Beyond Vectors

Hung-yi Lee

Introduction

- Many things can be considered as “vectors”.
  - E.g. a function can be regarded as a vector
- We can apply the concept we learned on those “vectors”.
  - Linear combination
  - Span
  - Basis
  - Orthogonal ……
- Reference: Chapter 6

Are they vectors?

Are they vectors?

- A matrix

$$A = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \Rightarrow \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \end{bmatrix}$$

- A linear transform
- A polynomial

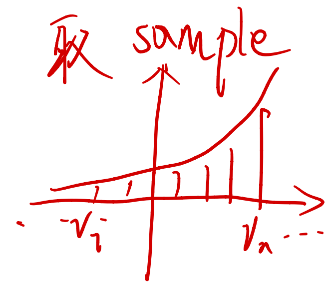
$$p(x) = a_0 + a_1 x + \cdots + a_n x^n \Rightarrow \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \end{bmatrix}$$

Are they vectors?

What is the zero vector?

- Any function is a vector?

$$f(t) = e^t \Rightarrow v = \begin{bmatrix} \vdots \\ ? \\ \vdots \end{bmatrix}$$



$$g(t) = t^2 - 1 \Rightarrow g = \begin{bmatrix} \vdots \\ ? \\ \vdots \end{bmatrix}$$

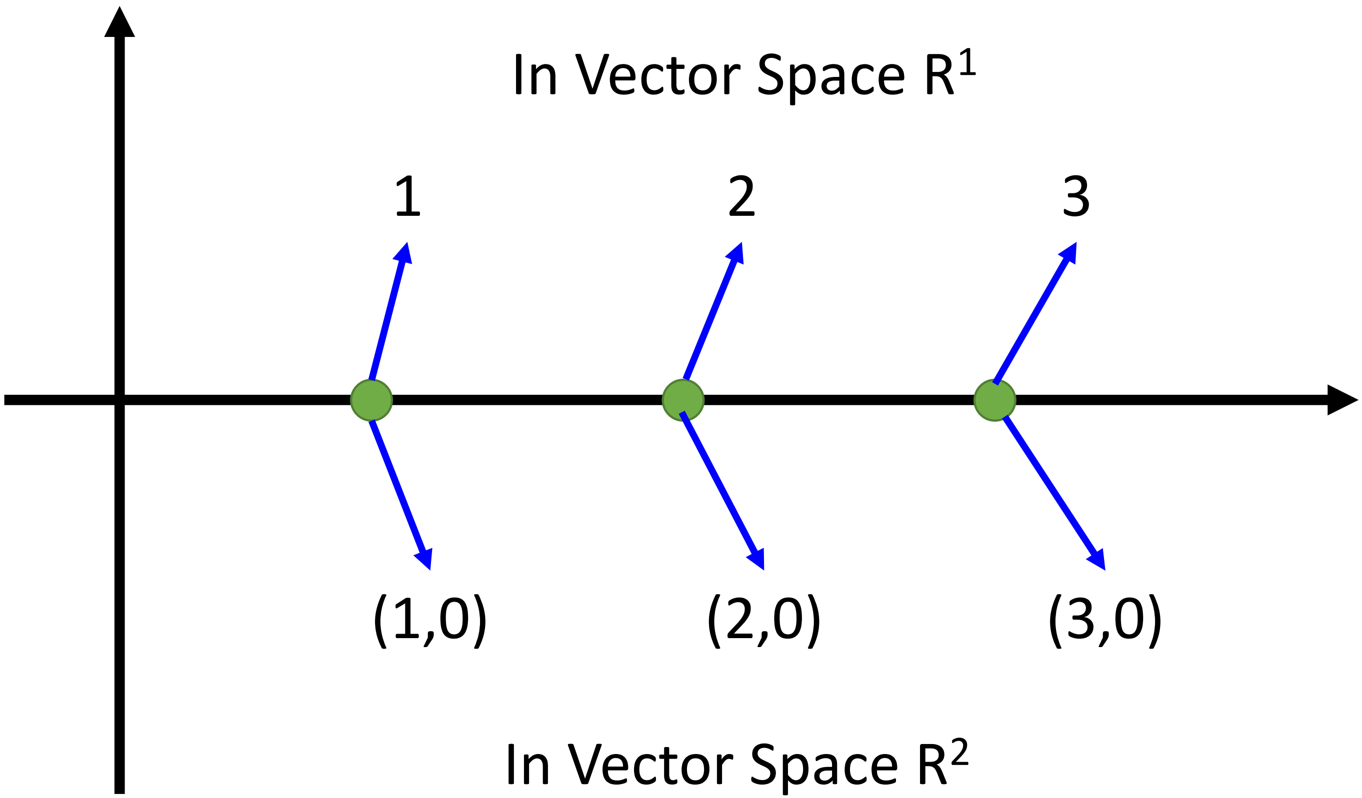
$$\mathrm{h}(t) = e^t + t^2 - 1 \Rightarrow v + g$$

What is a vector?

