt{\sum_{i=1}^{d} \left| x^{(i)} - y^{(i)} \right|^2} .$$

- Any closed and bounded subset of $\mathbb{R}^d$ is sequentially compact.
- The spaces of complex numbers $\mathbb{C}$ and $\mathbb{C}^d$ are complete. Any closed and bounded subset of $\mathbb{C}^d$ is sequentially compact.

• Continuity

- Let (*X*, ρ) and (*Y*, *m*) be metric spaces. Let *f*: $X \to Y$ be a function.
- (Continuity of a point) A function *f* is *continuous at a point* $\mathbf{x}_0$ if

$$\forall \varepsilon > 0, \exists \delta = \delta(\mathbf{x}_0, \varepsilon) \ni \forall \mathbf{x} \in X, \rho(\mathbf{x}, \mathbf{x}_0) < \delta \Leftrightarrow m(f(\mathbf{x}), f(\mathbf{x}_0)) < \varepsilon, \text{ or}$$

$$\forall \varepsilon > 0, \exists \delta = \delta(\mathbf{x}_0, \varepsilon) \ni \forall \mathbf{x} \in X, \mathbf{x} \in B_\rho(\mathbf{x}_0, \delta) \Leftrightarrow f(\mathbf{x}) \in B_m(f(\mathbf{x}_0), \varepsilon).$$

- (Continuity on a set) A function *f* is *continuous on a subset* $D \subset X$ if *f* is continuous at each point $\mathbf{x}_0 \in D$.

- A function *f* is continuous at a point $\mathbf{x}_0 \Leftrightarrow$ for every sequence $\mathbf{x}_n \to \mathbf{x}_0, f(\mathbf{x}_n) \to f(\mathbf{x}_0)$.

  In order words, *f* is *convergence preserving* iff *f* is continuous.
- (Uniform continuity) A function *f* is *uniformly continuous on a subset* $D \subset X$ if $\forall \varepsilon > 0, \exists \delta = \delta(\varepsilon) > 0 \ni \forall \mathbf{x}, \mathbf{x}_0 \in D, \rho(\mathbf{x}, \mathbf{x}_0) < \delta \Leftrightarrow m(f(\mathbf{x}), f(\mathbf{x}_0)) < \varepsilon$.

• Compact sets

Topology

Let X be a metric space with a metric ρ.

• Ball

- A <u>ball</u> is defined as $B(x,r) = B_r(x) := \{y \in X : \rho(x,y) < r\}, x \in X$.

• Open set

- A set $U \subset X$ is <u>open</u> if $\forall x \in U, \exists \varepsilon > 0$ with $B(x,\varepsilon) \subset U$.
- A set $U \subset X$ is <u>not open</u> if $\forall \varepsilon > 0, \exists x \in U$ with $B(x,\varepsilon) \not\subset U$.
- The whole space X and $\varnothing$ are both open.
- The set $B(x, r)$ is open, i.e. it is an <u>open ball</u>.

• Closed set

- A set $F \subset X$ is <u>closed</u> if its complement $F^c := \{x \in X : x \notin F\}$ is open.
- X, $\varnothing$, and $B(x,r)^c = \{y \in X : \rho(x,y) \geq r\}$ are all closed sets.
- Every (possibly infinite) union of open sets is an open set.
- Every intersection of finite number of open sets is an open set.

• Topological space

- Let X be a nonempty set and $\Im$ be a collection of subsets of X. $\Im$ is called a <u>topology</u> for X if
  - (1) $\varnothing \in \Im$ and $X \in \Im$
  - (2) If $U_\alpha \in \Im$, then $\cup_\alpha U_\alpha \in \Im$
  - (3) If $U_1 \in \Im$ and $U_2 \in \Im$, then $U_1 \cap U_2 \in \Im$.
- The pair $(X, \Im)$ or X is called a <u>topological space</u>.
- The elements of $\Im$ are open sets.
- A set F is closed if $F^c \in \Im$.

• Properties of topological space

- A set U is open $\Leftrightarrow$ for every $x \in U$, there is an open set containing x, say O_x, with $O_x \in U$.

