

A Bit About Hilbert Spaces

David Rosenberg

New York University

February 24, 2016

Inner Product Space (or “Pre-Hilbert” Spaces)

An **inner product space** (over reals) is a vector space \mathcal{V} and an **inner product**, which is a mapping

$$\langle \cdot, \cdot \rangle : \mathcal{V} \times \mathcal{V} \rightarrow \mathbf{R}$$

that has the following properties $\forall x, y, z \in \mathcal{V}$ and $a, b \in \mathbf{R}$:

- Symmetry: $\langle x, y \rangle = \langle y, x \rangle$
- Linearity: $\langle ax + by, z \rangle = a \langle x, z \rangle + b \langle y, z \rangle$
- Postive-definiteness: $\langle x, x \rangle \geq 0$ and $\langle x, x = 0 \rangle \iff x = 0$.

Norm from Inner Product

For an inner product space, we define a norm as

$$\|x\| = \sqrt{\langle x, x \rangle}.$$

Example

\mathbf{R}^d with standard Euclidean inner product is an inner product space:

$$\langle x, y \rangle := x^T y \quad \forall x, y \in \mathbf{R}^d.$$

Norm is

$$\|x\| = \sqrt{x^T x}.$$

What norms can we get from an inner product?

Theorem (Parallelogram Law)

A norm $\|v\|$ can be generated by an inner product on \mathcal{V} iff $\forall x, y \in \mathcal{V}$

$$2\|x\|^2 + 2\|y\|^2 = \|x + y\|^2 + \|x - y\|^2,$$

and if it can, the inner product is given by the **polarization identity**

$$\langle x, y \rangle = \frac{\|x\|^2 + \|y\|^2 - \|x - y\|^2}{2}.$$

Example

ℓ_1 norm on \mathbf{R}^d is NOT generated by an inner product. [Exercise]

Is ℓ_2 norm on \mathbf{R}^d generated by an inner product?

Pythagorean Theroem

Definition

Two vectors are **orthogonal** if $\langle x, y \rangle = 0$. We denote this by $x \perp y$.

Definition

x is orthogonal to a set S , i.e. $x \perp S$, if $x \perp s$ for all $s \in S$.

Theorem (Pythagorean Theorem)

If $x \perp y$, then $\|x + y\|^2 = \|x\|^2 + \|y\|^2$.

Proof.

We have

$$\begin{aligned}\|x + y\|^2 &= \langle x + y, x + y \rangle \\ &= \langle x, x \rangle + \langle x, y \rangle + \langle y, x \rangle + \langle y, y \rangle \\ &= \|x\|^2 + \|y\|^2.\end{aligned}$$

Projection onto a Plane (Rough Definition)

- Choose some $x \in \mathcal{V}$.
- Let M be a subspace of inner product space \mathcal{V} .
- Then m_0 is the **projection of x onto M** ,
 - if $m_0 \in M$ and is the closest point to x in M .
- In math: For all $m \in M$,

$$\|x - m_0\| \leq \|x - m\|.$$

Hilbert Space

- Projections exist for all finite-dimensional inner product spaces.
- We want to allow infinite-dimensional spaces.
- Need an extra condition called **completeness**.
- A space is **complete** if all Cauchy sequences in the space converge.

Definition

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

Example

Any finite dimensional inner product space is a Hilbert space.

The Projection Theorem

Theorem (Classical Projection Theorem)

- \mathcal{H} a Hilbert space
- M a closed subspace of \mathcal{H}
- For any $x \in \mathcal{H}$, there **exists a unique** $m_0 \in M$ for which

$$\|x - m_0\| \leq \|x - m\| \quad \forall m \in M.$$

- This m_0 is called the **[orthogonal] projection of x onto M** .
- Furthermore, $m_0 \in M$ is the projection of x onto M iff

$$x - m_0 \perp M.$$

Projection Reduces Norm

Theorem

Let M be a closed subspace of \mathcal{H} . For any $x \in \mathcal{H}$, let $m_0 = \text{Proj}_M x$ be the projection of x onto M . Then

$$\|m_0\| \leq \|x\|.$$

Proof.

$$\begin{aligned}\|x\|^2 &= \|m_0 + (x - m_0)\|^2 \text{ (note: } x - m_0 \perp m_0\text{)} \\ &= \|m_0\|^2 + \|x - m_0\|^2 \text{ by Pythagorean theorem} \\ \|m_0\|^2 &= \|x\|^2 - \|x - m_0\|^2 \\ \|m_0\|^2 &\leq \|x\|^2\end{aligned}$$