R^n is a vector space

- If a set of objects V is a **vector space**, then the objects are "vectors".
- Vector space:
  - There are operations called "***addition***" and "***scalar multiplication***".
  - u, v and w are in V, and a and b are scalars. u+v and au are unique elements of V
- The following axioms hold:
  - $u + v = v + u$, $(u + v) + w = u + (v + w)$
  - There is a "zero vector" 0 in V such that $u + 0 = u$ unique
  - There is –u in V such that $u + (-u) = 0$
  - $1u = u$, $(ab)u = a(bu)$, $a(u+v) = au + av$, $(a+b)u = au + bu$

Objects in Different Vector Spaces



Objects in Different Vector Spaces

All the polynomials with degree less than or equal to 2 as a vector space

$$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

$$f(t) = 1 \qquad g(t) = t + 1 \qquad h(t) = t^2 + t + 1$$

Vectors with infinite dimensions

All functions as a vector space

Subspaces

Review: Subspace

- A vector set V is called a subspace if it has the following three properties:
- 1. The zero vector **0** belongs to V
- 2. If **u** and **w** belong to V, then **u+w** belongs to V

Closed under (vector) addition

- 3. If **u** belongs to V, and c is a scalar, then c**u** belongs to V

Closed under scalar multiplication

Are they subspaces?

- All the functions pass 0 at t_0 yes
- All the matrices whose trace equal to zero yes
- All the matrices of the form

$$\begin{bmatrix} a & a+b \\ b & 0 \end{bmatrix}$$ yes

- All the continuous functions yes
- All the polynomials with degree n no $-1v_1 + 1v_2$ 可能不是 n
- All the polynomials with degree less than or equal to n yes

P: all polynomials, P_n: all polynomials with degree less than or equal to n

Linear Combination and Span

Linear Combination and Span

- Matrices

$$S = \left\{ \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \right\}$$

Linear combination with coefficient a, b, c

$$a \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} + b \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} + c \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} a & b \\ c & -a \end{bmatrix}$$

What is Span S?

All 2x2 matrices whose trace equal to zero

Linear Combination and Span

- Polynomials

$$S = \{1, x, x^2, x^3\}$$

Is $f(x) = 2 + 3x - x^2$ linear combination of the "vectors" in S?

$$f(x) = 2 \cdot 1 + 3 \cdot x + (-1) \cdot x^2$$

$$Span\{1, x, x^2, x^3\} \qquad = P_3$$

$$Span\{1, x, \cdots, x^n, \cdots\} \qquad = P$$

Linear Transformation

Linear transformation

- A mapping (function) T is called linear if for all "vectors" u, v and scalars c:
- Preserving vector addition:

$$T(u+v) = T(u) + T(v)$$

- Preserving vector multiplication: $T(cu) = cT(u)$

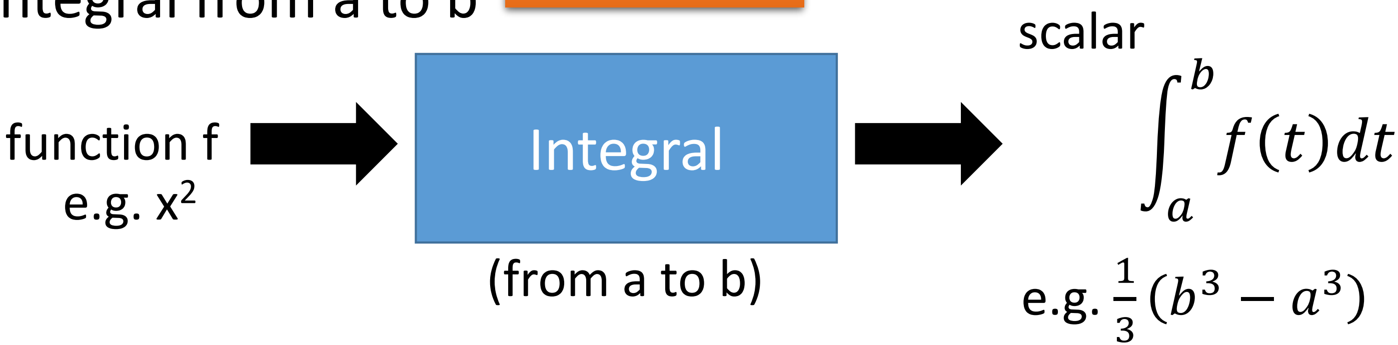
Is matrix transpose linear?