- The *closure* of a set E is $\overline{E} := \bigcap_{\substack{C:E\subset C \text{ and} \\ C \text{ is closed}}} C$ and $E \subset \overline{E}$. $\overline{E}$ is the smallest closed set containing E.
- A set E is closed $\Leftrightarrow$ $E = \overline{E}$.
- A point x is an *accumulation point* (or *cluster point* or *limit point*) of a set E if for every open set containing x, say O_x, there is a point $y \neq x$ with $y \in O_x \cap E$. We let E' denote the set of accumulation points of E. The point x may or may not be in E.
- E is closed $\Leftrightarrow$ $E' \subset E$.
- $\overline{E} = E \cup E'$
- The *boundary* of E is ∂E and $\partial E := \overline{E} \cap \overline{E^c}$.
- The *interior* of E is E^o and $E^o := \left(\overline{E^c}\right)^c$. E^o is an open set with $E^o \subset E$ and $\overline{E} \mid E^o = \overline{E} \cap \overline{E^c} = \partial E$.

Normed Vector Space

Let F denote $\mathbb{R}$ or $\mathbb{C}$ and V be a vector space over F.

• Norm

- $\|\bullet\|$ is a *norm* if

(1) $0 \le \|\mathbf{v}\| < \infty, \forall \mathbf{v} \in V$ and $\|\mathbf{v}\| = 0$ iff $\mathbf{v} = \mathbf{0}$,

(2) $\|a\mathbf{v}\| = |a|\,\|\mathbf{v}\|, \forall \mathbf{v} \in V, \forall a \in F$, and

(3) $\|\mathbf{v} + \mathbf{w}\| \le \|\mathbf{v}\| + \|\mathbf{w}\|, \forall \mathbf{v}, \mathbf{w} \in V$ (triangular inequality).

- Every normed vector space is a metric space with $\rho(\mathbf{v}, \mathbf{w}) = \|\mathbf{v} - \mathbf{w}\|$.

- A sequence $\mathbf{v}_n$ converges to $\mathbf{v}$ (i.e., $\mathbf{v}_n \to \mathbf{v}$) iff $\|\mathbf{v}_n - \mathbf{v}\| \to 0$.

- $\big|\|\mathbf{v}\| - \|\mathbf{w}\|\big| \le \|\mathbf{v} - \mathbf{w}\| \le \|\mathbf{v}\| + \|\mathbf{w}\|$.

• Banach space

- A complete normed vector space is called *Banach space*.

• Examples of norm

- The *p-norm* on $V = \mathbb{R}^n$ or $\mathbb{C}^n$. Let $\mathbf{v} = (v_1, v_2, \cdots, v_n)$, then

$$\|\mathbf{v}\|_p := \begin{cases} \left(\sum_{k=1}^{n} |v_k|^p \right)^{1/p}, & 1 \le p < \infty \\ \max_{1 \le k \le n} |v_k|, & p = \infty \end{cases}.$$

- When $p = 2$, we call it *Euclidean norm*.
- The *uniform norm*. Let U be any set and let $F = \mathbb{R}$ or $\mathbb{C}$. Let X denote the vector space of mappings from U into F. Let X_b denote the set of bounded mappings, i.e. $X_b := \left\{ x \in X : \sup_{u \in U} |x(u)| < \infty \right\}$. Note that if U is a finite set, then $X = X_b$. The uniform

norm of $x \in X_b$ is $\|x\| := \sup_{u \in U} |x(u)|$. X_b with the uniform norm is a Banach space.

• The ℓ^p spaces

- Let $U = \{1, 2, 3, \ldots\}$. For $k \in U$, we write x_k instead of $x(k)$. Then, X denotes the set of all real- or complex-valued sequences. For $1 \le p < \infty$, let

$$\ell^p := \left\{ x \in X : \sum_{k=1}^{\infty} |x_k|^p < \infty \right\},$$

and set

$$\ell^\infty := \left\{ x \in X : \sup_k |x_k| < \infty \right\}.$$

- ℓ^p spaces is equipped with the corresponding p-norm.

• Projections

- Let V be a normed vector space and G be a subset of V. If there exists a vector $\hat{\mathbf{v}} \in G$ such that $\|\mathbf{v} - \hat{\mathbf{v}}\| \le \|\mathbf{v} - \mathbf{w}\|, \forall \mathbf{w} \in G, \mathbf{v} \in V$, then $\hat{\mathbf{v}}$ is a *projection* of $\mathbf{v}$ onto G.
- A projection may not exist (for example, if G is open) and may not be unique (for example, if G is not convex).
- Projections exist when G is a closed ball in an arbitrary, possibly infinite-dimensional, normed vector space.

