LECTURE 11. INNER PRODUCT SPACES

Please treat the proof of every proposition in this lecture as an exercise.

1. Definition of an Inner Product

Definition 1.1. Let V be a vector space over $\mathbb{F} = \mathbb{R}$ or $\mathbb{F} = \mathbb{C}$. An inner product on V is a map

$$\langle \cdot, \cdot \rangle : V \times V \to \mathbb{F} \tag{1.1}$$

with the following properties:

(1) Conjugate symmetry (for $\mathbb{F} = \mathbb{C}$)

$$\langle y, x \rangle = \overline{\langle x, y \rangle}, \quad \forall x, y \in V; \tag{1.2}$$

Symmetry (for $\mathbb{F} = \mathbb{R}$)

$$\langle y, x \rangle = \langle x, y \rangle, \quad \forall x, y \in V; \tag{1.3}$$

(2) (Linearity in the first entry)

$$\langle \lambda x + \mu y, z \rangle = \lambda \langle x, z \rangle + \mu \langle y, z \rangle, \quad \forall x, y, z \in V, \forall \lambda, \mu \in \mathbb{F}; \tag{1.4}$$

(3) (Positive definiteness) For all $x \in V$,

$$\langle x, x \rangle \geq 0 \quad \text{and } (\langle x, x \rangle = 0) \iff (x = 0). \tag{1.5}$$

A real (or complex) vector space V, together with an inner product, is called a real (or complex) inner product space.

It follows from the first property that $\langle x, x \rangle \in \mathbb{R}$, $\forall x \in V$. Hence, the inequality in the third property makes sense even when $\mathbb{F} = \mathbb{C}$.

Exercise 1.2. Let V be a complex inner product space. Does the equality

$$\langle x, \lambda y + \mu z \rangle = \overline{\lambda} \langle x, y \rangle + \overline{\mu} \langle x, z \rangle \tag{1.6}$$

hold $\forall x, y, z \in V, \forall \lambda, \mu \in \mathbb{C}$?

Example 1.3. Define an inner product on $\mathbb{C}^n$ by

$$\left\langle \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}, \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} \right\rangle := \sum_{j=1}^{n} x_j \overline{y_j}. \tag{1.7}$$

Proposition 1.4 (Cauchy-Schwarz inequality)**.** *Suppose that V is an inner product space. Then*

$$|\langle x, y \rangle|^2 \leq \langle x, x \rangle \langle y, y \rangle, \quad \forall x, y \in V. \tag{1.8}$$

One can consider the expression $\langle x - \lambda y, x - \lambda y \rangle$ to show this result.

Definition 1.5. Suppose V is a vector space over $\mathbb{F} = \mathbb{R}$ or $\mathbb{F} = \mathbb{C}$. Then a function $|\cdot| : V \to \mathbb{R}$ is called a norm if the following conditions hold:

(1) $|x| \geq 0$;

(2)

$$((|x| = 0) \iff (x = 0)); \tag{1.9}$$

(3)

$$|\lambda x| = |\lambda| \cdot |x|, \quad \forall x \in V, \forall \lambda \in \mathbb{F}; \tag{1.10}$$

(4) (The triangle inequality)

$$|x+y| \le |x| + |y|, \quad \forall x, y \in V. \tag{1.11}$$

A vector space with a norm is called a normed space.

Note that in the third property, we use the same symbol to denote both the absolute value of a scalar and the norm of a vector.

Proposition 1.6. *For an inner product space V the formula*

$$|x| := \sqrt{\langle x, x\rangle} \tag{1.12}$$

defines a norm on V.

Exercise 1.7. Show that in every inner product space V the parallelogram law

$$|x+y|^2 + |x-y|^2 = 2(|x|^2 + |y|^2), \quad \forall x, y \in V \tag{1.13}$$

holds.

Proposition 1.8 (The polarization identities)**.** *a) If V is an inner product space over $\mathbb{R}$, then the following identity holds*

$$\langle x, y\rangle = \frac{1}{4}\left(|x+y|^2 - |x-y|^2\right), \quad \forall x, y \in V. \tag{1.14}$$

b) If V is an inner product space over $\mathbb{C}$, then

$$\langle x, y\rangle = \frac{1}{4}\left(|x+y|^2 - |x-y|^2 + i|x+iy|^2 - i|x-iy|^2\right), \quad \forall x, y \in V. \tag{1.15}$$

Definition 1.9. Let M be a set. A map $d : M \times M \to \mathbb{R}$ is called a metric or a distance if the following conditions hold:
1) $d(x, y) \ge 0$ and $((d(x, y) = 0) \iff (x = y))$;
2) $d(y, x) = d(x, y)$, $\forall x, y \in M$;
3) (The triangle inequality) $d(x, z) \le d(x, y) + d(y, z)$, $\forall x, y, z \in M$.
A set M with a distance is called a metric space.

Exercise 1.10. Show that every normed space is a metric space with the distance defined by

$$d(x, y) := |x - y|. \tag{1.16}$$

2. Orthogonality

Definition 2.1. Suppose that V is an inner product space. Two vectors x and y are said to be orthogonal if $\langle x, y\rangle = 0$. For an arbitrary subset S of V, we define its orthogonal complement by

$$S^{\perp} := \{x \in V \mid \forall y \in S \, \langle x, y\rangle = 0\}. \tag{2.1}$$

A subset M of V is called orthogonal if $\forall x, y \in M$ with $x \ne y$, we have that $\langle x, y\rangle = 0$. A subset M of V is called orthonormal if it is orthogonal and $|x| = 1$, $\forall x \in M$.