Input: m x n matrices, output: n x m matrices

Linear transformation

- Derivative: linear?

- Integral from a to b linear?



Null Space and Range

- Null Space
  - The null space of T is the set of all vectors such that T(v)=0
  - What is the null space of matrix transpose? 0
- Range
  - The range of T is the set of all images of T.
  - That is, the set of all vectors T(v) for all v in the domain
  - What is the range of matrix transpose?

$m \times n \longrightarrow m \times n$

domain co-domain = range

One-to-one and Onto

- U: $\mathcal{M}_{m\times n} \to \mathcal{M}_{n\times m}$ defined by $U(A) = A^T$.
  - Is U one-to-one? yes
  - Is U onto? yes

range($\mathcal{P}_2$)

- D: $\mathcal{P}_3 \to \mathcal{P}_3$ defined by $D(f) = f'$
  - Is D one-to-one? no
  - Is D onto? no

$3x \to 3$

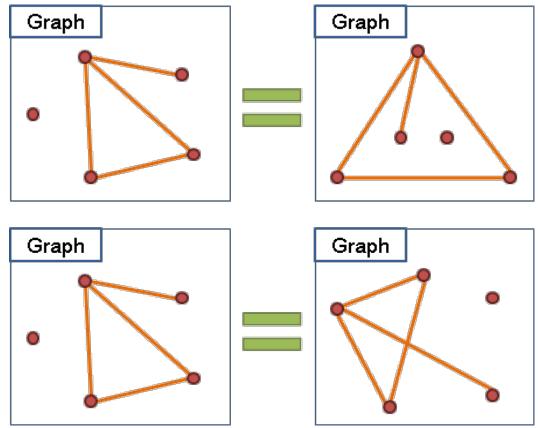
$3x+2 \to 3$

x^3 不行

Isomorphism (同構)

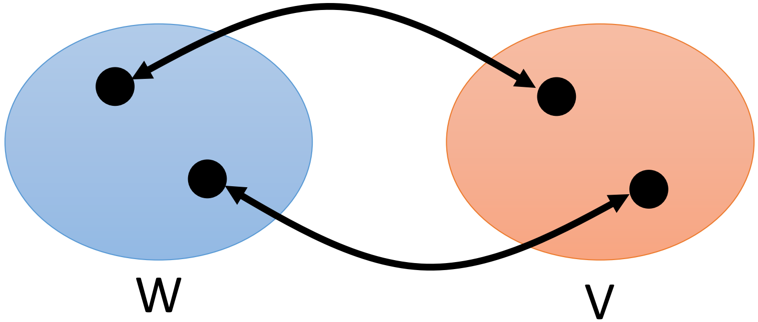
Biology

Graph



Chemistry

Isomorphism



- Let V and W be vector space.
- A linear transformation T: V→W is called an isomorphism if it is one-to-one and onto
    - Invertible linear transform
    - W and V are isomorphic.

Example 1: U: $\mathcal{M}_{m\times n} \rightarrow \mathcal{M}_{n\times m}$ defined by $U(A) = A^T$.

Example 2: T: $\mathcal{P}_2 \rightarrow \mathcal{R}^3$

$$T\left(a + bx + \frac{c}{2}x^2\right) = \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

Basis

A basis for subspace V is a linearly independent generation set of V.

Independent

- Example

S = {x^2 - 3x + 2, 3x^2 – 5x, 2x – 3} is a subset of $\mathscr{P}_2$.