• Finite-dimensional subspaces

- Let W be a finite-dimensional normed vector space or a finite-dimensional subspace of a normed vector space. W may be a subspace of a larger infinite-dimensional space V. Then,
  (1) W is complete, i.e., W is a Banach space.
  (2) Every closed and bounded subset G of W is (sequentially) compact.

• Projections onto closed finite-dimensional subsets

- If G is an nonempty closed and bounded subset of a finite-dimensional subspace W of a larger normed vector space V, then the projection of every $\mathbf{v} \in V$ onto G always exists.
- If W is a finite-dimensional subspace of a larger normed vector space V, then the projection of any $\mathbf{v} \in V$ onto W always exists.

Inner Product Spaces

Let F denote $\mathbb{R}$ or $\mathbb{C}$ and V be a vector space over F. For $a \in \mathbb{C}$, $\bar{a}$ denotes the complex conjugate of a.

• Inner product space (pre-Hilbert space)

- $\langle \cdot, \cdot \rangle$ is an *inner product* on V if the following properties hold:

  (1) $0 \le \langle \mathbf{v}, \mathbf{v} \rangle < \infty, \forall \mathbf{v} \in V$ and $\langle \mathbf{v}, \mathbf{v} \rangle = 0$ iff $\mathbf{v} = \mathbf{0}$,

  (2) $\langle \mathbf{v}, \mathbf{w} \rangle = \overline{\langle \mathbf{w}, \mathbf{v} \rangle}, \forall \mathbf{v}, \mathbf{w} \in V$

  (3) $\langle a\mathbf{u} + b\mathbf{v}, \mathbf{w} \rangle = a\langle \mathbf{u}, \mathbf{w} \rangle + b\langle \mathbf{v}, \mathbf{w} \rangle, \forall a, b \in F, \forall \mathbf{u}, \mathbf{v}, \mathbf{w} \in V$.

- $\langle \mathbf{v}, \mathbf{w} \rangle$ is in general complex number but $\langle \mathbf{v}, \mathbf{v} \rangle$ is always real.

- $\langle \mathbf{w}, a\mathbf{u} + b\mathbf{v} \rangle = \bar{a}\langle \mathbf{w}, \mathbf{u} \rangle + \bar{b}\langle \mathbf{w}, \mathbf{v} \rangle$

- $\langle \mathbf{v}, \mathbf{0} \rangle = 0$. If $\langle \mathbf{v}, \mathbf{w} \rangle = 0, \forall \mathbf{w} \in V$, then $\mathbf{v} = \mathbf{0}$.

• Hilbert space

- A complete inner product space is *Hilbert space*.

• Norm on an inner product space

- Given any inner product, $\|\mathbf{v}\| := \langle \mathbf{v}, \mathbf{v} \rangle^{1/2}$ defines a norm on V.

• Parallogram equality

- $\|\mathbf{u} + \mathbf{v}\|^2 + \|\mathbf{u} - \mathbf{v}\|^2 = 2\left(\|\mathbf{u}\|^2 + \|\mathbf{v}\|^2\right)$

• Cauchy-Schwarz inequality

- $|\langle \mathbf{u}, \mathbf{v} \rangle| \le \|\mathbf{u}\| \, \|\mathbf{v}\|$

- If $\mathbf{v} \neq \mathbf{0}$, then equality holds iff $\mathbf{u} = a\mathbf{v}$ for some $a \in F$.

- Angle between $\mathbf{u}$ and $\mathbf{v}$, $\theta = \angle(\mathbf{u},\mathbf{v}) = \cos^{-1}\dfrac{\langle \mathbf{u},\mathbf{v}\rangle}{\|\mathbf{u}\|\,\|\mathbf{v}\|}$ and $\langle \mathbf{u},\mathbf{v}\rangle = \|\mathbf{u}\|\,\|\mathbf{v}\|\cos\theta$

(a) $\theta = 0 \;\Rightarrow$ $\mathbf{u}$ and $\mathbf{v}$ are aligned $\Rightarrow \langle \mathbf{u},\mathbf{v}\rangle = \|\mathbf{u}\|\,\|\mathbf{v}\|$, $\mathbf{v} = \alpha\mathbf{u}$ for some $\alpha \geq 0$