Proposition 2.2 (Pythagorean theorem)**.** *Let $\{x_1, x_2, \ldots, x_k\}$ be an orthogonal set in an inner product space V. Then the following equality holds:*

$$\left|\sum_{j=1}^{k} x_j\right|^2 = \sum_{j=1}^{k} |x_j|^2. \tag{2.2}$$

Exercise 2.3. Is every orthogonal set of nonzero vectors linearly independent?

Proposition 2.4. *Suppose that $\{v_1, \dots, v_k\}$ is an orthogonal set of nonzero vectors in an inner product space V, $w \notin \operatorname{span}\{v_1, \dots, v_k\}$. Then there exists a vector v_{k+1}, unique up to multiplication by a scalar, satisfying the following properties:*

(1) *The set $\{v_1, \dots, v_k, v_{k+1}\}$ is an orthogonal set of nonzero vectors;*
(2)

$$v_{k+1} \in \operatorname{span}\{v_1, \dots, v_k, w\}. \tag{2.3}$$

This vector v_{k+1} can be expressed as

$$v_{k+1} := w - \sum_{j=1}^{k} \frac{\langle w, v_j \rangle}{\langle v_j, v_j \rangle} v_j. \tag{2.4}$$

Proposition 2.5 (Gram-Schmidt orthogonalization process)**.** *Suppose that $\{w_1, \dots, w_m\}$ is a linearly independent set in an inner product space V. Define the set $\{v_1, \dots, v_m\}$ by*

$$v_1 := w_1, \quad v_{k+1} := w_{k+1} - \sum_{j=1}^{k} \frac{\langle w_{k+1}, v_j \rangle}{\langle v_j, v_j \rangle} v_j, \quad k = 1, \dots, m-1. \tag{2.5}$$

Then the set $\{v_1, \dots, v_m\}$ is an orthogonal set of nonzero vectors and

$$\operatorname{span}\{v_1, \dots, v_k\} = \operatorname{span}\{w_1, \dots, w_k\}, \quad \forall 1 \le k \le m. \tag{2.6}$$

Proposition 2.6. *In a finite-dimensional inner product space, every orthogonal set is a subset of an orthogonal basis. In a finite-dimensional inner product space, every orthonormal set is a subset of an orthonormal basis. Every finite-dimensional inner product space possesses an orthonormal basis.*

3. Orthogonal Projection

Proposition 3.1. *Suppose V is a finite-dimensional inner product space and U is a subspace. Then*

$$V = U \oplus U^{\perp} \tag{3.1}$$

and

$$(U^{\perp})^{\perp} = U. \tag{3.2}$$

Proposition 3.2. *Suppose that $\{v_1, \dots, v_n\}$ is an orthonormal basis in an inner product space V. Then for every vector $x \in V$, the following decomposition holds*

$$x = \sum_{j=1}^{n} \langle x, v_j \rangle v_j. \tag{3.3}$$

Definition 3.3. Suppose that $S = \{v_1, \dots, v_k\}$ is an orthonormal set of an inner product space V and x is an arbitrary vector in V. The vector

$$\widehat{x} := \sum_{j=1}^{k} \langle x, v_j \rangle v_j \tag{3.4}$$

is called the orthogonal projection of the vector x onto $\operatorname{span}(S)$, or the Fourier expansion of x with respect to S. Every coefficient $\langle x, v_j \rangle$ is called a Fourier coefficient.

Proposition 3.4. *Suppose that $S = \{v_1, \dots, v_k\}$ is an orthonormal set of an inner product space V, $U = \operatorname{span}(S)$ and x is an arbitrary vector in V. Then*

(1) *$\widehat{x}$ is the unique vector in U such that $x - \widehat{x}$ is orthogonal to U;*
(2)
$$\forall u \in U \quad |x - \widehat{x}| \leq |x - u|; \tag{3.5}$$
(3) *(Bessel's inequality)*
$$\forall x \in V \quad |\widehat{x}| \leq |x|; \tag{3.6}$$
(4)
$$(|x| = |\widehat{x}|) \iff (x \in U). \tag{3.7}$$

Proposition 3.5. *Suppose that $S = \{v_1, \dots, v_k\}$ is an orthonormal set of an inner product space V and $U = \operatorname{span}(S)$, then the following four conditions are equivalent:*

(1) *S is an orthonormal basis of V;*
(2) *$\forall x \in V$ we have that $\widehat{x} = x$;*
(3) *(Bessel's identity) $\forall x \in V$ the equality*
$$|\widehat{x}| = |x| \tag{3.8}$$
holds;
(4) *(Parseval's identity) $\forall x, y \in V$ we have that*
$$\langle x, y \rangle = \sum_{j=1}^{k} \langle x, v_j \rangle \overline{\langle y, v_j \rangle}. \tag{3.9}$$

4. Riesz Representation Theorem

Definition 4.1. Suppose that V and W are complex vector spaces. A map $A : V \to W$ is called conjugate linear if $\forall x, y \in V, \forall \lambda, \mu \in \mathbb{C}$ the following equality holds
$$A(\lambda x + \mu y) = \overline{\lambda} A(x) + \overline{\mu} A(y). \tag{4.1}$$

Proposition 4.2 (Riesz Representation Theorem)**.** *Suppose that V is a finite-dimensional inner product space. Define the map $A : V \to V^*$ by*
$$A(x)(y) := \langle y, x \rangle. \tag{4.2}$$
Then A is an isomorphism if V is a real inner product space, and A is a conjugate linear bijective map (a conjugate isomorphism) if V is a complex inner product space.

Definition 4.3. Consider the map $A : V \to V^*$ defined in Proposition 4.2. For a covector $f \in V^*$ the preimage $A^{-1} f$ is called the Riesz vector of f.

Relevant chapters from the textbooks:

- Roman, Ch.9;
- Friedberg, Insel, Spence, Sections 6.1, 6.2;
- Axler, Ch.6.