Is it linearly independent?

$$3(x^2-3x+2)+(-1)(3x^2-5x)+2(2x-3)=\mathbf{0}$$

No

- Example

$$S=\left\{\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix},\begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix},\begin{bmatrix}0 & 0\\ 1 & 0\end{bmatrix}\right\}$$ is a subset of 2x2 matrices.

Is it linearly independent?

$$a\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}+b\begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}+c\begin{bmatrix}0 & 0\\ 1 & 0\end{bmatrix}=\begin{bmatrix}a & b\\ c & -a\end{bmatrix}=\begin{bmatrix}0 & 0\\ 0 & 0\end{bmatrix}$$

implies that $a = b = c = 0$

Yes

Independent

If $\{v_1, v_2, \ldots\ldots, v_k\}$ are L.I., and T is an isomorphism, $\{T(v_1), T(v_2), \ldots\ldots, T(v_k)\}$ are L.I.

- Example

The infinite vector set $\{1, x, x^2, \cdots, x^n, \cdots\}$

Is it linearly independent?

$\Sigma_i c_i x^i = 0$ implies $c_i = 0$ for all i.

Yes

- Example

$S = \{e^t, e^{2t}, e^{3t}\}$ Is it linearly independent?

Yes

$ae^t + be^{2t} + ce^{3t} = 0$ $\quad a + b + c = 0$

微分

$ae^t + 2be^{2t} + 3ce^{3t} = 0$ $\quad a + 2b + 3c = 0$

$ae^t + 4be^{2t} + 9ce^{3t} = 0$ $\quad a + 4b + 9c = 0$

Basis

- Example

For the subspace of all 2 x 2 matrices,

The basis is

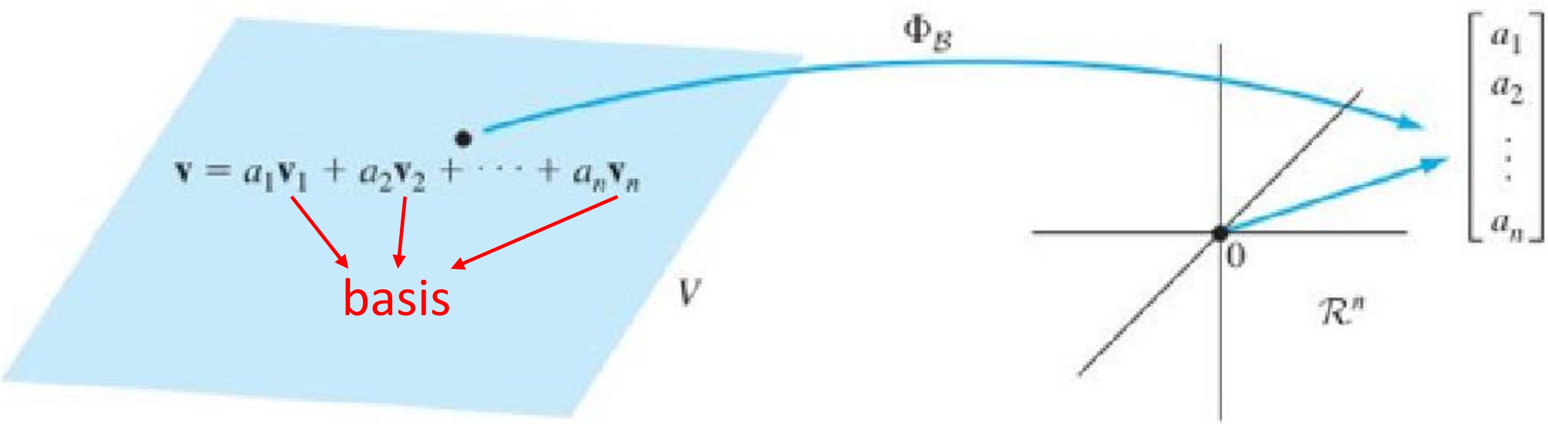
$$S = \left\{ \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \right\}$$ Dim = 4

- Example

$S = \{1, x, x^2, \cdots, x^n, \cdots\}$ is a basis of $\mathscr{P}$. Dim = inf

Vector Representation of Object

- Coordinate Transformation



P_n: Basis: $\{1, x, x^2, \cdots, x^n\}$

$$p(x) = a_0 + a_1 x + \cdots + a_n x^n \Rightarrow \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \end{bmatrix}$$