(b) $\theta = \pi \;\Rightarrow$ $\mathbf{u}$ and $\mathbf{v}$ are opposed $\Rightarrow \langle \mathbf{u},\mathbf{v}\rangle = -\|\mathbf{u}\|\,\|\mathbf{v}\|$, $\mathbf{v} = \alpha\mathbf{u}$ for some $\alpha < 0$

(c) $\theta = \pm\pi/2 \;\Rightarrow$ $\mathbf{u}$ and $\mathbf{v}$ are orthogonal $\Rightarrow \langle \mathbf{u},\mathbf{v}\rangle = 0$, $\mathbf{v} \perp \mathbf{u}$

• Orthogonality

- A collection of vectors G is (mutually) *orthogonal* if $\langle \mathbf{u},\mathbf{v}\rangle = 0, \forall \mathbf{u},\mathbf{v} \in G$ with $\mathbf{u} \neq \mathbf{v}$.

- If, in addition, $\|\mathbf{u}\| = 1, \forall \mathbf{u} \in G$, then they are *orthonormal*.

- Orthonormal set of vectors are *linearly independent*. The converse may not be true.

• Some identities

- (*Parallelogram law*) In any inner product space, $\|\mathbf{u}+\mathbf{v}\|^2 + \|\mathbf{u}-\mathbf{v}\|^2 = 2\left(\|\mathbf{u}\|^2 + \|\mathbf{v}\|^2\right)$.

- (*Polarization identity*) In a complex inner product space,

$$4\langle \mathbf{u},\mathbf{v}\rangle = \|\mathbf{u}+\mathbf{v}\|^2 - \|\mathbf{u}-\mathbf{v}\|^2 + j\|\mathbf{u}+j\mathbf{v}\|^2 - j\|\mathbf{u}-j\mathbf{v}\|^2.$$

• The orthogonality principle (OP)

- Let V be an inner product space. Let W be a subspace of V. Fix any $\mathbf{v} \in V$. Then, a vector $\tilde{\mathbf{v}} \in W$ has the property that

$$\|\mathbf{v}-\tilde{\mathbf{v}}\| \leq \|\mathbf{v}-\mathbf{w}\|, \forall \mathbf{w} \in W \quad \text{iff} \quad \langle \mathbf{v}-\tilde{\mathbf{v}},\mathbf{w}\rangle = 0, \forall \mathbf{w} \in W.$$

Furthermore, there is at most one element $\tilde{\mathbf{v}} \in W$ satisfying the condition.

- If $\tilde{\mathbf{v}} \in W$ exists, it is unique. But it may not exist.
- If $\tilde{\mathbf{v}} \in W$ exists, then $\tilde{\mathbf{v}}$ is the *orthogonal projection* of $\mathbf{v}$ onto W.
- Note that

(1) $\|\mathbf{v}\|^2 = \|\mathbf{v}-\tilde{\mathbf{v}}\|^2 + \|\tilde{\mathbf{v}}\|^2$

(2) $\|\mathbf{v}-\tilde{\mathbf{v}}\|^2 = \|\mathbf{v}\|^2 - \|\tilde{\mathbf{v}}\|^2$

(3) $\|\mathbf{v}\| \geq \|\tilde{\mathbf{v}}\|$

• Projections onto finite-dimensional spaces

- Let *V* be an inner product space. Let *W* be a finite-dimensional subspace of *V*. Then,

$\exists\{\mathbf{w}_1, \mathbf{w}_2, \cdots, \mathbf{w}_n\} \ni \text{span}\{\mathbf{w}_1, \mathbf{w}_2, \cdots, \mathbf{w}_n\} = W$ and OP is as follows.

$$\|\mathbf{v}-\tilde{\mathbf{v}}\| \leq \|\mathbf{v}-\mathbf{w}\|, \forall \mathbf{w} \in W \quad \text{iff} \quad \langle \mathbf{v}-\tilde{\mathbf{v}}, \mathbf{w}_i \rangle = 0, i = 1, 2, \cdots, n.$$

- If $\tilde{\mathbf{v}}$ exists, $\tilde{\mathbf{v}} = \sum_{j=1}^{n} c_j \mathbf{w}_j$ (i.e. $\tilde{\mathbf{v}} \in W$).