Matrix Representation of Linear Operator

- Example:
  - D (derivative): $P_2 \rightarrow P_2$

Represent it as a matrix

$$\begin{tikzcd}
\begin{bmatrix}2\\-3\\5\end{bmatrix} \text{ vector} \arrow[r, "\text{Multiply a matrix}"'] & \text{vector } \begin{bmatrix}-3\\10\\0\end{bmatrix} \\
2-3x+5x^2 \text{ polynomial} \arrow[u] \arrow[r, "\text{Derivative}"'] & \text{polynomial } -3+10x \arrow[u]
\end{tikzcd}$$

Matrix Representation of Linear Operator

- Example:
  - D (derivative): $P_2 \rightarrow P_2$

Represent it as a matrix

$$\begin{bmatrix}1\\0\\0\end{bmatrix} \quad \begin{bmatrix}0\\1\\0\end{bmatrix} \quad \begin{bmatrix}0\\0\\1\end{bmatrix}$$

$$\begin{tikzcd}
\text{vector} \arrow[r, "\text{Multiply a matrix}"'] & \text{vector} \\
\text{polynomial} \arrow[u] \arrow[r, "\text{Derivative}"'] & \text{polynomial} \arrow[u]
\end{tikzcd}$$

$$\begin{bmatrix}0\\0\\0\end{bmatrix} \quad \begin{bmatrix}1\\0\\0\end{bmatrix} \quad \begin{bmatrix}0\\2\\0\end{bmatrix}$$

$$\begin{bmatrix}0 & 1 & 0\\0 & 0 & 2\\0 & 0 & 0\end{bmatrix}$$

1

x

x^2

0

1

$2x$

Matrix Representation of Linear Operator

$$\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 2 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 5 \\ -4 \\ 3 \end{bmatrix}$$

- Example:
  - D (derivative): $P_2 \to P_2$

Represent it as a matrix

Not invertible

$$\begin{tikzcd}[column sep=huge, row sep=huge]
\begin{bmatrix} 5 \\ -4 \\ 3 \end{bmatrix} \text{ vector} \arrow[r, "\text{Multiply a matrix}"'] & \text{vector } \begin{bmatrix} -4 \\ 6 \\ 0 \end{bmatrix} \\
5 - 4x + 3x^2 \text{ polynomial} \arrow[u] \arrow[r, "\text{Derivative}"'] & \text{polynomial } -4 + 6x \arrow[u]
\end{tikzcd}$$

$$\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 2 \\ 0 & 0 & 0 \end{bmatrix}$$

Matrix Representation of Linear Operator

- Example:
  - D (derivative): Function set F → Function set F
  - Basis of F is $\{e^t \cos t, e^t \sin t\}$

$\begin{bmatrix}1\\0\end{bmatrix}$ $\begin{bmatrix}0\\1\end{bmatrix}$

vector $\xrightarrow{\text{invertible}}$ vector

$\begin{bmatrix}1\\-1\end{bmatrix}$ $\begin{bmatrix}1\\1\end{bmatrix}$

Multiply a matrix

$$\begin{bmatrix}1 & 1\\-1 & 1\end{bmatrix}$$

$e^t \cos t$

$e^t \sin t$

Function in F $\xrightarrow{\text{Derivative}}$ Function in F

$\boxed{(1)e^t \cos t + (-1)e^t \sin t}$

$\boxed{(1)e^t \cos t + (1)e^t \sin t}$

Matrix Representation of Linear Operator

Basis of F is
$\{e^t \cos t\,, e^t \sin t\}$

$$\begin{bmatrix} 1/2 & -1/2 \\ 1/2 & 1/2 \end{bmatrix}$$

$$\begin{bmatrix} -1/2 \\ 1/2 \end{bmatrix} \quad \text{vector} \quad \underset{\text{Multiply a matrix}}{\overset{\longleftarrow}{\longrightarrow}} \quad \text{vector} \quad \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Multiply a matrix

$$\begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}$$

Antiderivative 不定积分

$$\boxed{(-\tfrac{1}{2})e^t \cos t + (\tfrac{1}{2})e^t \sin t}$$

Function in F ⟵ Antiderivative / Derivative ⟶ Function in F

$e^t \sin t$

Derivative

Eigenvalue and Eigenvector

$T(v) = \lambda v$, $v \neq 0$, v is eigenvector, λ is eigenvalue

Eigenvalue and Eigenvector

- Consider derivative (linear transformation, input & output are functions)

yes

a

Is $f(t) = e^{at}$ an "eigenvector"? What is the "eigenvalue"?