- Note that

(1) $\langle \mathbf{v}, \mathbf{w}_i \rangle = \sum_{j=1}^{n} \langle \mathbf{w}_j, \mathbf{w}_i \rangle c_j, i = 1, 2, \cdots, n$, or equivalently

(2) $\mathbf{A}\mathbf{c} = \mathbf{b}$ where $A_{ij} := \langle \mathbf{w}_j, \mathbf{w}_i \rangle, \mathbf{b} := [\langle \mathbf{v}, \mathbf{w}_1 \rangle, \cdots, \langle \mathbf{v}, \mathbf{w}_n \rangle]^T, \mathbf{c} := [c_1, \cdots, c_n]^T$.

And, $\mathbf{A}$ is nonsingular if $\{\mathbf{w}_1, \mathbf{w}_2, \cdots, \mathbf{w}_n\}$ is linearly independent.

- If $\{\mathbf{w}_1, \mathbf{w}_2, \cdots, \mathbf{w}_n\}$ is orthonormal, then $\mathbf{A} = \mathbf{I}$ and $c_i = \langle \mathbf{v}, \mathbf{w}_i \rangle$, and thus

$$\tilde{\mathbf{v}} = \sum_{j=1}^{n} \langle \mathbf{v}, \mathbf{w}_j \rangle \mathbf{w}_j \quad \text{and} \quad \|\tilde{\mathbf{v}}\|^2 = \sum_{j=1}^{n} |\langle \mathbf{v}, \mathbf{w}_j \rangle|^2$$

- Bessel's inequality for an orthonomal basis is $\sum_{j=1}^{n} |\langle \mathbf{v}, \mathbf{w}_j \rangle|^2 \leq \|\mathbf{v}\|^2 < \infty$.

- Since $\mathbf{v} = \tilde{\mathbf{v}}$ iff $\mathbf{v} \in W$, $\|\mathbf{v}\|^2 = \sum_{j=1}^{n} |\langle \mathbf{v}, \mathbf{w}_j \rangle|^2, \forall \mathbf{v} \in W$.

• Orthogonal complement

- For any subset *W* of an inner product space *V*, we define the ***orthogonal complement*** of *W* as

$$W^{\perp} := \{\mathbf{v} \in V : \langle \mathbf{w}, \mathbf{v} \rangle = 0, \forall \mathbf{w} \in W\}$$

- $W^{\perp}$ is a subspace of *V*.
- $W^{\perp}$ is a closed set.

- $W \subset \left(W^{\perp}\right)^{\perp}$. If W is a closed subspace of a Hilbert space, $W = \left(W^{\perp}\right)^{\perp}$.

- If W is an arbitrary subset of a Hilbert space, $\left(W^{\perp}\right)^{\perp} = \overline{\text{span } W}$.

• Convex set

- Let X be an arbitrary vector space over ℝ or ℂ. A subset $C \subset X$ is <u>*convex*</u> if
  $\lambda\mathbf{x} + (1-\lambda)\mathbf{y} \in C, \forall \mathbf{x}, \mathbf{y} \in C, \forall \lambda \in [0, 1]$.
- In a normed vector space, open balls are convex.
- A subspace is a convex set.

• Projection theorem

- Let C be a closed, convex subset of a Hilbert space X. Then, for every $\mathbf{x} \in X$, there exists the unique $\tilde{\mathbf{x}} \in C$ such that $\|\mathbf{x} - \tilde{\mathbf{x}}\| \le \|\mathbf{x} - \mathbf{y}\|, \forall \mathbf{y} \in C$.
- If M is a closed subspace of a Hilbert space X, then $\mathbf{x} = \tilde{\mathbf{x}} + (\mathbf{x} - \tilde{\mathbf{x}}), \forall \mathbf{x} \in X$ where $\tilde{\mathbf{x}} \in M$ and $\mathbf{x} - \tilde{\mathbf{x}} \in M^{\perp}$.

• Sums and direct sums of subspaces

- If U and W are two subspaces of a vector space V, their sum is

$$U + W := \left\{\mathbf{u} + \mathbf{w} : \mathbf{u} \in U \text{ and } \mathbf{w} \in W\right\}.$$

- If every element in $U + W$ has a unique representation, their sum becomes the direct sum as $U \oplus W$.
- $U + W = U \oplus W$ iff $U \cap W = \left\{\mathbf{0}\right\}$.
- If M is a closed subspace of a Hilber space X, then $X = M \oplus M^{\perp}$.