Every scalar is an eigenvalue of derivative.

- Consider Transpose (also linear transformation, input & output are functions)

Is $\lambda = 1$ an eigenvalue?

Symmetric matrices form the eigenspace

Is $\lambda = -1$ an eigenvalue?

Skew-symmetric matrices form the eigenspace.

Symmetric:

$$A^T = A$$

Skew-symmetric:

$$A^T = -A$$

Consider Transpose of 2x2 matrices

tran 的逆是 tran

$$\begin{bmatrix}1\\0\\0\\0\end{bmatrix}\begin{bmatrix}0\\1\\0\\0\end{bmatrix}\begin{bmatrix}0\\0\\1\\0\end{bmatrix}\begin{bmatrix}0\\0\\0\\1\end{bmatrix}$$

vector

$$\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&1\end{bmatrix}$$

$$\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&1\end{bmatrix}$$

vector

$$\begin{bmatrix}1\\0\\0\\0\end{bmatrix}\begin{bmatrix}0\\0\\1\\0\end{bmatrix}\begin{bmatrix}0\\1\\0\\0\end{bmatrix}\begin{bmatrix}0\\0\\0\\1\end{bmatrix}$$

What are the eigenvalues?

$$\begin{bmatrix}1&0\\0&0\end{bmatrix}$$ 2x2 matrices $\xrightarrow{\text{transpose}}$ 2x2 matrices $$\begin{bmatrix}1&0\\0&0\end{bmatrix}$$

Eigenvalue and Eigenvector

- ***Consider Transpose of 2x2 matrices***

Matrix representation of transpose

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Characteristic polynomial

$$(t-1)^3(t+1)$$

$$\lambda = 1$$

Symmetric matrices

$$\begin{bmatrix} a & b \\ b & c \end{bmatrix}$$

Dim=3

$$\lambda = -1$$

Skew-symmetric matrices

$$\begin{bmatrix} 0 & a \\ -a & 0 \end{bmatrix}$$

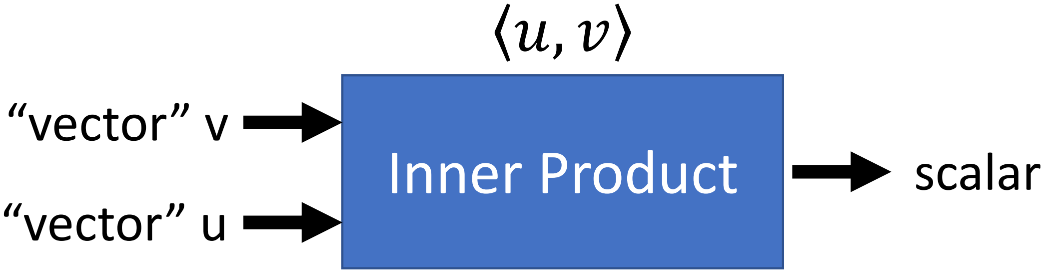
Dim=1

Inner Product

Inner Product

Norm (length): $\|v\| = \sqrt{\langle v, v \rangle}$

Orthogonal: Inner product is zero



For any vectors u, v and w, and any scalar a, the following axioms hold:

1. $\langle u, u \rangle > 0$ if $u \neq 0$
2. $\langle u, v \rangle = \langle v, u \rangle$
3. $\langle u + v, w \rangle = \langle u, w \rangle + \langle v, w \rangle$
4. $\langle au, v \rangle = a\langle u, v \rangle$

Dot product is a special case of **inner product**

Can you define other inner product for normal vectors?

Inner Product

- Inner Product of Matrix

Frobenius inner product

$$\langle A, B\rangle = trace(AB^T) = trace(BA^T)$$

$$\left\langle \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}, \begin{bmatrix} 5 & 6 \\ 7 & 8 \end{bmatrix} \right\rangle = 1 \cdot 5 + 2 \cdot 6 + 3 \cdot 7 + 4 \cdot 8 = 70$$

Element-wise multiplication

$$A = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \qquad \|A\| = \sqrt{1^2 + 2^2 + 3^2 + 4^2}$$

Inner Product

1. $\langle u, u \rangle > 0$ if $u \neq 0$
2. $\langle u, v \rangle = \langle v, u \rangle$
3. $\langle u + v, w \rangle = \langle u, w \rangle + \langle v, w \rangle$
4. $\langle au, v \rangle = a\langle u, v \rangle$

- Inner product for general functions

$$\langle g, h \rangle = \int_{-1}^{1} g(x)h(x)\, dx$$

Is $g(x) = 1$ and $h(x) = x$ orthogonal?

yes

$$\langle g, h \rangle = \sum_{i=-10}^{10} g(i)h(i)$$

N

Can it be inner product for general functions?

这21个点都为0
其它不为0

Orthogonal/Orthonormal Basis

- Let u be any vector, and w is the orthogonal projection of u on subspace W.
- Let $S = \{v_1, v_2, \cdots, v_k\}$ be an orthogonal basis of W.

$$w = c_1 v_1 + c_2 v_2 + \cdots + c_k v_k$$

$$\langle u \cdot v_1 \rangle \leftarrow \frac{u \cdot v_1}{\|v_1\|^2} \qquad \frac{u \cdot v_2}{\|v_2\|^2} \qquad \qquad \frac{u \cdot v_k}{\|v_k\|^2}$$

- Let $S = \{v_1, v_2, \cdots, v_k\}$ be an orthonormal basis of W.

$$w = c_1 v_1 + c_2 v_2 + \cdots + c_k v_k$$

$$u \cdot v_1 \qquad u \cdot v_2 \qquad \qquad u \cdot v_k$$

$$\hookrightarrow \langle u \cdot v_1 \rangle$$

Orthogonal Basis

Let $\{u_1, u_2, \cdots, u_k\}$ be a basis of a subspace V. How to transform $\{u_1, u_2, \cdots, u_k\}$ into an orthogonal basis $\{v_1, v_2, \cdots, v_k\}$?

$$v_1 = u_1$$

$$v_2 = u_2 - \frac{\langle u_2, v_1 \rangle}{\|v_1\|^2} v_1$$

- - - - -

Gram-Schmidt Process

Then $\{v_1, v_2, \cdots, v_k\}$ is an orthogonal basis for W

After normalization, you can get orthonormal basis.

Orthogonal/Orthonormal Basis

- Find orthogonal/orthonormal basis for P_2
  - Define an inner product of P_2 by

$$\langle f(x), g(x)\rangle = \int_{-1}^{1} f(t)g(t)\,dt$$

  - Find a basis $\{1, x, x^2\}$ $\overset{u_1, u_2, u_3}{}$ $\Rightarrow$ v_1, v_2, v_3

$$\mathbf{v}_1 = \mathbf{u}_1 = 1$$

$$\mathbf{v}_2 = \mathbf{u}_2 - \frac{\langle \mathbf{u}_2, \mathbf{v}_1\rangle}{\|\mathbf{v}_1\|^2}\mathbf{v} = x$$

$\int_{-1}^{1} x^2 dx$

$$\mathbf{v}_3 = \mathbf{u}_3 - \frac{\langle \mathbf{u}_3, \mathbf{v}_1\rangle}{\|\mathbf{v}_1\|^2}\mathbf{v}_1 - \frac{\langle \mathbf{u}_3, \mathbf{v}_2\rangle}{\|\mathbf{v}_2\|^2}\mathbf{v}_2 = x^2 - \frac{1}{3}$$

$\int_{-1}^{1} 1\, dx$

Orthogonal/Orthonormal Basis

- Find orthogonal/orthonormal basis for P_2
  - Define an inner product of P_2 by

$$\langle f(x), g(x) \rangle = \int_{-1}^{1} f(t)g(t)\,dt$$

  - Get an orthogonal basis $\{1, x, x^2 - 1/3\}$

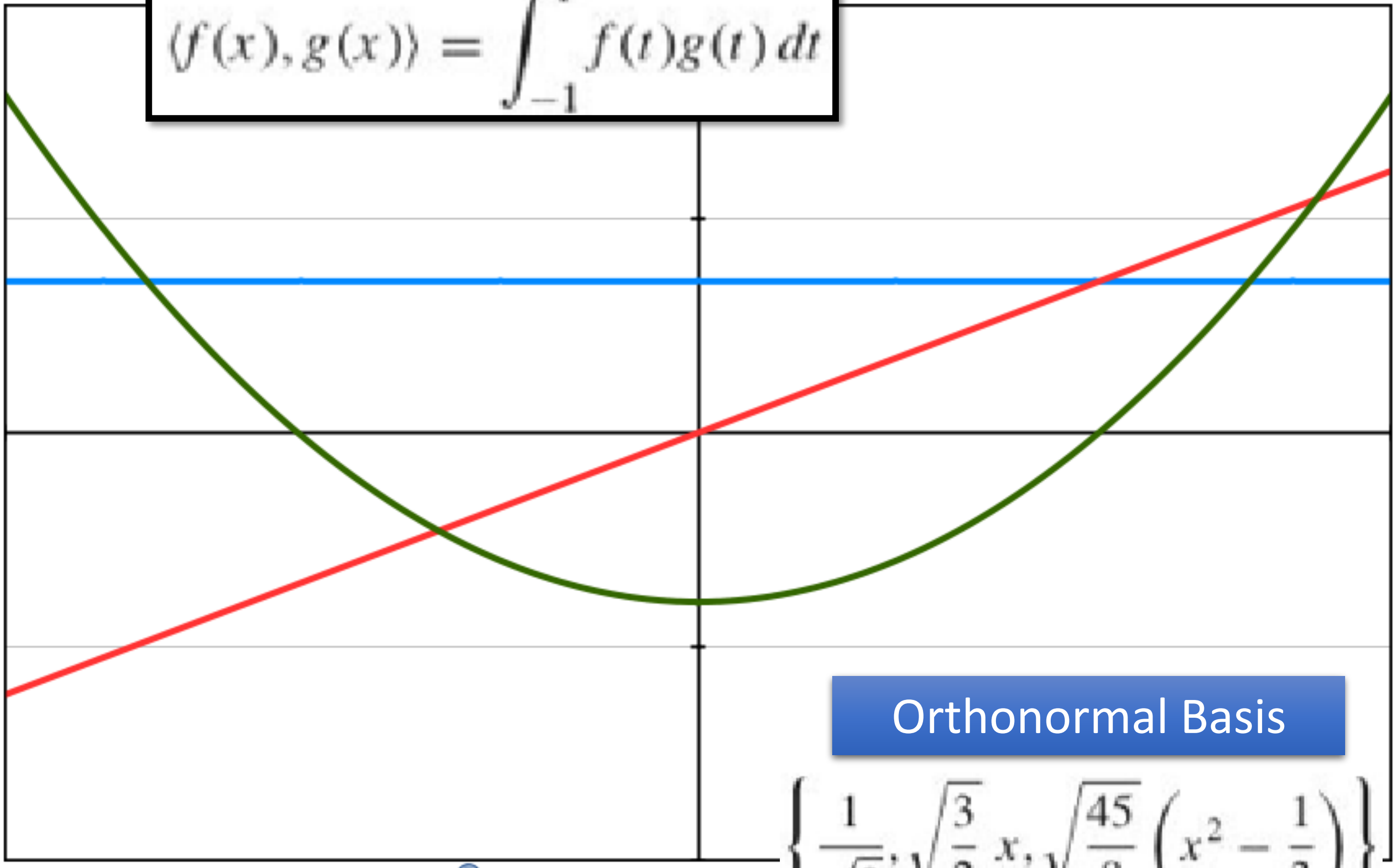
$$\|\mathbf{v}_1\| = \sqrt{\int_{-1}^{1} 1^2\,dx} = \sqrt{2} \qquad \|\mathbf{v}_2\| = \sqrt{\int_{-1}^{1} x^2\,dx} = \sqrt{\frac{2}{3}}$$

$$\|\mathbf{v}_3\| = \sqrt{\int_{-1}^{1} \left(x^2 - \frac{1}{3}\right)^2 dx} = \sqrt{\frac{8}{45}}$$

Orthonormal Basis

$$\left\{ \frac{1}{\sqrt{2}}, \sqrt{\frac{3}{2}}\,x, \sqrt{\frac{45}{8}}\left(x^2 - \frac{1}{3}\right) \right\}$$

$$\langle f(x), g(x)\rangle = \int_{-1}^{1} f(t)g(t)\,dt$$



Orthonormal Basis

$$\left\{\frac{1}{\sqrt{2}}, \sqrt{\frac{3}{2}}\,x, \sqrt{\frac{45}{8}}\left(x^2-\frac{1}{3}\right)\right\}$$